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Research Article

Performance Analyses Of Solar Water Heating System With Thermal Storage Using SAM Simulation

Abdulrahman Y. Abu-Aeshah[1*], Muftah A. Alghafoud[1], Mustafa M. Elsherif[1]

[1] Department of Mechanical Technologies, Higher Institute of Engineering Technologies, Zliten, Libya

*Corresponding author: abdalrhmanabuaisha@gmail.com

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Abstract: This paper examines the development and evaluation of a solar water heating system integrated with a 900-liter thermal storage tank. Heated water from the solar collectors is stored in the tank and made available to meet domestic demand as required. The study outlines a methodological framework for designing a solar water heating system with thermal storage, capable of providing adequate hot water for an average household in Misrata, Libya. The System Advisor Model (SAM) was employed to perform detailed simulations, calculating hot water consumption and the associated system costs. The solar collector, with an area of 4.4079 m^2, achieved an efficiency of 28%, and the system's circulation pump required 16 W of power. The simulation results provided insights into monthly energy production and annual savings, with total energy savings amounting to 6050 kWh. The auxiliary energy required when supplemented by solar energy was 2409 kWh, compared to 8542.5 kWh without solar integration. Additionally, the cost of energy (COE) for the system was determined to be 25 ¢/kWh. These findings highlight the potential for solar water heating systems to enhance energy efficiency and reduce reliance on conventional energy sources in residential applications.

Keywords: Solar Water Heating System, Thermal Storage Tank, System Advisor Model, Energy Savings.

1. Introduction

Global warming has emerged as one of the most pressing challenges of our time, necessitating the development of strategies to optimize energy utilization for the collective benefit of humanity [1-5]. The rapid expansion of the global population has driven a significant increase in energy demand, with reliance on non-renewable resources serving as a primary contributor to global warming. Consequently, there is a growing focus on enhancing the efficiency of heating systems and mitigating greenhouse gas emissions [6-11].

Thermal energy storage (TES) systems play a pivotal role in this transition by enabling consumers to reduce electricity costs, particularly by circumventing higher tariffs during peak demand periods [12-18]. TES systems allow for the collection of thermal energy whenever it is available, with the capability to store and deploy this energy across different time frames or even seasons [18-21]. For example, solar thermal collectors can harvest heat during summer months, which can subsequently be utilized for space heating during the winter. This decoupling of energy supply from demand underscores the strategic significance of energy storage technologies, empowering users to reduce dependency on conventional energy practices while fostering a more sustainable energy paradigm.

Hot water storage tanks represent one of the most efficient and cost-effective technologies for thermal energy storage, owing to the low cost and high specific heat capacity of water. These tanks are typically installed either in the basement or at ground level within buildings [22-25]. Cylindrical designs are preferred due to their ability to minimize heat loss. The heat exchange process occurs directly within the tank, with a control system managing the charging and discharging of thermal energy to optimize efficiency.

Solar energy serves as the primary heat source for these systems, with solar panels commonly mounted on rooftops to capture and convert solar radiation [26-30]. The effectiveness of solar energy storage is influenced by various factors, including the tank's internal temperature and the quality of the materials used, particularly the metal components. Sensible heat storage, a method in which the material's temperature increases or decreases to store energy, is the predominant mechanism employed in these systems [31-33].

This study aims to present a systematic approach to designing a solar water heating system integrated with thermal energy storage, specifically tailored to meet the hot water demands of a small household. The design methodology leverages the System Advisor Model (SAM), a suite of computational tools capable of accurately estimating hot water consumption and associated system costs. The proposed system seeks to optimize energy efficiency and reduce reliance on conventional energy sources, contributing to more sustainable residential energy solutions.

2. Design Parameters:

The design parameters of a solar water heating system must be carefully determined based on specific user requirements. These parameters include the dimensions of the solar thermal collector, the capacity of the heat storage tank, the configuration of the heat exchanger, the specifications of the circulating pump, and the design of sensing and control instrumentation. Solar energy is harnessed using a concentrating solar collector, which elevates the temperature of the circulating fluid in accordance with user-defined needs and the intensity of available solar irradiance. The integration of these components ensures an efficient and reliable system capable of meeting the thermal energy demands while optimizing performance under varying operational conditions.

