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Modified Concentrated Solar Power (CSP) System Using Parabolic Stirling Dish Approach for Electricity Generation: A Review

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ABSTRACT **Original Research Article**

This study presents a modified Concentrated Solar Power (CSP) system that integrates the parabolic Stirling dish approach for enhanced electricity generation efficiency and scalability. The research addresses the inherent limitations of conventional CSP technologies as high capital cost, heat losses, and limited adaptability for decentralized applications, by developing a cost-effective prototype using locally available materials. The system employs a synthetic reflective dish to concentrate solar irradiance onto a pressure pot, which generates steam to drive a single-stage turbine coupled to a DC generator. Key performance metrics, including concentration ratio, heat flux, mass flow rate, energy transfer, and turbine output power, were derived and analysed. Results show that increasing the collector area while maintaining a constant receiver area proportionally improves heat flux and thermal efficiency, whereas increasing the receiver area reduces energy concentration. Similarly, higher mass flow rates and greater enthalpy differences significantly enhance turbine output. The study demonstrates that the modified Stirling dish-based CSP system achieves efficient energy conversion and operational stability while remaining scalable and economically viable for rural electrification and small-scale industrial applications.

Keywords: Concentrated Solar Power, Stirling Dish, Renewable Energy Generation, Heat Flux, Turbine Performance.

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1. Introduction

The global transition to renewable energy has increased the demand for efficient and scalable technologies in electricity generation. Among these, Concentrated Solar Power (CSP) systems are gaining attention due to their free and renewable nature of converting sunlight into thermal energy for electricity generation. This approach offers a renewable solution for large-scale power production (Hu and Yue, 2021). Traditional CSP technologies, such as Parabolic Troughs, Solar Towers, and linear Fresnel reflector systems, are well-suited for standard renewable utility-scale power plants; however, they have some inherent inefficiencies when used in modular approaches(Angel *et al.*, 2014). Parabolic troughs, for example, use curved mirrors to focus sunlight onto receiver tubes but suffer from significant heat losses due to their linear design(Bader *et al.*, 2010). Solar towers, although more efficient at higher temperatures, require extensive land use and complex heliostat tracking systems, which increase capital costs(Spelling *et al.*, 2012). The Linear Fresnel reflector system also has limited efficiency (Abbas *et al.*, 2013). Additionally, all these standard approaches tend to experience performance fluctuations under inconsistent solar irradiance, limiting their viability in regions with variable weather. Recent innovations have focused on hybrid configurations to enhance CSP efficiency, and the integration of thermal storage with combined-cycle systems has increased energy dispatchability, ensuring consistent power output even during intermittent sunlight (Costa *et al.*, 2024).

However, these solutions often remain cost-prohibitive for small-scale or decentralized applications.

The parabolic Stirling Dish system presents a promising alternative due to its scalability and modularity tendencies. Unlike large-scale CSP plants, Stirling dishes are modular, allowing for flexible deployment in off-grid or distributed energy systems. These systems use a parabolic dish to concentrate sun-thermal energy onto a Stirling engine, which converts thermal energy directly into mechanical power and, subsequently, electricity. This method reduces thermal losses by eliminating intermediate heat transfer fluids, improving overall efficiency but at a high production cost (Ghaithan, 2024).This study, therefore, evaluates a modified Stirling dish configuration designed to enhance scalability and performance by incorporating advanced materials for reflectors and receivers, along with improved heat exchangers. The system aims to achieve higher energy conversion rates while minimizing costs. Additionally, modularity enables incremental capacity expansion, making it suitable for both rural electrification and industrial applications.

While conventional CSP systems remain effective for large-scale energy production, their limitations in smaller applications necessitate innovative alternatives. The modified Stirling dish approach helps to overcome these limitations by integrating boiler-turbine setups combined with a parabolic reflector to enhance heat retention and energy output in pilot projects. Building on these advancements, this study reviews the potential of a modified CSP system based on the Stirling dish approach, which offers scalability and modularity for broader adoption (Karim *et al.*, 2014). The other sections of this article are sectioned into 2, 3, and 5. The overview of CSP system's development, highlights of the material and method used in the research, the results and discussions, and the conclusions and recommendations are presented in each of the sections, respectively.

