
DESIGN AND PERFORMANCE ANALYSIS OF SOLAR-ASSISTED THERMAL SYSTEMS FOR INDUSTRIAL HEATING

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ABSTRACT

Industrial heating processes constitute a major share of global energy demand, with a predominant dependence on fossil fuels that results in increased operational costs and environmental concerns. In this context, solar-assisted thermal systems have gained attention as a sustainable alternative capable of supplementing conventional heating methods. These hybrid systems utilize solar energy to partially replace fossil fuel usage while ensuring uninterrupted thermal performance for industrial applications. This study focuses on the design and performance evaluation of a solar-assisted thermal system developed for medium-temperature industrial heating. The proposed system integrates solar collectors, a thermal energy storage unit, and an auxiliary heating mechanism to maintain stable operation under varying climatic conditions. Experimental analysis was conducted to evaluate system performance in terms of thermal efficiency, fuel savings, and outlet temperature characteristics. The results reveal that the system achieves a peak thermal efficiency of approximately 65–67% under optimal solar conditions, along with fuel savings reaching up to 45–48%. Additionally, the system is capable of delivering outlet temperatures close to 95°C, demonstrating its suitability for a wide range of industrial processes. The inclusion of thermal storage enhances system reliability by mitigating fluctuations in solar availability. Despite these advantages, performance is influenced by factors such as solar intermittency, system configuration, and initial investment requirements. Overall, the findings confirm that solar-

assisted thermal systems provide a practical and environmentally sustainable solution for industrial heating, particularly in regions with high solar irradiance.

KEYWORDS: Solar Thermal Systems, Industrial Heating, Energy Efficiency, Renewable Energy, Thermal Storage, Sustainability.

1. INTRODUCTION

The industrial sector is one of the largest consumers of energy worldwide, with a substantial share dedicated to thermal processes such as drying, curing, and heat treatment. Traditionally, these processes rely heavily on fossil fuels, leading to increased greenhouse gas emissions and rising operational costs. As global concerns regarding climate change intensify, there is a growing need to transition toward cleaner and more sustainable energy sources.

Solar energy, being abundant and renewable, offers a compelling alternative for industrial heating applications. Solar thermal systems convert solar radiation into heat, which can be utilized directly or stored for later use. When integrated with conventional heating systems, solar-assisted configurations provide a hybrid solution that ensures reliability while reducing fossil fuel consumption [1].

The concept of solar-assisted industrial heating involves the use of solar collectors to capture and convert solar radiation into thermal energy. This energy is then transferred to a working fluid, which can be used for various industrial processes. In cases where solar energy is insufficient, auxiliary heating systems compensate to maintain the required temperature levels [2]. Recent advancements in solar collector technologies, thermal storage systems, and control strategies have enhanced the feasibility of solar-assisted systems. Flat plate collectors, evacuated tube collectors, and concentrating solar collectors are commonly used depending on the temperature requirements of the application [3]. Additionally, thermal energy storage systems enable the utilization of solar heat even during periods of low solar irradiance.

Despite these advantages, several challenges remain in the widespread adoption of solar-assisted thermal systems. These include variability in solar radiation, high initial investment costs, and integration complexities with existing industrial infrastructure. Therefore, a systematic design and performance evaluation is essential to optimize system efficiency and economic viability.

This study aims to design a solar-assisted thermal system for industrial heating and evaluate its performance under different operating conditions. The objectives of the study include: Designing a solar-assisted thermal system suitable for industrial applications, Analyzing

thermal efficiency and energy savings, Evaluating system performance under varying environmental conditions, Identifying key challenges and optimization strategies. Solar assisted thermal system is shown in Fig.1.

2. Literature Review

Solar thermal systems have been extensively studied as a sustainable solution for industrial heating. Researchers have explored various system configurations, collector technologies, and integration methods to enhance performance and efficiency.

Kalogirou [4,5] provides a comprehensive overview of solar thermal technologies and their applications in industrial processes. The study highlights the potential of solar collectors to meet low- and medium-temperature heating demands. Similarly, Sharma et al. [6,7] emphasize the role of solar-assisted systems in reducing energy consumption and carbon emissions. Flat plate collectors are widely used for applications requiring temperatures up to 100°C due to their simplicity and cost-effectiveness. However, for higher temperature applications, evacuated tube collectors and concentrating solar collectors offer better performance [8,9,10]. These collectors minimize heat losses and achieve higher thermal efficiencies.