A. *Solar Collector:*

The system simulation conducted using the SAM software utilized components and configurations available within its comprehensive library. The solar collector model employed in the simulation was selected from the predefined options within the SAM database, ensuring compatibility with the system design and performance requirements. Table 1 provides a detailed summary of the key parameters of the solar collector, including specifications critical to its operation and integration within the overall solar water heating system.

Table 1. The parameters of the collector.

Quantity	Value
SRCC number	20060 15D
Type	Glazed flat-plate
Area	4.49
Test flow rate	0.0617
FRta	0.658

B. *System Description and Schematics:*

In this study, the proposed system is a closed-loop configuration that operates as both active and indirect. The system comprises several interconnected components, including a collector fluid loop consisting of fluid manifolds, collector plates, a storage tank with an integrated heat exchanger, a drain-back tank, a circulating pump (mounted near the collector plates on the roof and powered by a DC motor driven by a photovoltaic panel), a controller unit, and additional auxiliary components. To ensure the continuous availability of hot water during cloudy weather conditions, the storage tank is equipped with two auxiliary heating elements powered by the main electrical supply. The drain-back tank is strategically placed indoors to prevent freezing in colder climates and positioned at an elevated level to minimize the power required for pumping. Figure 1 illustrates the configuration of the solar energy-based water heating system, highlighting the integration of these components to optimize efficiency and reliability.

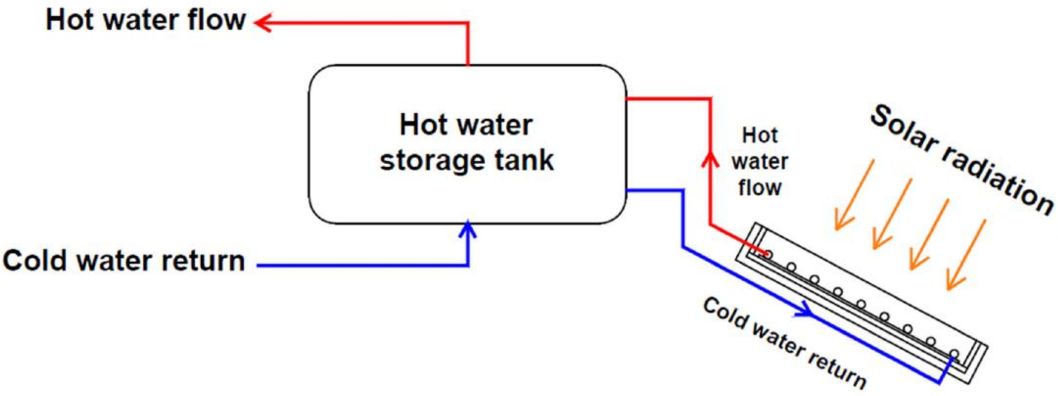

Figure 1. A water heating system using solar energy.

Within the storage tank, a heat exchanger facilitates the transfer of thermal energy via natural convection from the solar collector loop to the solar storage tank. On the roof, the system incorporates two 4.4 m² glazed collectors mounted on a support frame. These collectors are connected using foam-insulated copper piping with a diameter of 25 mm to minimize heat loss and ensure efficient energy transfer. The system is designed to circulate water through the solar collectors only when solar irradiance reaches a sufficient threshold to justify energy collection. The circulating pump is activated by the collector panel when solar radiation exceeds the predefined level. This process is controlled by a DC motor powered by the solar collector panel through an integrated linear current booster (LCB), which is equipped with a differential temperature controller. The LCB enables proportional speed control of the pump, dynamically adjusting its operation based on the variable output of the collector module. This setup ensures the system operates optimally under all levels of solar irradiance, enhancing efficiency. Moreover, the design allows the pump to initiate circulation with as little as one watt of power, ensuring functionality even under low solar radiation conditions.