2. Overview of CSP System's Development

The evolution of Concentrated Solar Power (CSP) systems has undergone significant advancements over the past few decades, driven by improvements in reflector design, heat transfer mechanisms, and power cycle efficiency. Early milestones include the Solar Energy Generating Systems (SEGS) developed in the 1980s, which employed parabolic trough collectors using synthetic oil as the heat transfer fluid (HTF). These early systems achieved operational efficiencies around 14%, setting a foundational benchmark for subsequent innovations (Bader *et al.*, 2010).

In the early 2000s, the use of molten salt as both a heat transfer and thermal storage medium enabled the development of central receiver (power tower) systems. These systems achieved higher operating temperatures and improved energy dispatchability, with thermal efficiencies reaching approximately 20%. However, such improvements came with trade-offs, particularly concerning spatial requirements and infrastructure costs (Cheang *et al.*, 2015).

Recent technological breakthroughs have further pushed the boundaries of CSP performance. For example, the incorporation of nanofluid-enhanced HTFs has led to a 30% improvement in thermal conductivity and specific heat capacity, thereby optimizing heat absorption and transfer (Shahabuddin *et al.*, 2021). Additionally, artificial intelligence and machine learning algorithms have been applied to heliostat field control, leading to more precise solar tracking and a 12% reduction in the Levelized Cost of Energy (Ghaithan, 2024). Furthermore, advances in materials science have enabled the fabrication of 3D-printed parabolic reflectors coated with graphene, achieving up to 92% solar reflectivity and enhancing overall system efficiency (Yao *et al.*, 2024).However, despite these advancements, two key gaps persist in translating enhanced CSP systems to decentralized or modular applications:

a. Cost: current CSP implementations require expensive setups, which are unrealistic for rural or off-grid deployments.
b. Scalability: most CSP approaches and optimisations focus on renewable large utility-scale plants (>50 MW), relying on extensive sensor networks and high-performance computing impractical for small-scale utility.

This research bridges these gaps by developing a modified CSP, tailored for low-cost and scalability implementation, which promotes academic research on the CSP and its modular deployment. The system prioritises the approaches of presenting a novel modified CSP combining synthetic parabolic reflectors, a high-efficiency boiler, and a micro-scale steam turbine.

3. Materials and Methods

This research examines the energy loss deficiencies in the basic principles of formation and operation of standard approaches to concentrated solar power systems, as depicted in the flow charts of Figures 1a and 1b, respectively. It aims to design a modified Stirling dish approach for concentrated solar systems. The parabolic Stirling dish standard was chosen for modification over the parabolic trough, solar tower, and linear Fresnel approaches due to its scalability, to design a modified prototype CSP system that helps mitigate energy losses and high-cost implications, as observed in the Stirling dish systems.

3.1. System design

Local materials were sorted to ensure the sustainability and the scalability of the modified prototype CSP system as itemised in Table 1. The function of each of the materials used was clearly stated and defined. The heat loss deficiency from the heat transfer fluid was mitigated through the modification approach using the heat pressure pot and a high-tech single-stage steam turbine.

