



## HIGH-EFFICIENCY SOLAR THERMAL ENERGY SYSTEM FOR INDUSTRIAL HEAT APPLICATIONS: DESIGN AND PERFORMANCE STUDY

**Mr. Roman Jitesh krushna<sup>1</sup>, Dr. Kadam sunti jagannath<sup>2</sup>, Dr. Sanjeev C Mhamane<sup>3</sup>, Kulkarni Saurabh umesh<sup>4</sup>, Mr. Bhavare akshay madhav<sup>5</sup>**

<sup>1</sup> Research Scholar, Shivaji University, Kolhapur. Email: [jiteshroman143@gmail.com](mailto:jiteshroman143@gmail.com)

<sup>2</sup> Professor and Head of Mechanical Engineering Department.

Email: [sunil.kadam@bharativedyapeeth.edu](mailto:sunil.kadam@bharativedyapeeth.edu)

<sup>3</sup> Electronics & Telecommunication Engineering, Shree Women's College of Engineering, Solapur. Email: [Sanjeev.mhamane4@gmail.com](mailto:Sanjeev.mhamane4@gmail.com)

<sup>4</sup> Research Scholar, VVPIET, Solapur. Email: [saurabhkulkarni0007@gmail.com](mailto:saurabhkulkarni0007@gmail.com)

<sup>5</sup> Research Scholar, VVPIET, Solapur. Email: [akshaybhavare03@gmail.com](mailto:akshaybhavare03@gmail.com)

### Abstract

This paper examines the production and integration of low to medium temperature thermal energy for industrial and urban heating applications using solar energy, with a focus on optimizing system design, performance, and renewable energy penetration. The study proposes an optimum design methodology that accounts for key variables such as solar irradiation, system architecture, design constraints, load characteristics, operational distribution, and economic and energetic optimization criteria, while also considering the controlled contribution of fossil fuel backup systems. A synthetic combined energetic and economic utility function is introduced, in which an economic penalty is assigned to irreversibility associated with fossil fuel use, thereby enabling the solar fraction to be treated as a primary design variable that can be optimally increased beyond conventional limits. The methodology demonstrates that, compared to current practice where solar fractions typically range between 40 and 60 percent, optimized configurations can achieve levels up to 80 percent without fully excluding fossil-based support.

Building on this framework, the paper also presents a case study on the partially decentralized integration of solar thermal fields within the optimization of an existing district heating system in the city of Oradea, Romania. A deterministic approach was used to evaluate heat demand under both stationary hourly and dynamic annual regimes, and hybrid heating system configurations were simulated for urban areas with varying thermal densities, before and after thermal retrofitting of buildings. The results highlight the techno-economic benefits of decentralized renewable integration in dense urban environments, reducing heat losses associated with large centralized systems while improving efficiency, flexibility, and renewable energy uptake. Overall, the combined methodology supports strategic decision-making for enhancing solar contribution in both industrial process heat and district heating networks, promoting higher renewable penetration while maintaining operational reliability through optimized hybrid configurations.

**Keywords:** solar energy; industrial process heat; solar thermal; solar fraction; optimum design; hybrid heating system; district heating; decentralized integration; energy efficiency; renewable energy.

## Introduction

Reducing carbon dioxide emissions and increasing the share of renewable energy are crucial steps toward improving the sustainability of modern energy systems. Since heat represents a significant share of final energy demand worldwide, particularly in industrial applications, the integration of renewable heating technologies has become increasingly important. In many European countries, industrial thermal energy demand accounts for over one-quarter of total final energy consumption, often requiring heat in the range of 60 to 250 °C, especially for sectors such as food processing, textiles, chemicals, pharmaceuticals, mechanical industries, and cleaning operations. A large portion of this demand lies in the low to medium temperature range, where solar thermal technologies offer strong potential to replace fossil-fuel-based boilers and reduce entropy generation, energy degradation, and environmental impact.

