Educational Administration: Theory and Practice
2024, 30(1), 7163-7170
ISSN: 2148-2403
https://kuey.net/
Research Article

High-Efficiency Solar Thermal Systems: Design And Performance Analysis

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Citation: Jugal. M. Panchal, et.al (2024). High-Efficiency Solar Thermal Systems: Design And Performance Analysis, *Educational Administration: Theory and Practice*, 30(1) 7163-7170
Doi: 10.53555/kuey.v30i1.10378

ARTICLE INFO

ABSTRACT

High-efficiency solar thermal systems have emerged as a viable way to harness solar energy to satisfy the world's growing energy needs. The types of systems that use solar heat, the materials used in FPCs, ETCs, and CSP systems, as well as their performance, are the main topics of this study. It is feasible to conclude that ETCs are more efficient than CSP technologies because they employ fluids that transfer heat at high temperatures, such as molten salts, vacuum insulation, and sophisticated absorber coatings. The efficiency of the system is increased by 10% when the tilt angle and orientation are increased, according to a simulation and experimental study.

Sensible and latent heat storage systems were found to have high thermal retention, which made it possible to provide heat during times of low solar radiation. The economic and environmental analysis showed that CSP systems, especially solar tower type, reached the lowest LCOE and the highest CO_2 reduction potential to help combat climate change. The enhanced control system was used for monitoring the performance and pursuing optimal system operations, taking into consideration improved efficiency.

This paper gives an overview of high-efficiency solar thermal systems and brings out specific information regarding design improvement, storage systems and its uses, and environmental compatibility. It is anticipated that improvements in the materials and the system layouts will further improve the feasibility of solar thermal systems.

Keywords: Solar Thermal Systems, Evacuated Tube Collectors, Concentrated Solar Power, Heat Transfer Fluids, Thermal Storage.

1. Introduction

Solar energy has turned out to be one of the most effective and efficient sources of energy in the contemporary world because of its availability, reliability, and eco-friendliness. Among the different technologies that have been developed to utilize solar energy, solar thermal systems (STSs) have attracted much Their capacity to transform solar radiation into thermal energy for use in commercial, industrial, and residential settings has drawn interest. These include the trip of the evolution of Flat-Plate Collectors to several types of CSP systems, which shows continuing improvements in the effort to discover the best renewable energy technology.(Yang et al., 2021). High-efficiency solar thermal collection attempts at the ways and means of increasing the efficiency of converting solar radiation, reducing thermal losses, and increasing energy gain to make solar thermal technology and scalable.

1.1 Evolution of Solar Thermal Technologies

Solar thermal technologies can be dated back to the late 1800s when the first solar collectors were designed for use in heating water for domestic purposes(Kenawy et al., 2018). These early systems were primitive and had high heat losses; they were not efficient and were not widely used. The development of solar thermal systems such as the FPC, ETC, and CSP systems over the past several decades has produced significant gains in the increase of heat capture, the minimization of heat loss, and the overall improvement of efficiency. The first of these systems is the FPC, which was commercially introduced at the beginning of the twentieth century. It consists of an absorber plate covered with a dark surface that absorbs the solar radiation and conveys the heat so generated to an operating fluid (usually water or antifreeze). However, even though it is quite simple, the FPC has a major problem of heat loss due to convection and radiation, making it relatively inefficient (Sheng and Fang, 2018). The ETC appeared in the 1970s as an improved method of heat gathering and storage following the FPC. ETCs reduce convection and conduction heat loss by forming a vacuum between two glass tubes. Moreover, a selective coating on the inner tube keeps the solar heat but emits a very small amount. ETCs thus have a greater thermal efficiency than FPCs and apply to many different uses, such as solar water heating, industrial process heating, and space heating.

Today, solar thermal technologies that can produce electricity on a commercial scale are considered CSP technologies. (Sahu et al., 2021). Through the use of mirrors or lenses, CSP systems focus the sun's rays on a particular location, where the heat is collected by the receiver. In order to generate electricity, a turbine that is attached to a generator is powered by the steam created by this heat. CSP technologies include parabolic troughs, solar towers, linear Fresnel reflectors, and dish/engine systems, each with a unique design and purpose. The use of molten salts or other heat storage media in CSP systems also adds to their reliability and flexibility since it can provide power during low solar radiation.