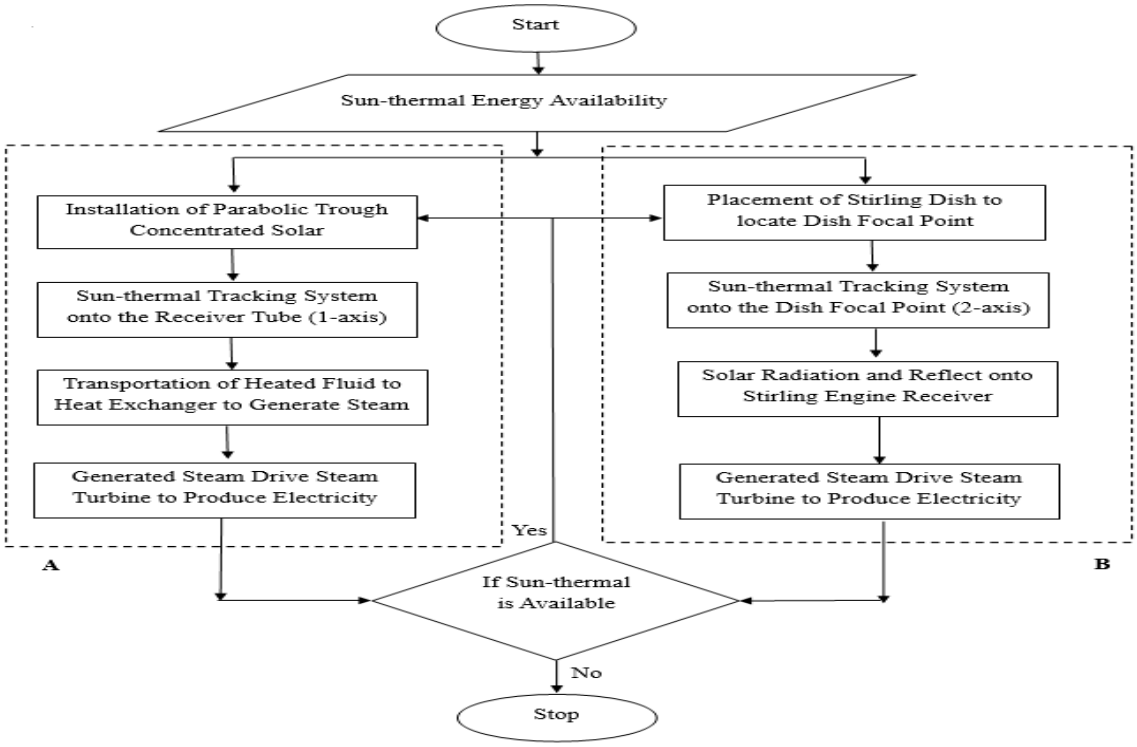
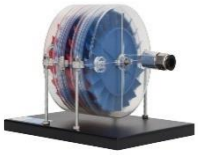


Figure 1: The Basic Formation and Principle of (a) Parabolic Trough CSP and (b) Stirling Dish CSP Systems.

Table 1: Design Material Characteristics

Material's Name	**Material's Image**	**Function**
Single-stage Steam Turbine		Convert Steam Energy to Rotational Energy
Synthetic Mirror Sticker		Beaming Sun-Thermal Energy to the Pressure Cooker
Pressure Pot		Convert Sun-Thermal to Steam Energy
DC 3 – 15 V Electric Generator		Convert Turbine Rotational Energy to Electric Energy

3.2 Data collection and performance metrics

Data represent the numerical information obtained from the modified system, and the analytical assessment that allows engineering insight into the efficiency of the modified system is termed performance metrics. Therefore, the sun-thermal energy incident on the dish is estimated using the Concentration ratio (C_r) as expressed by (Yao *et al.*, 2024) in equation 1 and the thermal power (P) in equation 2.

$$C_r = \frac{A_{collector}}{A_{receiver}} \quad 1$$

$$P = eff.\ x\ A_{collector}\ x\ C_r(W) \quad 2$$

Where $A_{collector}$,$A_{receiver}$ and *eff.* are the Area of collector of the dish, Area of receiver's focal point and the projected efficiency of the modified CSP system, respectively. Also, the Heat flux is expressed in equation 3 by (Peinado-Gonzalo *et al.*, 2019)

$$H_f = \frac{P}{A_{receiver}}(W/m^2) \quad 3$$

The mass flow (M_f) rate on the turbine is expressed by(Dowling *et al.*, 2017) in equation 4 as:

$$M_f = \rho x A x v \quad 4$$

Where ρ is the steam density (kg/m^3), A is the cross-sectional area of the steam flow (m^2) and $v$is the steam velocity (m/s). The Energy transfer (E_t) on the turbine blade is as expressed in equation 5 by (Ghaithan, 2024)

$$E_t = M_f x\ h \quad 5$$

Where h is the specific enthalpy of the steam (J/kg) and the Turbine power (T_p) output is expressed in equation 6 by (reference)

$$T_p = M_f x\ (h_1 - h_2) \quad 6$$

Where h_1 and h_2 are the steam enthalpy at the inlet and outlet of the turbine respectively

3.3 Design system evaluation and benchmarking

The modified prototype design performance metrics values were compared against the COMSOL Multiphysics simulations to benchmark the performance of the modified system against standard Stirling dish system. The design and the implementation layout for the modified prototype diagram is as presented in Figure 1.