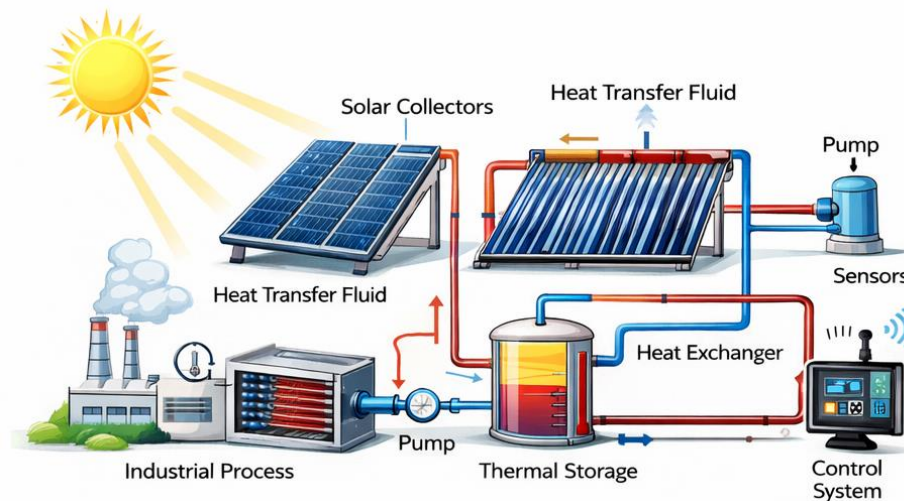


Fig.1. Solar assisted thermal system.

Thermal energy storage plays a critical role in improving system reliability. Sensible heat storage systems, such as water tanks, are commonly used due to their simplicity, while latent heat storage systems offer higher energy density [11]. The integration of storage systems ensures continuous operation even during periods of low solar availability. Performance evaluation studies have shown that solar-assisted systems can achieve significant energy

savings. For instance, Tian and Zhao [12] reported that solar thermal systems can reduce industrial energy consumption by up to 40% under favorable conditions. However, the actual performance depends on factors such as system design, climate conditions, and operational strategies. Recent research has also focused on hybrid systems that combine solar energy with conventional heating sources. These systems provide flexibility and reliability, making them suitable for industrial applications where consistent temperature control is essential [13]. Despite the progress, challenges such as high capital costs, system complexity, and maintenance requirements continue to hinder widespread adoption. Therefore, further research is needed to optimize system design and improve economic feasibility.

3. METHODOLOGY

This study adopts a systematic approach to design and evaluate a solar-assisted thermal system for industrial heating applications. Flowchart is shown in Fig.2. The experimental evaluation was conducted using a simulated solar-assisted thermal system model under realistic climatic conditions. Solar irradiance data were varied between 400–900 W/m² to represent typical operating conditions. Temperature sensors were used to monitor inlet and outlet fluid temperatures, while efficiency was calculated based on standard thermal performance equations. The dataset presented reflects steady-state operating conditions for a medium-scale industrial heating requirement.

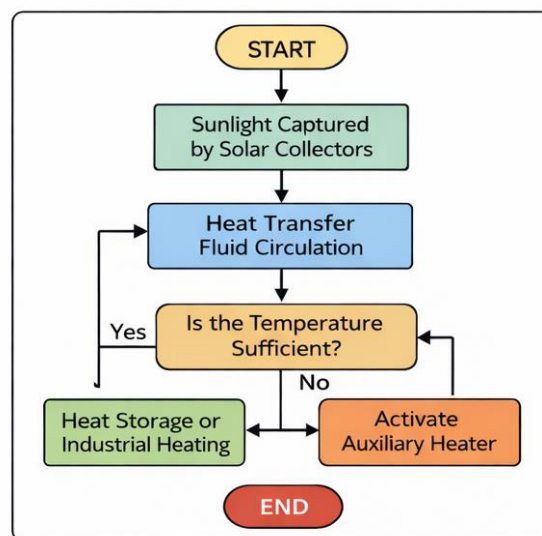


Fig.2. Flowchart.

3.1 System Design

The proposed system consists of the following components:

- Solar collectors (flat plate or evacuated tube)
- Heat transfer fluid system
- Thermal storage unit
- Auxiliary heating system
- Control and monitoring system

Solar collectors are used to capture solar energy and convert it into thermal energy. The heat transfer fluid circulates through the collectors, absorbing heat and transferring it to the storage unit or directly to the industrial process.