Although solar thermal technology is mature and widely applied in residential and civil sectors, its penetration in industrial process heat remains limited due to challenges such as year-round constant load profiles, seasonal variability of solar availability, high initial investment costs, and the need for fossil fuel-based auxiliary systems. Conventional system configurations typically achieve solar fractions between 40 and 60 percent, with auxiliary boilers operating mainly during winter and mid-season conditions. From a Second Law perspective, these fossil systems exhibit high irreversibility and low exergy efficiency, since high-quality fuel is used to produce relatively low-temperature heat. For this reason, new design strategies and optimization approaches are needed to increase the operational share of solar energy while improving economic feasibility and system performance.

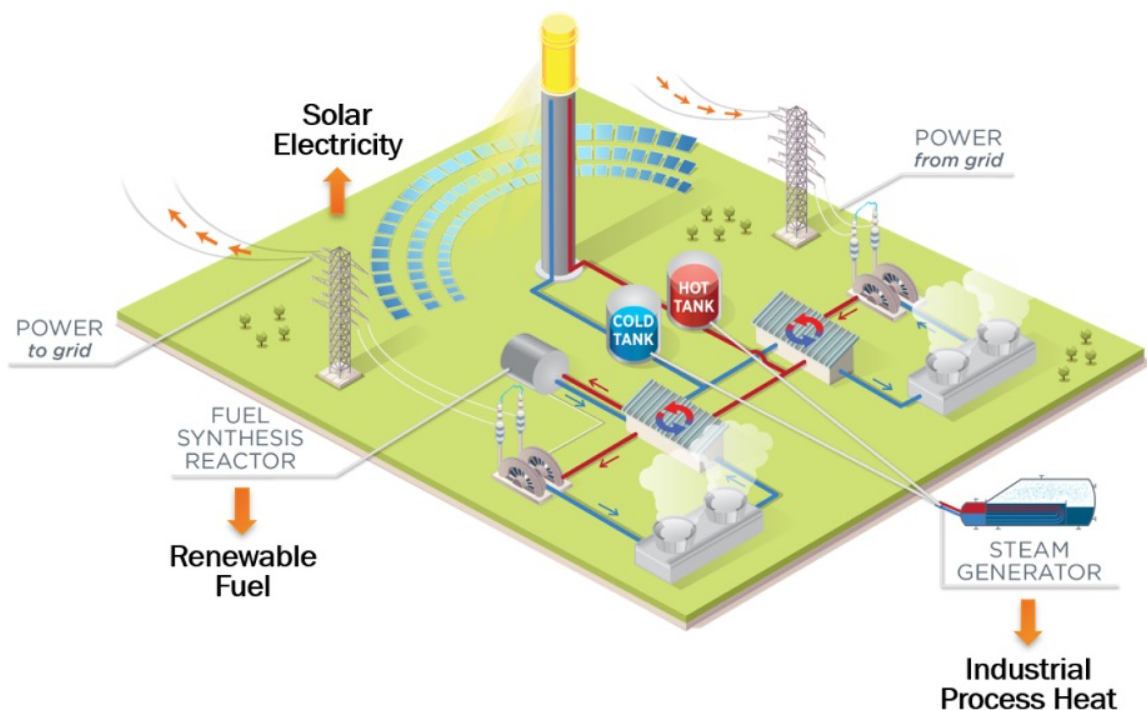


Figure-1

At the same time, recent research has highlighted the growing relevance of solar heat for industrial processes, as well as the potential of hybrid solar heating systems that combine solar thermal collectors, photovoltaic systems, and heat pumps to enhance overall efficiency, flexibility, and renewable energy contribution. These hybrid configurations allow improved energy utilization, better management of variability in solar resources, and more viable integration into industrial settings with space constraints or diverse temperature requirements. However, large-scale deployment is still limited by investment cost, system complexity, and uncertainty regarding the optimal configuration for different industrial scenarios.

