COMPREHENSIVE REVIEW OF SOLAR COLLECTOR TECHNOLOGIES FOR MANUFACTURING PROCESSES

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Abstract. The industrial sector is a paramount consumer of global energy, primarily derived from fossil fuels, contributing significantly to greenhouse gas emissions and climate change. Solar thermal energy presents a viable, sustainable alternative to supply the vast amounts of heat required for manufacturing processes, which account for approximately 74% of industrial energy demand. This review article provides a detailed analysis of the state-of-the-art in solar collector technologies and their integration into industrial processes. We systematically categorize and evaluate Non-Concentrating Collectors (Flat Plate, Evacuated Tube), Concentrating Solar Collectors (Parabolic Trough, Linear Fresnel, Parabolic Dish, Solar Tower), and emerging hybrid systems against the temperature requirements of key industrial sectors. The paper synthesizes findings from over 40 scientific studies, technical reports, and case studies to discuss the technical performance, integration methodologies, economic feasibility, and environmental benefits of these systems. A critical discussion on the persistent challenges—including intermittency, energy storage, and initial costs—is presented, alongside an outlook on future research directions focusing on advanced materials, thermal energy storage, and hybrid system optimization. The conclusion underscores the transformative potential of solar thermal technology in decarbonizing the industrial heat landscape.

Keywords: Solar Thermal Energy, Industrial Process Heat, Solar Collectors, Concentrating Solar Power, Thermal Energy Storage.

Аннотация. Промышленный сектор является основным потребителем мировой энергии, получаемой преимущественно из ископаемого топлива, что вносит значительный вклад в выбросы парниковых газов и изменение климата. Солнечная тепловая энергия представляет собой жизнеспособную, устойчивую альтернативу для обеспечения огромных объемов тепла, необходимых для производственных процессов, на которые приходится примерно 74% промышленного спроса на энергию. Данный обзор представляет собой детальный анализ современных технологий солнечных коллекторов и их интеграции в промышленные процессы. Мы систематически классифицируем и оцениваем Неконцентрирующие коллекторы (Плоские, Вакуумные трубчатые), Концентрирующие солнечные коллекторы (Параболические желоба, Линейные зеркала Френеля,

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Параболические тарелки, Солнечные башни) и перспективные гибридные системы в соответствии с температурными требованиями ключевых отраслей промышленности. В статье обобщены данные более 40 научных исследований, технических отчетов и примеров внедрения для обсуждения технических характеристик, методик интеграции, экономической целесообразности и экологических преимуществ этих систем. Представлена критическая дискуссия о сохраняющихся проблемах, включая прерывистость генерации, накопление энергии и высокие первоначальные затраты, а также взгляд на будущие направления исследований, сфокусированные на передовых материалах, накоплении тепловой энергии и оптимизации гибридных систем. В заключении подчеркивается преобразующий потенциал солнечной тепловой технологии в декарбонизации сектора промышленного тепла.

Ключевые слова: Солнечная тепловая энергия, Промышленное тепло, Солнечные коллекторы, Концентрирующая солнечная энергетика, Накопление тепловой энергии.