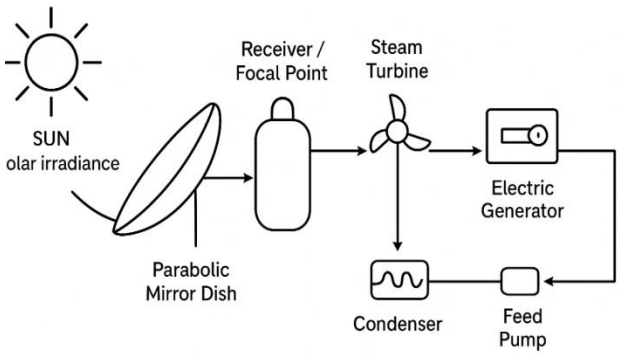


Figure 1: The Implementation of the Modified Stirling Dish Concentrated Solar Power System

4. Results and Discussions

Table 2 shows that when the area of the collector is increased while the receiver area remains constant, the concentration ratio (Cr) increases proportionally. This means that a larger reflective surface gathers and focuses more solar radiation onto the same receiver area, thereby increasing the receiver's temperature and enhancing the overall thermal efficiency of the system. Conversely, when the receiver area is increased while the collector area remains unchanged, the concentration ratio decreases because the same amount of solar energy becomes distributed over a larger surface area. This leads to a reduction in the intensity of the concentrated heat and consequently lowers the operating temperature and thermal output of the receiver. In cases where both the collector and receiver areas are increased simultaneously, the concentration ratio may either increase or decrease depending on the relative rate of their increase. If the receiver area grows more rapidly than the collector area, the concentration ratio will drop, indicating a dilution of the concentrated solar flux.

Table 2: Variational Effect of the Concentration Ratios

Case	(A_{collector}) (m²)	(A_{receiver}) (m²)	(Cr)
1	1.0	0.1	10
2	2.0	0.1	20
3	4.0	0.1	40
4	4.0	0.2	20
5	6.0	0.2	30
6	6.0	0.3	20

Therefore, in designing an efficient solar concentrator system, it is essential to optimise both the collector and receiver areas to achieve a balance between maximum heat concentration and material safety, avoiding excessive thermal stress or energy loss.

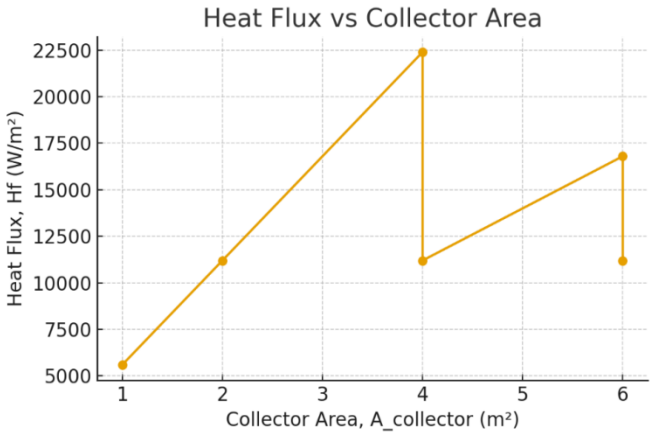


Figure 3: Heat Flux against Dish Collector Area

In Figure 3, when the collector area increases while the receiver area remains constant, the thermal power delivered to the receiver rises proportionally, which consequently increases the heat flux (Hf) on the receiver surface. A higher heat flux implies that more thermal energy per unit area is concentrated onto the receiver, resulting in a higher receiver temperature and improved steam generation efficiency. Conversely, if the receiver area is enlarged while the collector area remains fixed, the heat flux decreases because the same amount of solar energy becomes distributed over a larger surface area. This reduction in heat flux lowers the receiver temperature and decreases the amount of energy available for steam production.