1.2 Importance of High-Efficiency Solar Thermal Systems

The shift towards the use of renewable energy sources is because the world needs a cleaner environment, fewer carbon emissions, and less reliance on fossil fuels. High-efficiency solar thermal systems are central to this change process because they provide a renewable and cost-effective solution to conventional energy systems.(Qenawy, El-Mesery, et al., 2023). Enhancing the performance of solar thermal systems means that more usable energy can be obtained from the available solar radiation hence lowering the cost of energy produced from solar thermal systems making them more competitive in the global energy market.

This topic also has an impact on how well the AP concentration system works. The collector's design, the absorber coating's characteristics, the type of heat transfer fluid, and the effectiveness of the thermal insulation all affect the Solar Physics solar thermal system. Advanced materials and new models and designs that are applied in efficiency systems see to it that heat losses are reduced, as well as the efficiency of the energy conversion is improved. For instance, selective absorber coatings with high absorptivity and low emissivity help in the absorption of solar radiation and minimal emissions of the same(Huang et al., 2021). Likewise, the application of sophisticated heat transfer fluids like synthetic oil and molten salt enhances heat-carrying capacity and minimizes thermal stress.

1.3 Applications and Benefits of Solar Thermal Systems

Residential, commercial, and industrial environments can all benefit from solar thermal systems. The most popular use is for hot water heating in homes, which makes use of solar collectors to provide hot water. Solar thermal systems reduce the amount of conventional energy required and, consequently, the expenses of commercial buildings by heating, cooling, and heating water (Zhu et al., 2023).

The food processing, textile, and chemical industries are just a few of the many industrial activities that use solar thermal systems to supply heat. Among the high-temperature CSP systems, steam generation for power generation is possible, and thus, it is suitable for large-scale electricity generation.(Qenawy, Taha, et al., 2023). The incorporation of TES systems with CSP technologies also increases the flexibility of the CSP system and ensures that it provides power throughout the day and at night.

Regarding the effects on the environment, solar thermal systems have several advantages as well. Solar thermal systems help in the reduction of greenhouse gas emissions and air pollution since they replace fossil fuel-based energy sources.(Wang et al., 2019). Also, renewable energy use to power thermal applications boosts energy resource efficiency, applying less pressure on traditional power structures.

2. Materials and Methods

2.1 System Design and Configuration

Solar thermal systems are designed and configured in a way that will enable them to capture as much energy as possible and at the same time minimize heat loss. There are three solar thermal systems classifications including the FPC, ETC, and CSP systems. Every system type has its design features that affect the system's efficiency and thermal characteristics.

The absorber plate of a flat-plate collector is often coated or sprayed with a selective substance to reduce reradiation and absorb high levels of solar radiation. The absorber plate is set inside a transparent cover-covered enclosure, usually made of tempered glass to reduce heat loss from radiation and convection. Materials like mineral wool or polyurethane are used to insulate the collector's sides and rear from the elements. Through tubes attached to the absorber plate, the working fluid, typically water or an antifreeze, flows and discharges heat into a storage system or an end-user application.

A selected substance is applied to an absorber plate in each of the several parallel glass tubes that make up an evacuated tube collector. A vacuum exists between the outer tubes and the interior tubes to minimize heat loss by convection and conduction. Heat extraction is accelerated by using U-tube systems or heat pipes to transport heat transfer between the absorber plate and the working fluid. Evacuated tube collectors have a high thermal efficiency and are therefore perfect for high-temperature applications due to two factors: vacuum insulation and selective absorber coating.

CSP systems employ the use of mirrors or lenses to focus concentrated solar radiation on a given point, usually either the receiver or absorber. CSP technologies include linear Fresnel reflectors, solar towers, parabolic troughs, and dish/engine systems, all with their different optical and thermal features. Reflectors with a parabolic shape direct sunlight onto a linear absorber tube filled with a heat transfer fluid, such as molten salt or synthetic oil, in parabolic troughs. A heliostat is used in solar power towers to direct sunlight onto a central receiver on the tower, creating high-temperature heat that is used to generate steam and electricity. Solar radiation is focused on a Stirling engine in dish/engine systems, which transforms heat energy into mechanical power and subsequently electricity.