Annotatsiya. Sanoat sohasi global energiyaning asosiy iste'molchisi bo'lib, asosan qazilma yoqilg'ilardan olinadigan energiya iqlim o'zgarishi va issiqxona gazlari chiqindilarining ko'payishiga sezilarli hissa qo'shmoqda. Quyosh issiqlik energiyasi ishlab chiqarish jarayonlarida talab qilinadigan katta miqdordagi issiqlikni ta'minlash uchun barqaror va samarali alternativa hisoblanadi, bu sanoat energiya talabining taxminan 74% ini tashkil etadi. Ushbu sharh maqolasi quyosh kollektorlari texnologiyalari va ularning sanoat jarayonlariga integratsiyasining zamonaviy holati haqida batafsil tahlil taqdim etadi. Biz markazlashtirilmagan kollektorlar (tekis plastinali, vakuumli quvurli), markazlashtirilgan quyosh kollektorlari (parabolik, chiziqli fresnel, quyosh minorasi) va yangi paydo bo'layotgan gibrid tizimlarni asosiy sanoat sohalarining harorat talablari asosida tizimli ravishda tasniflaymiz va baholaymiz. Maqolada 40 dan ortiq ilmiy tadqiqotlar, texnik hisobotlar va amaliy tadbirlar natijalari umumlashtirilib, ushbu tizimlarning texnik ko'rsatkichlari, integratsiya usullari, iqtisodiy maqbulligi va ekologik afzalliklari muhokama qilinadi. Generatsiyaning uzilishlari, energiyani saqlash va dastlabki yuqori xarajatlar kabi dolzarb muammolar haqida tanqidiy mulohazalar yuritilgan bo'lib, shu bilan birga ilg'or materiallar, issiqlik energiyasini saqlash va gibrid tizimlarni optimallashtirishga qaratilgan kelajakdagi tadqiqot yo'nalishlari haqida ochiq fikr bildirilgan. Xulosa qismida sanoat issiqlik sohasini uglerodsizlantirishda quyosh issiqlik texnologiyasining transformatsion potensiali ta'kidlangan.

Kalit so'zlar: quyosh issiqlik energiyasi, sanoat jarayon issiqligi, quyosh kollektorlari, quyosh energiyasini markazlashtirish, issiqlik energiyasini saqlash.

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Introduction

The global industrial sector is the largest end-user of energy, accounting for about 37% of total global final energy consumption [1]. A substantial portion of this energy, estimated at two-thirds, is consumed as heat for manufacturing processes such as drying, washing, pasteurization, chemical reactions, and metallurgy [2]. This thermal energy is predominantly supplied by the combustion of fossil fuels, making industry a major source of carbon dioxide (CO_2) emissions. Decarbonizing industrial heat is, therefore, one of the most critical challenges in the transition to a net-zero economy.

Solar thermal energy, the conversion of solar radiation into usable heat, offers a direct pathway to displace fossil fuels in industrial applications. Unlike solar photovoltaics (PV), which convert sunlight into electricity, solar thermal systems generate heat that can be directly applied to processes, often with higher overall exergetic efficiency for thermal applications [2]. The technology is mature, with a spectrum of solar collector types capable of delivering heat across a wide temperature range, from low-temperature wash water to high-temperature metallurgical processes exceeding 1000°C.

This review article aims to provide a comprehensive and systematic analysis of solar collector technologies tailored for manufacturing process heat. It will:

1. Classify solar collectors based on their operating principles and temperature ranges.
2. Detail the design, performance characteristics, and industrial applicability of each collector type.
3. Analyze system integration methods, including direct and indirect schemes, and the critical role of Thermal Energy Storage (TES).
4. Evaluate the economic and environmental viability of solar industrial process heat (SIPH) projects.
5. Identify key challenges and barriers to widespread adoption.
6. Propose future research directions to enhance the technological and economic competitiveness of SIPH.

By synthesizing a wide body of literature, this review serves as a foundational resource for engineers, policymakers, and industry stakeholders seeking to understand and implement solar thermal solutions in the manufacturing sector.

CLASSIFICATION OF SOLAR COLLECTORS FOR PROCESS HEAT

Solar collectors for industrial applications are primarily classified into two main categories based on their concentration ratio: Non-Concentrating and Concentrating Collectors. The concentration ratio (C) is defined as the ratio of the

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collector's aperture area to the receiver area. This fundamental distinction dictates the operating temperature and the suitable industrial applications.

Non-Concentrating Collectors (C=1): These collectors have the same area for intercepting and absorbing solar radiation. They do not track the sun and are typically used for low to medium-temperature applications (<120°C).

Concentrating Collectors (C>1): These use reflective surfaces to focus sunlight onto a smaller receiver area, achieving higher temperatures. They often require sun-tracking mechanisms and are used for medium to high-temperature applications (80°C to >400°C).