The heat-transfer fluid (HTF) utilized in the system is a mixture of water and polypropylene glycol in a ratio of 60% to 40%, respectively. This fluid operates within an unpressurized, closed-loop configuration, ensuring its circulation through the collectors is separate from the potable water heated via the heat exchanger. When the pump is deactivated, the HTF drains from the sloped collectors and piping into the drain-back tank, effectively eliminating the risk of stagnation. This process is facilitated by air from the drain-back tank filling the collectors, thereby mitigating potential hazards associated with high temperatures and pressure in the loop, particularly during summer conditions. The heated water from the solar collectors is stored in a 900-liter standard water tank, ensuring sufficient capacity to meet household hot water demands efficiently and reliably. This design enhances system safety and performance while accommodating seasonal variations in solar energy availability.

C. *Solar radiation:*

Solar radiation data for the specified location (latitude 32.377533° N, longitude 15.092017° W) was imported from NASA on an hourly basis to ensure accurate simulation inputs. Figure 2 presents the monthly solar radiation profile as modeled using the System Advisor Model (SAM) software, leveraging the high-resolution data acquired from NASA. Additionally, Table 2 provides a comprehensive overview of the parameters utilized within SAM software for the simulation, detailing key variables and system configurations employed to optimize the performance analysis. This approach ensures the reliability of the simulation results and their applicability to the selected geographic location.

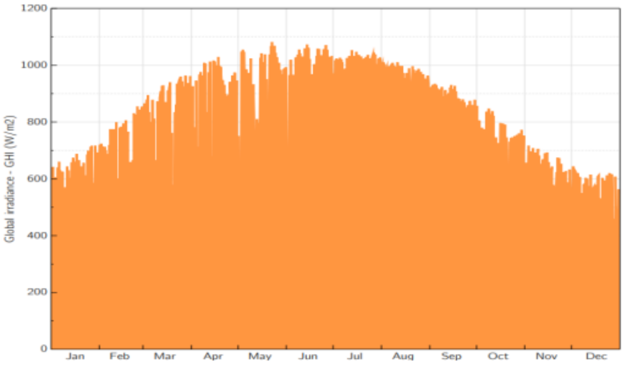

Figure 2. Monthly solar radiation This data collected from NASA.

Table 2. Parameters used in SAM software for simulation.

Parameter	Value	Unit	Noted
Location	Misruta		
Latitude	32.377533°		given
Longitude	15.092017		given
Storage tank			
Solar tank volume	0.9	m^3	
Solar tank height to diameter	1.4	m	
Solar tank heat loss coefficient	1	W/m^2. k	
Solar tank maximum	90	°C	
Heat exchanger			
Effectiveness	0.80	%	Assumed
Outlet set temperature	50	°C	Assumed
Room temperature	25	°C	Assumed
Piping			
Total piping length	25	m	
Pipe diameter	0.04	m	selected
Conductivity coefficient of copper pipe	0.043	W/m.K	
Thickness	25	mm	selected
Pump			
Pump power	16	W	
Pump efficiency	60	%	
Solar collector			
Area	4.4	m^2	
Tilt angle	50	Degree	
Azimuth angle	180	Degree	

3. Simulation in System Advisor Model and Results:

The optimal solar thermal system was modeled using the *System Advisor Model* (SAM) software, which integrates capabilities from the Transient System Simulation Tool (TRNSYS) with equivalent components from its simulation studio platform. The system was designed to include an initial water volume of 900 liters. SAM leverages user-provided inputs, such as installation and operational costs along with design parameters, to estimate energy costs and system performance for grid-connected power applications. Table 3 presents key performance metrics, including a capacity factor of 19.67%, annual energy savings of 6050 kWh, and a levelized cost of energy (COE) of 25 ¢/kWh. SAM operates as an hourly time-series simulation tool, capable of modeling the performance of both photovoltaic (PV) and solar water heating (SWH) systems using detailed weather data. Simulation results confirmed that the system performed as expected over the analyzed period. Detailed characteristics of the collector's temperature profile and useful energy gains were evaluated. The pump control strategy was observed to intermittently halt circulation during specific periods of the day, allowing stagnation within the collectors for brief intervals. This led to elevated collector temperatures, which were consistent with anticipated system behavior under varying solar irradiance conditions.

Table 3. Simulation Results System at 900L.