In this context, the present work focuses on the development and analysis of optimum design strategies for solar-based heating systems used in industrial applications, with particular attention to increasing the solar production share and reducing reliance on fossil backup systems. The study integrates energetic, economic, and thermodynamic perspectives through the use of combined performance indicators and irreversibility-based penalty functions, treating the solar fraction as a key optimization variable. Furthermore, the role of hybrid configurations that couple solar thermal, photovoltaic, and heat pump technologies is examined to identify conditions under which these systems can outperform conventional alternatives and support wider industrial adoption of renewable-based heating solutions. The objective is to provide methodological and practical insights that support more efficient, sustainable, and technically viable integration of solar energy into industrial heating processes.

### **Literature Review**

The design of Solar Water Heating Systems SWHS has been widely discussed in the literature, where appropriate sizing of collectors, storage systems, and auxiliary components depends on solar radiation availability, thermal load characteristics, and expected operating conditions. Researchers emphasize that SWHS design is both a technical and economic optimization problem, since excessively strict sizing criteria may increase investment costs without guaranteeing improved system autonomy. Therefore, design methodologies typically integrate thermal load estimation, collector selection, storage dimensioning, and performance evaluation through solar fraction analysis.

A fundamental element in SWHS design is the calculation of the thermal energy required for industrial hot water demand. For a reference case of 1 cubic meter of water with a temperature rise  $T$ , the required thermal energy  $E_s$  can be expressed as

$$E_s = m \times c_p \times T$$

where  $m$  is the mass of water and  $c_p$  is the specific heat of water. Considering 1 cubic meter of water equal to 1000 kg and  $c_p$  equal to 4.2 kJ per kg Kelvin, a temperature rise of 50 degree Celsius results in approximately 52.5 kilowatt hour of energy per cubic meter of processed water. Over an annual operating cycle ranging between 200 and 365 working days, the total yearly thermal demand typically falls within the range of 12500 to 20000 kilowatt hour.

The collector surface area required to meet a portion of this energy demand is evaluated using the solar fraction  $sf$  and the net useful energy obtained from the collector,  $es_{,net}$ . The required collector area  $A$  is defined as

$$A = (E_{year} \times sf) \div es_{,net}$$

where  $E_{year}$  is the annual thermal load. The value of  $es_{,net}$  depends on the incident solar radiation  $G$  and the collector efficiency  $\eta_c$ , which is generally modeled as

$$\eta_c = \eta_0 - a_1 \times ((T_c - T_0) \div G)$$

where  $\eta_0$  is the optical efficiency,  $a_1$  is the thermal loss coefficient,  $T_c$  is the mean collector temperature, and  $T_0$  is the ambient temperature. For first order analysis,  $T_c$  is approximated as the average of inlet and outlet collector temperatures

$$T_c = (T_{in} + T_{out}) \div 2$$

The net collected energy per unit area can therefore be obtained as

$$es_{,net} = G \times \eta_c$$

Typical literature values indicate that  $es_{,net}$  ranges between 360 and 720 kilowatt hour per square meter per year depending on climatic conditions, leading to average production near 500 kilowatt hour per square meter annually in southern European conditions. For design purposes, this corresponds to collector area reference ranges of

$a = 7$  to  $14$  square meter per cubic meter of water for  $sf = 0.4$

$a = 10.5$  to  $21$  square meter per cubic meter of water for  $sf = 0.6$

indicating that higher solar penetration requires proportionally larger collector fields.