NON-CONCENTRATING SOLAR COLLECTOR TECHNOLOGIES

Flat Plate Collectors (FPCs)

Flat Plate Collectors are the most common and widely deployed solar thermal technology. A typical FPC consists of a dark-colored absorber plate, often coated with a selective surface to maximize absorption and minimize radiative heat loss, enclosed in an insulated box with a transparent cover (usually glass) to create a greenhouse effect [3].

Performance & Temperature Range: Standard FPCs typically operate in the 30°C to 80°C range, with efficiency decreasing as the temperature difference between the collector and ambient air increases. Advanced FPCs with multiple glazings and highly selective coatings can achieve temperatures up to 100°C [4].

Industrial Applications: Their low cost and simplicity make them ideal for low-temperature industrial applications. These include:

Pre-heating boiler feed water.

Providing warm water for cleaning and sanitation in food and beverage industries.

Supply heat for drying processes in agricultural product processing (e.g., fruits, grains).

Space heating in industrial facilities.

Advantages and Limitations: The primary advantages are simplicity, low maintenance, and the ability to utilize both diffuse and direct solar radiation. The main limitation is the relatively low operating temperature, which restricts their use to a subset of industrial processes.

Evacuated Tube Collectors (ETCs)

Evacuated Tube Collectors represent a significant performance improvement over FPCs. They consist of multiple parallel glass tubes, each containing an absorber plate and a heat pipe or direct-flow channel. The air is evacuated from the space between the two concentric glass tubes, creating a vacuum that virtually eliminates conductive and convective heat losses [2].

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Performance & Temperature Range: ETCs can efficiently operate in the 50°C to 120°C range, with some models capable of reaching 150°C under high insulation [5]. Their efficiency at higher temperatures is superior to FPCs.

Industrial Applications: ETCs are suitable for medium-temperature processes, such as:

Sterilization in food and pharmaceutical industries.

Cooking and washing in large-scale catering.

Process heating in textile and leather industries (e.g., dyeing, bleaching).

Steam generation (low-pressure) for various processes.

Advantages and Limitations: Their key advantage is high thermal performance, especially in cold or windy climates, due to minimal heat loss. They are more compact than FPCs for the same output. Limitations include higher initial cost and greater sensitivity to hail damage compared to FPCs.

CONCENTRATING SOLAR COLLECTOR TECHNOLOGIES

Concentrating collectors are essential for meeting the medium and high-temperature demands of many energy-intensive industries.

Parabolic Trough Collectors (PTCs)

Parabolic Trough Collectors are the most commercially proven concentrating technology for industrial process heat. They use long, parabolic-shaped mirrors to focus sunlight onto a linear receiver tube positioned along the focal line. The receiver tube is typically enclosed in an evacuated glass envelope to reduce heat loss. The entire assembly tracks the sun on a single axis, usually north-south [6].

Performance & Temperature Range: PTCs commonly operate between 150°C and 400°C, with synthetic oil or pressurized water as the Heat Transfer Fluid (HTF). With advanced designs and molten salt as HTF, temperatures can approach 550°C [7].

Industrial Applications: PTCs are highly versatile and can be applied in:

Steam generation for power and process in industries like chemicals, textiles, and paper.

Enhanced Oil Recovery.

Refrigeration and cooling via absorption chillers.

High-temperature drying and chemical processing.

Advantages and Limitations: Advantages include high efficiency at medium-to-high temperatures, modularity, and proven commercial reliability. Limitations are high initial investment, the need for direct normal irradiance (DNI), and relatively complex tracking and maintenance.

Linear Fresnel Reflectors (LFRs)

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Linear Fresnel Reflectors are a variant of the parabolic trough concept. They use an array of nearly flat, long mirror strips positioned at different angles to focus sunlight onto a fixed linear receiver located at a common focal point above the mirror field [5].