Metric	Value
Annual AC energy saved (year 1)	6,050 kWh
Aux with solar	2409.7 kWh
Aux without solar	8542.1 kWh
Capacity factor	19.6%
levelized costs of energy	25.75 ¢/kWh

Figure 3 illustrates the reduction in energy production, as modeled by SAM software, over several months due to the natural degradation of the system's performance. Monthly energy production showed seasonal variation, peaking in September and reaching its lowest levels in December. Figure 4 shows the transmitted irradiance. It gave satisfactory results during all periods of the year, with an almost constant rate in the summer.

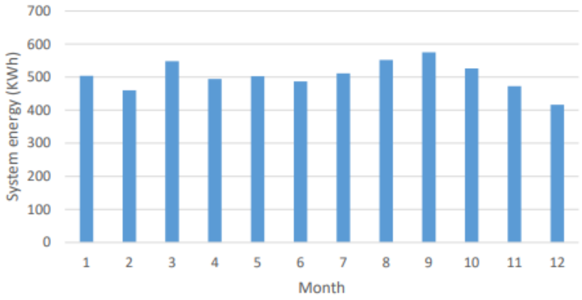

Figure 3. The decrease in energy production by SAM software.

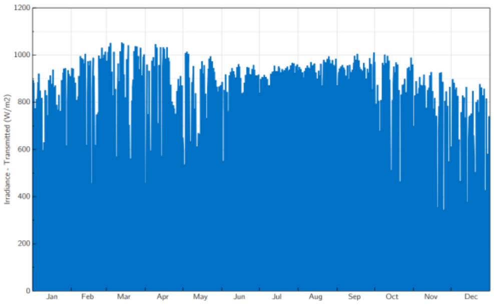

Figure 4. The transmitted irradiance.

Figure 5 depicts the annual peak temperatures achievable for energy storage. As expected, the summer months exhibit significantly higher temperatures compared to winter, reflecting the increased solar irradiance and system efficiency during this period.

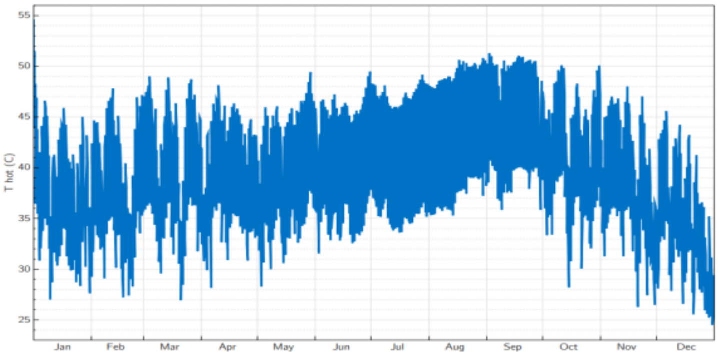

Figure 5. Temperature (Hot, in °C) over a period of 12 months.

Figure 6 highlights the seasonal disparity in stored heat, with the storage tank maintaining significantly higher temperatures in the summer months than in winter. This variation underscores the enhanced thermal storage capacity and availability of heat energy during periods of increased solar intensity, optimizing system performance during peak solar seasons.

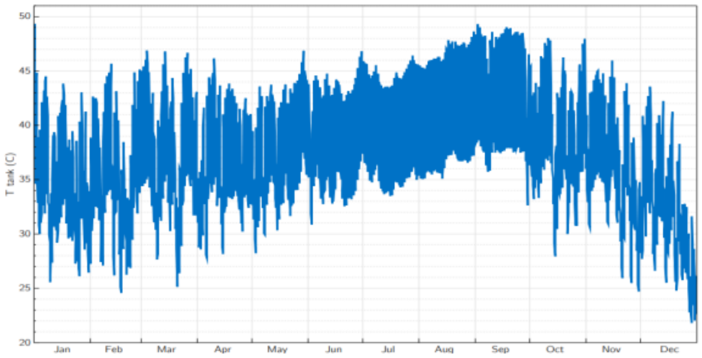

Figure 6. Temperature (in °C) of the tank over a period of 12 months.