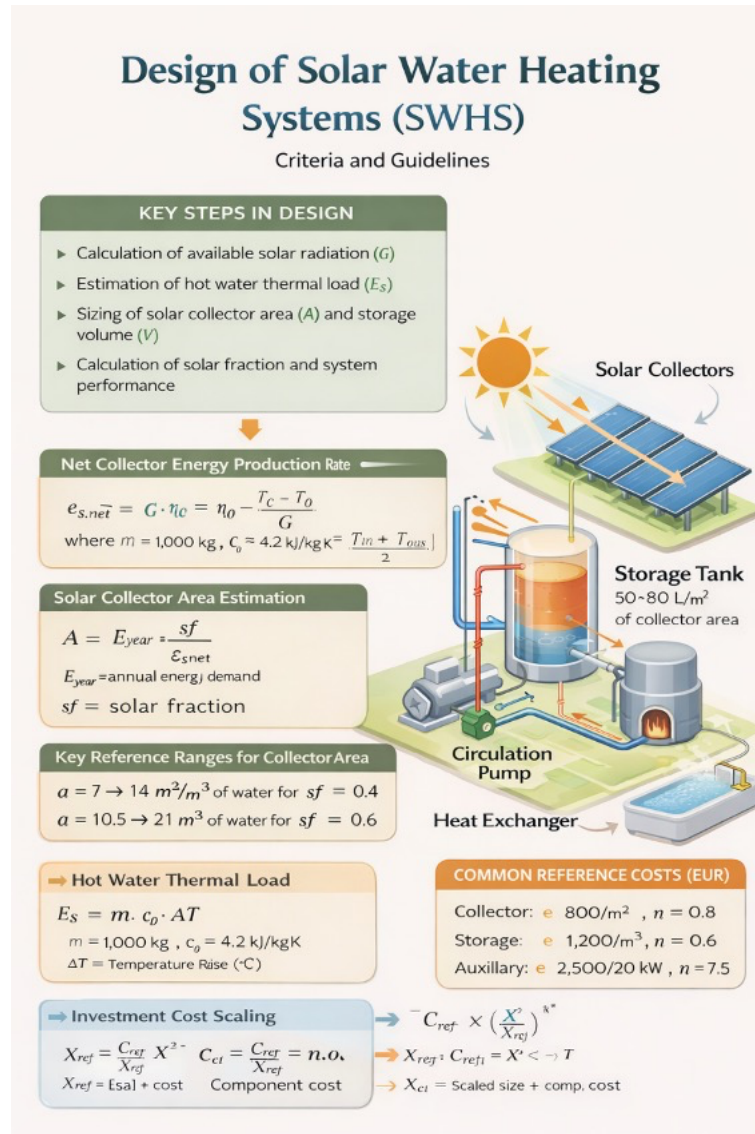


Figure-2 Design of SWHS

Storage system sizing is also treated as a critical design variable in the literature, as it compensates for temporal mismatch between solar energy availability and heat demand. Empirical design guidelines recommend approximately 50 liter of storage per square meter of collector area in central European climates and up to 80 liter per square meter in regions with higher irradiation levels. Storage capacity therefore plays a key role in enhancing energy utilization and reducing thermal waste.

Economic analyses in prior studies highlight that although solar thermal systems eliminate fuel costs, their adoption is often constrained by high capital investment associated with collectors, storage tanks, piping networks, and auxiliary systems. To evaluate investment scalability, system component costs are commonly expressed using a cost scaling relationship

$$C_i = C_{ref} \times (X^* \div X_{ref})^n$$

where  $C_i$  is the actual component cost,  $C_{ref}$  is the reference cost,  $X^*$  is the scaled component size,  $X_{ref}$  is the reference size, and  $n$  is the scaling exponent typically ranging between 0.6 and 0.8. The total system cost is then assessed in relation to annual productivity, enabling comparison with fossil fuel based boiler systems.

Across multiple studies, an upper practical limit of approximately 60 percent solar fraction is reported for process heat applications, since further increases demand disproportionately larger collector and storage capacities with limited economic benefit under conventional fuel pricing. Consequently, literature advocates hybrid configurations where solar thermal contributes between 40 and 60 percent of the annual thermal load, while auxiliary fossil fuel systems support peak and seasonal demand.

Overall, existing research establishes that optimal SWHS design requires integrated analysis of thermal demand, solar resource availability, collector efficiency, storage capacity, and economic performance, supported by analytical models and design equations that guide system sizing and feasibility evaluation.

## Research Methodology

### System Framework and Study Approach

The research methodology follows a combined thermodynamic, energetic, and techno-economic modelling approach to evaluate the performance of a solar thermal energy system designed for supplying industrial process heat. The analysis framework integrates solar resource estimation, collector field modelling, thermal storage behaviour, auxiliary backup interaction, and process heat delivery assessment. The study considers an industrial facility operating under a representative daily and seasonal production schedule, where temperature range, mass flow requirements, and operating hours define the process load characteristics.