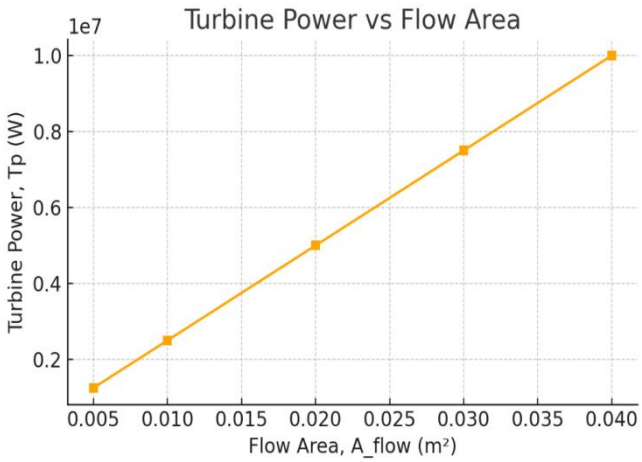


Figure 4: Turbine Power against the Flow Area.

The mass flow rate (Mf), as depicted in Figure 4, depends directly on the steam density, the cross-sectional flow area, and the velocity of the steam. Therefore, increasing either the flow area or the steam velocity results in a higher mass flow rate, meaning a greater quantity of steam is transported per second. This rise in mass flow increases the total thermal energy carried by the steam, enhancing the energy available for conversion in the turbine. The energy transfer rate (Et) to the turbine blades is the product of the mass flow rate and the specific enthalpy of the steam. Consequently, an increase in either the mass flow rate or the specific enthalpy directly raises the energy transfer to the turbine, thereby increasing its mechanical power potential. In a similar manner, the turbine output power (Tp) is determined by both the mass flow rate and the enthalpy differential between the inlet and outlet of the turbine. A larger enthalpy difference or greater mass flow rate leads to a higher turbine output, improving the overall system performance.

However, these benefits must be balanced carefully. Excessive heat flux without sufficient mass flow can overheat the receiver, causing material stress or energy losses, while excessive mass flow with inadequate heat flux can result in poor steam quality and lower turbine efficiency. Therefore, in practical design, an optimal balance between collector area, receiver size, and flow parameters is essential to achieve maximum efficiency, stable operation, and safe thermal performance in the solar thermal power system.

Case	*A_collec*	*A_recei*	*A_flow*	*Th_power*	*Hf*	*Mflo*	*Et_W*	*Tp_W*
1	1	0.1	0.005	560	5600	1.25	3500000	1250000
2	2	0.1	0.01	1120	11200	2.5	7000000	2500000
3	4	0.1	0.02	2240	22400	5	14000000	5000000
4	4	0.2	0.02	2240	11200	5	14000000	5000000
5	6	0.2	0.03	3360	16800	7.5	21000000	7500000
6	6	0.3	0.04	3360	11200	10	28000000	10000000

5. Conclusion

The development and analysis of the modified Concentrated Solar Power (CSP) system based on the Stirling dish configuration have demonstrated that effective optimization of collector and receiver areas is central to achieving high thermal performance. The results confirm that a larger collector area increases the concentration ratio and heat flux, thereby enhancing receiver temperature and system efficiency. In contrast, increasing the receiver area at constant collector size dilutes the solar flux and reduces efficiency. The investigation of steam dynamics further reveals that higher mass flow rates and greater enthalpy differentials across the turbine substantially increase the mechanical and electrical outputs. Nevertheless, system balance is crucial; excessive heat flux without adequate steam flow may cause thermal stress, while excessive flow with insufficient heating reduces efficiency. The prototype's reliance on locally sourced materials, combined with its modular and scalable design, supports its suitability for low-cost, decentralized energy production. Hence, the modified Stirling dish-based CSP system presents a sustainable and adaptable solution for enhancing renewable power generation, particularly in rural and developing regions, while contributing to the global transition toward cleaner energy technologies.

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