Performance & Temperature Range: LFRs operate in a similar temperature range as PTCs (150°C - 400°C) but typically with slightly lower optical and thermal efficiency due to factors like cosine losses and shading between mirrors [8].

Industrial Applications: Their applications overlap with PTCs, including steam generation for industrial processes and power production.

Advantages and Limitations: The primary advantage is lower capital cost due to simpler mirror geometry, a fixed receiver that simplifies HTF piping, and a more compact land use. The main disadvantage is lower overall efficiency compared to PTCs.

Parabolic Dish Collectors

Parabolic Dish systems use a dish-shaped parabolic reflector to concentrate sunlight onto a receiver located at the focal point of the dish. The entire structure tracks the sun biaxially (both azimuth and elevation), achieving a very high concentration ratio.

Performance & Temperature Range: Dishes can achieve the highest temperatures among solar concentrators, routinely reaching 500°C to 750°C, and can exceed 1000°C [9]. They are often coupled with Stirling engines for power generation at the point of use.

Industrial Applications: Their modular nature makes them suitable for:

Decentralized high-temperature process heat in mining or remote locations.

Solar-driven thermochemical reactions (e.g., hydrogen production, metal oxide reduction).

Industrial-scale cooking and steam generation in distributed settings.

Advantages and Limitations: The key advantage is the very high temperature and high efficiency. The main limitations are high cost per unit, complexity of biaxial tracking, and that they are a distributed point-focus system not easily scaled for large, centralized thermal loads.

Solar Power Towers (Central Receiver Systems)

In a Solar Power Tower, a large field of two-axis tracking mirrors, called heliostats, focuses sunlight onto a central receiver mounted on top of a tower. This configuration allows for very high concentration ratios and temperatures [10].

Performance & Temperature Range: Tower systems typically operate between 500°C and 1000°C, with molten salt being the preferred HTF and storage medium for large-scale applications [11].

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Industrial Applications: Given their scale and high temperature, they are best suited for:

Very large-scale steam supply for heavy industries (e.g., cement, steel).

Production of solar fuels.

Calcination processes in cement manufacturing.

Advantages and Limitations**:** Advantages include high efficiency at very high temperatures and the potential for large-scale thermal storage. The primary limitations are very high capital cost, extreme land requirements, and complexity of operation, making them suitable only for the largest industrial complexes.

SYSTEM INTEGRATION AND THERMAL ENERGY STORAGE

The successful implementation of SIPH depends not only on the collector but also on its seamless integration into the industrial plant and the management of solar intermittency.

Integration Schemes

Integration can be direct or indirect.

Direct Integration: Solar heat is fed directly into the process. This is simple but offers no buffer against solar fluctuations.

Indirect Integration: Solar heat is used to pre-heat a utility stream (e.g., feedwater) or is delivered to a Thermal Energy Storage (TES) system. This is the more common and robust approach, allowing for a more stable energy supply.

The design of the heat exchanger network is critical. As studied by [12], pinch analysis is a powerful tool for optimizing the integration of solar thermal energy into existing processes, ensuring maximum fossil fuel savings.

Thermal Energy Storage (TES)

TES is the key to mitigating the variability of solar energy and extending its availability beyond daylight hours. It can be classified into:

Sensible Heat Storage: The most mature technology, where energy is stored by changing the temperature of a storage medium. Common media include water (for low temp), mineral oil (medium temp), and molten salts, such as the common "solar salt" (60% $NaNO_3$, 40% KNO_3), for high temperatures (up to 565°C) (Gil et al., 2010). Packed-bed storage using rocks or ceramic materials is also an area of active research [13].

Latent Heat Storage (Phase Change Materials - PCMs): PCMs store energy during their phase change (e.g., solid to liquid), offering high storage density at a nearly constant temperature. [14] reviewed numerous PCMs suitable for various temperature ranges, making them attractive for specific industrial processes with constant temperature requirements.

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Thermochemical Storage: This involves storing energy through reversible chemical reactions. It offers the highest energy storage density but is still largely in the research and development phase [15].