Figure 7 illustrates the variation in the volume of hot water stored in the tank throughout the year, with the highest volumes observed in August and September. This trend is strongly correlated with external temperatures, as the increased solar irradiance and higher ambient temperatures during the summer months contribute to greater energy collection and storage efficiency. This seasonal dependency underscores the system's enhanced performance during periods of peak solar intensity. During the winter months, hot water consumption significantly increases compared to the summer, primarily due to the lower ambient temperatures necessitating greater demand for heated water. This seasonal variation is illustrated in Figure 8, which presents the annual usage of hot water, measured systematically throughout the year. Figure 9 depicts the annual energy losses (*Q loss*), revealing that the summer months exhibit the highest levels of energy loss. This trend can be attributed to elevated ambient temperatures and prolonged solar exposure, which increase heat dissipation from the system.

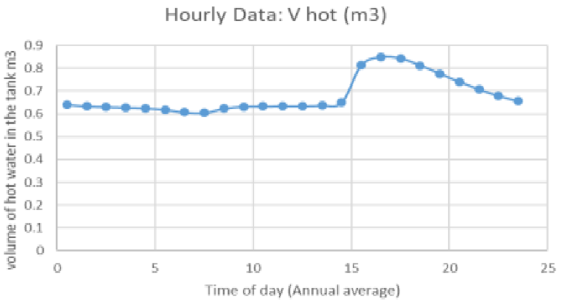

Figure 7. Volume of hot water (m3) in tank storage during a period of 12 months.

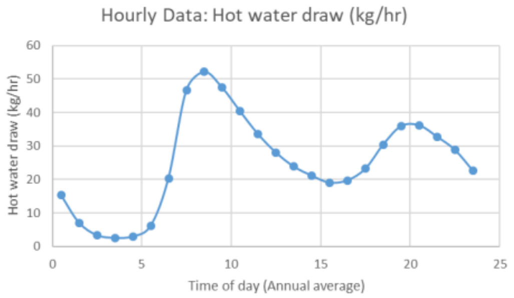

Figure 8. The Q loss of energy through the year, with the summer months having the highest loss of energy.

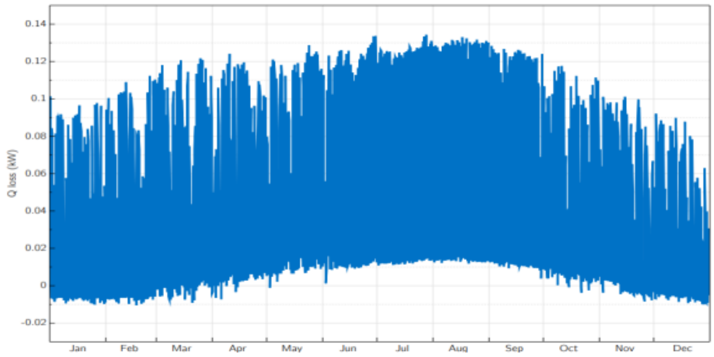

Figure 9. Q Loss (in KW) over a period of 12 months.

4. Conclusions:

The proposed design focused on a solar water heating system with thermal storage tailored for a small household, with primary objectives encompassing optimal technical performance, cost minimization, high reliability, and consistent availability. The selected site, Misrata, Libya, benefits from an average global solar radiation of approximately 5.85 kWh/m²/day and an average beam solar radiation of around 6.12 kWh/m²/day, making it a suitable location for solar energy applications. The system includes a 900-liter storage tank as the initial volume for heated water. Solar energy collected by the system is transferred to the storage tank, where it is made available for household use on demand. The study developed a design methodology for a solar water heating system with thermal storage capable of meeting the hot water requirements of a typical household in Misrata. The System Advisor Model (SAM) software was employed to simulate and analyze the system, focusing on hot water consumption and cost estimation. Key design parameters included a collector area of 4.4079 m² with a solar collector efficiency of 28% and a circulating pump powered by a 16 W system. The simulation results revealed annual energy savings of 6050 kWh, auxiliary energy consumption with solar energy of 2409 kWh, and auxiliary energy consumption without solar energy of 8542.5 kWh. The levelized cost of energy (COE) for the system was calculated at 25 ¢/kWh, underscoring the economic viability of the proposed design.

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ORCID
Abdulrahman Y. Abu-Aeshah https://orcid.org/0009-0006-8517-1731
Muftah A. Alghafoud https://orcid.org/0009-0002-4803-5651
Mustafa M. Elsherif https://orcid.org/0009-0006-5814-771X

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