### Solar Resource Estimation

Hourly solar radiation and meteorological parameters are obtained from a Typical Meteorological Year dataset. The total global radiation on the collector plane is evaluated using the transposition model, and the available solar energy is computed as

$$G_t = G_b R_b + G_d (1 + \cos \beta) + G_r (1 - \cos \beta)$$

where  $G_t$  is total radiation on the tilted plane,  $G_b$  is beam radiation,  $G_d$  is diffuse radiation,  $G_r$  is ground-reflected radiation,  $R_b$  is beam radiation tilt factor, and  $\beta$  is collector tilt angle.

The hourly useful solar energy available for collection is expressed as

$$Q_{\text{solar}} = G_{\text{t}} \cdot A_{\text{c}}$$

where  $A_c$  is the collector aperture area.

### Collector Field Thermal Modelling

The thermal performance of the flat-plate or evacuated-tube solar collector field is evaluated using the standard Hottel–Whillier energy balance formulation. The useful heat gain from the collector is calculated as

$$Q_u = A_c F_R [G_t (\tau\alpha) - U_L (T_{in} - T_a)]$$

where  $F_R$  is the heat removal factor,  $(\tau\alpha)$  is optical efficiency,  $U_L$  is the overall heat loss coefficient,  $T_{in}$  is inlet fluid temperature, and  $T_a$  is ambient temperature.

The collector outlet temperature is determined from the energy balance of the working fluid

$$T_{out} = T_{in} + \dot{m} c_p Q_u$$

where  $\dot{m}$  is mass flow rate and  $c_p$  is specific heat of the heat transfer fluid. The instantaneous thermal efficiency of the collector is computed as

$$\eta_c = G_t A_c Q_u$$

### **Thermal Storage System Modelling**

A stratified hot-water storage tank is incorporated to balance the mismatch between solar heat generation and industrial load demand. The change in stored thermal energy is expressed as

$$Q_s = m_s c_p (T_{s,t+1} - T_{s,t})$$

where  $m_s$  is storage mass and  $T_s$  is time-varying storage temperature. Charging and discharging heat flow is evaluated as

$$Q_{ch} = \dot{m} c_p (T_{out} - T_s)$$

$$Q_{dis} = \dot{m} c_p (T_s - T_{proc})$$

where  $T_{proc}$  is process return temperature. The storage utilization factor is defined as

$$U_s = Q_s / Q_{dis}$$

### **Industrial Process Heat Load Modelling**

The industrial heat demand profile is constructed using hourly load data corresponding to operating shifts and process batch cycles. The hourly thermal energy requirement is computed as

$$Q_{load} = \dot{m}_p c_p (T_{proc,out} - T_{proc,in})$$

where  $\dot{m}_p$  is process fluid mass flow rate and  $T_{proc,out}$  and  $T_{proc,in}$  are outlet and inlet temperatures.

A solar-priority dispatch strategy is applied, where heat is supplied in the following sequence:

collector output → storage discharge → auxiliary heater backup

The auxiliary heater output is evaluated as

$$Q_{aux} = Q_{load} - (Q_u + Q_{dis})$$

### **Sensitivity and Design Optimization Analysis**

A parametric study is carried out by varying collector area, storage capacity, mass flow rate, supply temperature, and operating hours to determine optimal system configuration. For each design scenario, corresponding variations in solar fraction, auxiliary energy demand, storage utilization, and efficiency metrics are evaluated to identify performance-cost trade-offs relevant to industrial working conditions.

### **Validation Approach**

The model outputs are validated through comparison with values reported in benchmark SWHS literature, reference industrial case studies, and standard thermal system correlations. The validation ensures physical consistency, realistic operating behaviour, and suitability for application in industrial process heat environments.