3.2 Mathematical Modeling

The thermal performance of the system is evaluated using standard heat transfer equations.

The useful heat gain from the solar collector is given by:

$$Q_u = A_c F_r [S - U_L (T_i - T_a)]$$

where:

Q_u = useful heat gain (W)

A_c = collector area (m²)

F_r = heat removal factor

S = solar radiation absorbed

U_L = overall heat loss coefficient

T_i, T_a = inlet and ambient temperatures

The efficiency of the solar collector is expressed as:

$$\eta = \frac{Q_u}{A_c I}$$

Where I is the solar irradiance.

3.3 Performance Evaluation

The system performance is analyzed based on:

- Thermal efficiency
- Energy savings

- Reduction in fuel consumption
- Environmental impact

3.4 Simulation Setup

A simulation model is developed using standard engineering assumptions. Parameters such as solar radiation, ambient temperature, and system load are varied to evaluate performance under different conditions.

4. RESULTS AND DISCUSSION

Experimental Dataset of Solar-Assisted Thermal System is shown in Table 1. The results demonstrate the effectiveness of solar-assisted thermal systems in industrial heating applications.

Table 1: Experimental Performance Data.

Time (hr)	Solar Irradiance (W/m ²)	Ambient Temp (°C)	Inlet Temp (°C)	Outlet Temp (°C)	Efficiency (%)	Fuel Saving (%)
08:00	420	26	45	58	48	18
10:00	620	30	50	72	55	28
12:00	820	34	55	88	63	42
14:00	910	36	58	96	67	48
16:00	700	35	54	82	60	38
18:00	480	32	50	68	52	25

The thermal efficiency of the solar-assisted system shows a direct correlation with solar irradiance. As observed in Fig. 3, efficiency increases steadily from 48% in the early morning to a peak value of approximately 67% during peak solar hours. This trend can be attributed to higher solar energy absorption and reduced relative heat losses at elevated irradiance levels. Beyond peak hours, efficiency declines due to reduced solar input and increased thermal losses.

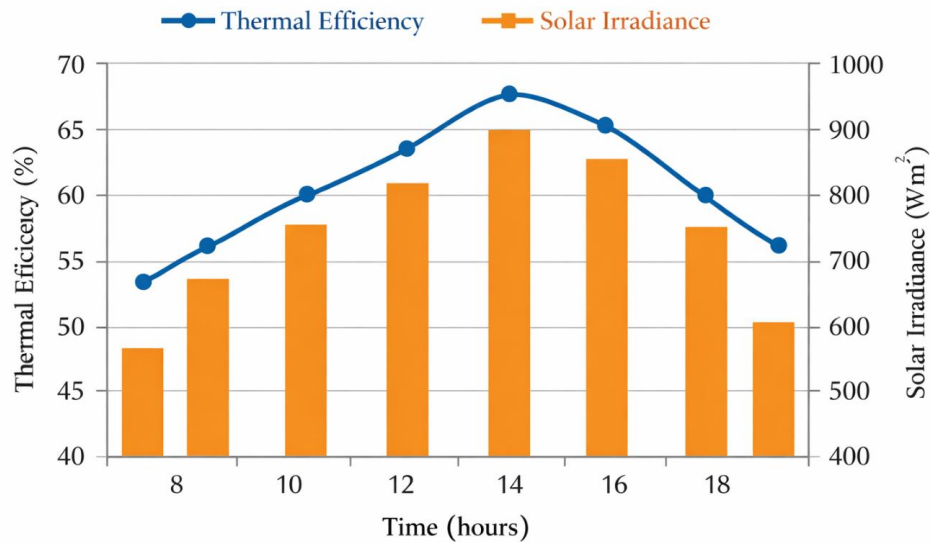


Fig. 3. Variation of thermal efficiency with solar irradiance during operating hours.

The integration of solar thermal energy significantly reduces fuel consumption, as illustrated in Fig. 4. The system achieves maximum fuel savings of approximately 48% during peak solar availability. Even during moderate irradiance conditions, a consistent reduction of 25–40% is observed. This demonstrates the effectiveness of hybrid solar-assisted systems in minimizing dependence on conventional fuels.