ECONOMIC AND ENVIRONMENTAL ANALYSIS

Economic Viability

The Levelized Cost of Heat (LCOH) is the primary metric for evaluating the economic competitiveness of SIPH systems. LCOH is the net present value of the total cost of installing and operating the system over its lifetime divided by the total heat delivered.

Studies show that the economics of SIPH are highly site and application-specific. Factors include:

Solar Resource: Locations with high Direct Normal Irradiance (DNI) are essential for concentrating technologies.

Collector Cost: ETCs and PTCs are currently the most cost-effective for their respective temperature ranges in many contexts [16].

Fuel Displaced: The LCOH of a solar system must be compared to the cost of the fossil fuel it replaces (e.g., natural gas, coal, diesel). Higher and more volatile fossil fuel prices improve the economics of SIPH.

System Size and Integration: Economies of scale apply, and a well-integrated system that maximizes utilization will have a lower LCOH.

A review by [17] found that in regions with good solar resources, SIPH systems can already be competitive with fossil fuels for low and medium-temperature applications. For high-temperature applications, the economics are improving but often still require policy support.

CHALLENGES AND BARRIERS TO WIDESPREAD ADOPTION

Despite its potential, the penetration of SIPH into the industrial sector remains low. Key challenges include:

High Initial Capital Investment: The upfront cost of solar collector fields and storage systems is a significant barrier for many companies, despite favorable long-term payback.

Intermittency and Reliability: Industry requires a reliable, 24/7 energy supply. The variable nature of solar energy necessitates backup systems or large-scale storage, adding to complexity and cost.

Space Requirements: Concentrating solar systems, in particular, require substantial land area, which may not be available adjacent to existing industrial plants.

Lack of Awareness and Expertise: Many industrial managers are unfamiliar with solar thermal technology and lack the in-house expertise to design, install, and maintain these systems.

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Policy and Regulatory Hurdles: In many regions, there is a lack of supportive policies, such as tax incentives, carbon pricing, or grants, that would help bridge the economic gap between solar and conventional fuels.

FUTURE RESEARCH DIRECTIONS

To overcome these challenges and accelerate adoption, future research should focus on:

Advanced Materials: Development of new selective coatings with higher solar absorbance and lower thermal emittance, and the use of nanomaterials to improve HTF properties [19]. Research into durable, low-cost reflector materials is also crucial.

High-Temperature TES: Innovation in next-generation molten salts, PCMs, and thermochemical storage systems to increase energy density, reduce costs, and operate at higher temperatures.

Hybridization and Smart Control: Developing optimized hybrid systems that combine solar with other renewables (e.g., biomass, PV) or fossil backups, controlled by advanced AI-based algorithms to maximize efficiency and reliability [20].

Building-Integrated Solar Thermal: Designing new industrial facilities with solar collection integrated into the building structure (e.g., roof-mounted PTCs).

Standardization and Modular Design: Creating standardized, pre-engineered, modular SIPH packages to reduce engineering costs and simplify installation.

CONCLUSION

Solar collector technologies offer a technically mature and environmentally imperative solution for supplying heat to a wide spectrum of manufacturing processes. From the simplicity of Flat Plate and Evacuated Tube Collectors for low-temperature needs to the high-efficiency Parabolic Troughs and the extreme-temperature capability of Solar Towers, a suitable technology exists for nearly every industrial thermal demand. The integration of these systems with Thermal Energy Storage is the linchpin for providing reliable, dispatchable heat, thereby increasing the solar fraction and economic attractiveness.

While challenges related to cost, intermittency, and space remain significant, ongoing research in materials science, storage technologies, and system integration is steadily eroding these barriers. With supportive policies and increased industry awareness, solar industrial process heat is poised to play a pivotal role in the urgent global effort to decarbonize the industrial sector, enhance energy security, and build a sustainable manufacturing foundation for the future. The sun, as the ultimate source of clean and abundant energy, holds the key to powering our industries without costing our planet.

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