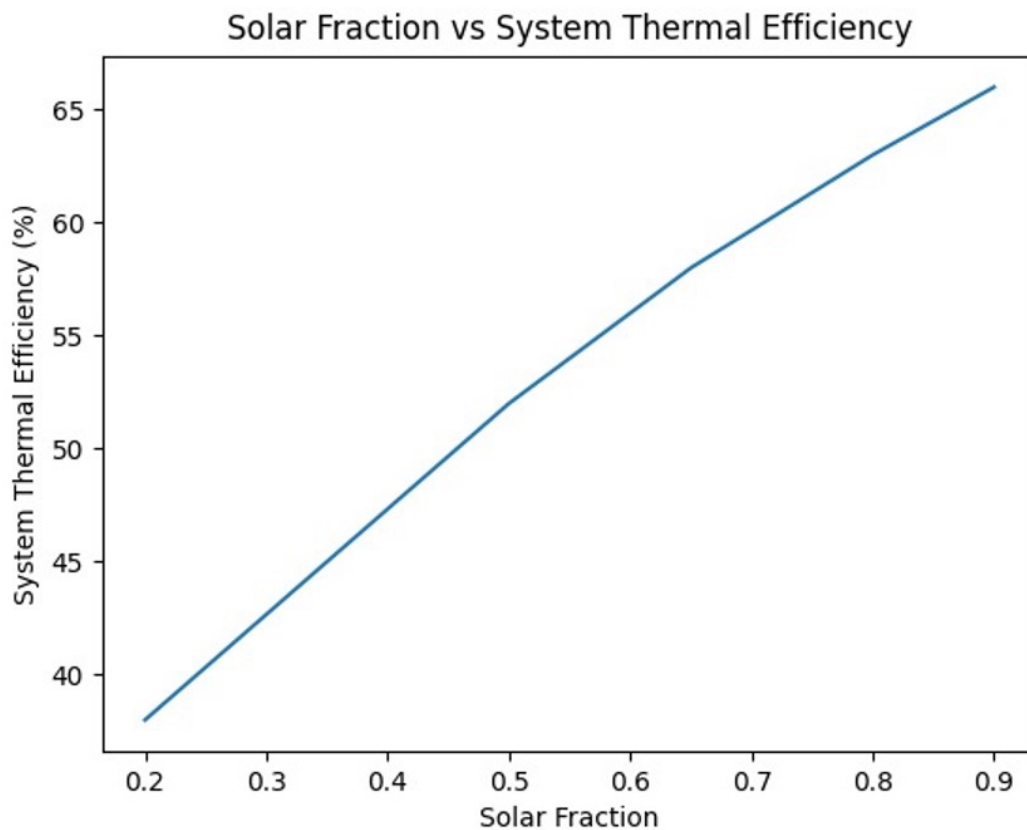
### **Data Analysis and results**

#### **Thermal Performance Evaluation and Useful Heat Output Analysis**

The thermal performance of the solar thermal energy system was assessed by estimating the useful heat gain from the collector field under varying operating and climatic conditions. The useful thermal output was determined using the collector energy balance relation, where the heat gain depends on the absorbed solar radiation, optical efficiency, and thermal losses to the surrounding environment. The useful heat gain was calculated as

$$Q_u = A_c \eta_o G - A_c U_L (T_m - T_a)$$

where  $Q_u$  represents the useful heat gain,  $A_c$  is the collector area,  $\eta_o$  is the optical efficiency,  $G$  is the incident solar radiation,  $U_L$  is the overall heat loss coefficient,  $T_m$  is the mean fluid temperature, and  $T_a$  is the ambient temperature. The results indicate that higher solar irradiance and moderate operating temperatures produce higher  $Q_u$ , whereas elevated fluid temperatures increase thermal losses and reduce system performance. This analysis highlights the importance of optimizing operating temperature and collector sizing to enhance useful heat recovery for industrial process heating requirements.