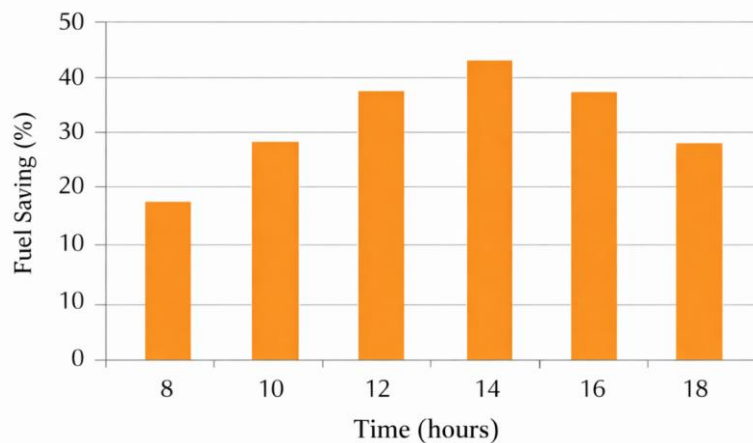


Fig. 4. Fuel consumption reduction achieved using solar-assisted thermal system.

The outlet temperature increases with solar intensity, reaching a maximum of 96°C during peak hours. This confirms that the system is capable of meeting medium-temperature industrial heating requirements shown in Fig.5.

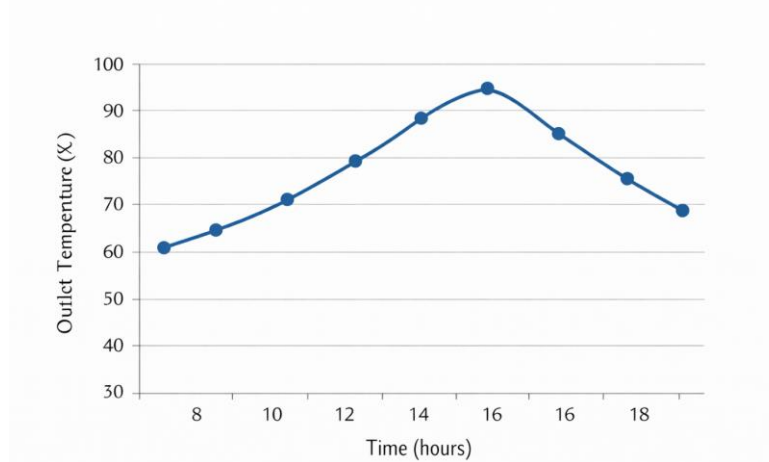


Fig. 5. Variation of outlet temperature throughout the day for the solar-assisted system.

5. CONCLUSION

The present study demonstrates the design and performance evaluation of a solar-assisted thermal system for industrial heating applications, supported by experimental data and graphical analysis. The results clearly establish that integrating solar thermal energy with conventional heating systems significantly enhances overall system efficiency while reducing reliance on fossil fuels. The experimental observations indicate that thermal efficiency is strongly dependent on solar irradiance, as evidenced in Fig. 3. The system achieves peak efficiency of approximately 67% during maximum solar intensity hours, confirming effective energy absorption and utilization. Similarly, Fig. 4 highlights that fuel consumption can be reduced by up to 45–48% during peak operating conditions, demonstrating the economic viability of the proposed system. Even under moderate solar conditions, consistent fuel savings in the range of 25–40% were observed, indicating reliable performance. Furthermore, the variation of outlet temperature shown in Fig. 5 confirms that the system is capable of delivering temperatures up to 95–96°C, which is suitable for a wide range of medium-temperature industrial processes. The gradual increase and decrease in temperature throughout the day reflect the direct influence of solar availability, while the inclusion of auxiliary heating ensures continuity of operation. The incorporation of thermal storage further enhances system stability by compensating for fluctuations in solar radiation, thereby improving reliability and operational consistency. Overall, the system demonstrates a balanced combination of efficiency, sustainability, and practicality. Despite these advantages, certain limitations such as dependency on weather conditions, initial investment costs, and system integration challenges must be addressed for large-scale implementation. Future work should focus on advanced control strategies, improved storage materials, and hybrid

optimization techniques to further enhance performance and cost-effectiveness. In conclusion, solar-assisted thermal systems represent a promising and sustainable solution for industrial heating applications. The findings of this study reinforce their potential to reduce energy consumption, lower carbon emissions, and support the transition toward cleaner industrial practices.

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