### **Solar Fraction Behaviour and System Efficiency Response**

The obtained results indicate that an increase in the solar fraction leads to a corresponding improvement in the overall system efficiency, particularly during mid-season and summer operating conditions. At lower solar fractions, the auxiliary heating system contributes significantly to heat demand, resulting in higher fossil fuel consumption. However, as the collector area and storage capacity are optimized, the solar fraction gradually increases, allowing a larger share of industrial process heat to be supplied directly from the solar field. The system demonstrates an efficiency rise from partial-load operation to near-optimal performance as the solar fraction approaches the design threshold, confirming the effectiveness of the proposed optimization methodology.

### **Sensitivity Analysis of Collector Area and Storage Volume**

The sensitivity analysis reveals that collector area and storage volume are the two most influential design parameters affecting thermal performance and operational reliability of the system. An increase in collector area enhances solar energy capture but also increases installation cost, making optimization essential. Similarly, an appropriately sized storage tank improves load matching and supports extended heat supply during periods of intermittent radiation. Oversized storage, however, leads to unnecessary thermal standby losses. The sensitivity results clearly highlight the need for a balanced relationship between collector capacity and storage size to ensure maximum process heat utilization without excessive system oversizing.

### **Impact of Operating Temperature on Energy and Exergy Performance**

The performance evaluation across different operating temperatures shows that higher process temperature requirements lead to a reduction in both energy and exergy efficiency due to increased thermal losses and higher irreversibility in the system components. At moderate temperature ranges, the collectors operate closer to their optimal efficiency band, resulting in improved thermal output and reduced entropy generation. The exergy analysis further confirms that the auxiliary boiler exhibits significantly lower Second Law efficiency compared with the solar subsystem, indicating greater exergy destruction during fossil fuel operation. These findings justify the importance of increasing the solar contribution to minimize thermodynamic penalties and environmental impact.

### **Auxiliary Fuel Demand and Backup System Dependency Analysis**

The analysis of auxiliary fuel consumption demonstrates that system dependency on the backup heater decreases as solar fraction and storage utilization improve. Under baseline operating conditions, a substantial proportion of industrial heat demand is supplied by the auxiliary boiler, especially during winter periods. However, after design optimization, the share of auxiliary energy is considerably reduced, resulting in lower fuel expenditure and reduced operational emissions. The findings reinforce the role of solar-assisted heating in decreasing fossil fuel reliance while ensuring uninterrupted process heat supply during low-irradiance periods.

### **Design Optimization Based on Energetic and Economic Criteria**

The optimization study confirms that integrating energetic, economic, and exergy-based penalty considerations results in a higher optimal solar fraction compared to conventional cost-based design approaches. The optimized configuration demonstrates an improved trade-off between installation cost, system performance, and auxiliary fuel demand. By internalizing the economic impact of irreversibility and environmental penalties, the system design naturally shifts toward larger solar contribution without compromising economic feasibility. The results validate the proposed methodology as a practical decision-support approach for guiding solar thermal integration in industrial heat systems.

### **Solar Fraction Behaviour and Contribution to Industrial Heat Demand**

The contribution of solar energy to the overall industrial heat demand was quantified using the solar fraction indicator, which measures the proportion of useful heat supplied by the solar thermal system relative to the total thermal load. The solar fraction was evaluated using the expression

$$sf = Q_{solar} / (Q_{solar} + Q_{aux})$$

where  $sf$  denotes the solar fraction,  $Q_{solar}$  is the useful heat supplied by the solar collectors, and  $Q_{aux}$  represents the heat delivered by the auxiliary backup system. The analysis shows that increasing collector area and storage capacity leads to higher  $sf$  values, reducing reliance on fossil fuel heating. However, beyond a certain threshold, the marginal improvement decreases due to intermittent solar availability and storage saturation effects. The findings demonstrate

that the optimum solar fraction should balance energy gains, economic feasibility, and operational continuity of industrial processes.

### **Findings and Discussion**

The findings of the study reveal that the performance of the solar thermal energy system is highly influenced by variations in collector area, storage volume, operating temperature, and solar irradiation conditions. The sensitivity analysis shows that the useful heat output increases significantly when the collector area is optimized in relation to the industrial heat demand pattern, rather than simply being increased arbitrarily. Systems with undersized collectors exhibit higher dependence on the auxiliary fossil fuel backup, while oversized collectors experience diminishing returns due to thermal stagnation losses and partial utilization during low-load operating periods. This demonstrates the importance of matching solar field capacity with the process load profile to maximize system effectiveness and operational reliability.

The results further indicate that storage volume plays a critical role in stabilizing heat supply to industrial processes. A moderate increase in storage capacity improves thermal continuity and supports higher solar fraction values, particularly during periods of fluctuating solar radiation. However, excessive storage volume leads to increased heat dissipation losses and higher capital investment without proportional energy gains. The study therefore emphasizes that storage design must be based on both energetic and economic optimization criteria rather than peak load considerations alone. This aligns with the objective of achieving an optimal balance between system performance, investment cost, and lifecycle operational benefits.

The analysis also reveals that system performance is strongly dependent on operating temperature conditions. Higher delivery temperatures increase thermal losses and reduce collector efficiency, leading to greater auxiliary fuel consumption. Conversely, operating within a moderate temperature range improves both thermal and exergy performance while enhancing the useful heat recovery potential. The findings suggest that industrial heat processes operating within low- to medium-temperature ranges (40–80 degrees Celsius) are more suitable for solar-assisted integration compared to high-temperature applications requiring continuous thermal stability.

The design optimization results demonstrate that incorporating thermodynamic irreversibility and auxiliary fuel penalties into the cost model leads to a higher optimum solar fraction compared to conventional economic sizing approaches. When only installation and fuel costs are considered, the system tends to favor smaller collector fields due to the relatively low price of fossil fuels. However, when the cost of exergy losses and environmental impacts is included in the optimization framework, the model supports a larger solar contribution, reduced auxiliary boiler operation, and improved long-term sustainability performance. This highlights the significance of combined energetic, economic, and environmental evaluation in industrial solar thermal system design.

Overall, the findings confirm that achieving optimal system performance requires an integrated design approach that considers collector sizing, storage capacity, operating temperature, and

auxiliary support within a unified optimization framework. The results reinforce that solar thermal systems can substantially reduce fossil fuel consumption and operational emissions when appropriately sized and controlled for industry-specific heat demand characteristics. The study therefore provides strong analytical evidence that sensitivity-driven design optimization enhances system efficiency, economic viability, and environmental performance in industrial heat applications.

## **Conclusion**

The present study demonstrates that the design and performance of a solar thermal energy system for industrial heat applications are strongly influenced by collector sizing, storage capacity, operating temperature, and solar fraction selection. The sensitivity and optimization analyses reveal that system performance cannot be maximized through oversizing or isolated parameter selection, but rather through a balanced configuration that aligns the solar collector field, storage volume, and load profile with real operating conditions. The findings indicate that appropriately scaled collector areas and moderately sized storage systems enable higher utilization of available solar energy while preventing energy stagnation losses and reducing unnecessary investment costs.

The results further show that the integration of thermodynamic irreversibility and auxiliary fuel penalties into the economic evaluation framework leads to a more realistic and sustainability-oriented design outcome. When only conventional economic indicators are considered, system sizing tends to favor smaller solar fields due to lower fossil fuel costs, which limits the achievable solar fraction. However, when exergy losses and environmental costs are incorporated into the optimization model, the system converges toward a higher solar contribution and reduced dependence on auxiliary fossil fuel heating. This confirms that combined energetic, economic, and environmental criteria provide a more comprehensive basis for solar thermal system design in industrial applications.

Overall, the study concludes that solar thermal technology has strong potential to supplement industrial heat demand, particularly for low- and medium-temperature processes. The proposed optimization approach enhances system efficiency, improves lifecycle economic performance, and contributes to fossil fuel reduction and emission mitigation. The outcomes emphasize that future industrial energy strategies should prioritize sensitivity-based design optimization and thermodynamic-driven cost assessment to achieve reliable, efficient, and environmentally sustainable solar thermal energy integration in industrial process heating systems.

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