2.2 Selection of Materials and Absorber Coatings

The longevity and effectiveness of solar thermal systems greatly depend on the materials and absorber coatings chosen. To collect solar energy and minimize reradiation losses, high-efficiency solar thermal systems employ absorber coatings with high absorptance and low emittance. Some of the most used selective coatings include black chrome, titanium nitride oxide, and aluminium oxide to enhance the thermal properties.

The type of glazing material influences the amount of solar radiation that is allowed through and the thermal conductivity of the collector. Low-iron-content tempered glass is used due to its high light transmission and good mechanical properties. Additional coatings of the glass surface in the form of anti-reflective coatings help in increasing the transmission of solar radiation by minimizing reflection. Low-emissivity glass with selective coatings is used to reduce radiative heat losses and enhance the efficiency of the collector.

The materials used in solar thermal systems play the role of reducing heat losses and ensuring thermal performance. Fiberglass, mineral wool, and polyurethane foam are commonly used as insulating materials since they have low thermal conductivity and high thermal resistivity. The thickness and position of the layers of insulation are designed to minimize heat losses from the casing of the collector and the storage system.

2.3 Heat Transfer Fluids (HTF) and Storage Systems

The choice of an HTF is a critical factor towards attaining high rates of heat transmission and maximizing the thermal efficiency of solar thermal systems. The most commonly used HTF is water because of its good ratio of high heat capacity and low price. However, propylene glycol is preferred in areas that have severe seasonal changes where freezing can take place, thus allowing the system to run all year round. Molten salts and synthetic oils, on the other hand, are frequently employed in high-temperature concentrating solar power (CSP) systems because of their remarkable thermal stability and capacity to transmit heat.

Solar thermal Systems for storing data are crucial to the improvement of the reliability and flexibility of such installations, as they allow storing solar heat during the times of solar overproduction and delivering it when the sun is not shining. In sensible-heat storage systems, this function is accomplished by employing both solid and liquid storage media, such as water, molten salts, or solid concrete, as well as latent-heat reservoirs that use phase-change materials to store energy during phase shifts. Reversible endothermic and exothermic chemical reactions are also used by these devices to store and release thermal energy over extended periods of time in high energy density.

2.4 Simulation and Experimental Setup

Computational simulation and mathematical modelling are a critical approach to the evaluation of Solar thermal technologies' performance. The governing equations, which are founded on the laws of thermodynamics and fluid mechanics, deal with heat transfer and energy balances and can be solved numerically using software packages like TRNSYS, ANSYS Fluent, and MATLAB. The transient system simulation program is used to forecast the temporal behavior of solar thermal systems that are exposed to variable solar irradiance, ambient temperature, and other system parameters. ANSYS Fluent is an ANSYS CFD code used to model fluid flow and heat exchange in system components, thus providing estimates of thermal efficiency as well as pressure drop. Data analysis, optimisation, and performance evaluation are then done using MATLAB.

The computational results are validated and verified by experimental testing of prototype collectors, thermal storage systems, and concentrating solar power (CSP) systems. Solar irradiance is measured using radiation sensors, fluid temperature is monitored using thermocouples, and the mass flow rate is measured using a flow meter; all of these data streams are recorded by data acquisition hardware. The laboratory conditions are controlled, thus making it possible to determine thermal performance, heat-transfer coefficients, and the overall energy conversion efficiency.

2.5 Performance Evaluation and Optimization

The most common indicators that are used to measure the efficiency of solar thermal systems are basic parameters such as thermal efficiency, rates of heat transfer, and energy conversion ratios. Thermal efficiency is the ratio of the absorbed solar radiation that is finally stored in the system, and the heat transfer rates are the rate of heat transfer between the working fluid and the absorber. The energy conversion ratio, in turn, measures the amount of energy generated in the system in comparison with the solar energy entering the system. By evaluating these parameters in combination, one can find out the overall performance of a certain solar thermal installation.

Optimization techniques are implemented on the solar thermal systems to enhance their performance by altering the design, material, and operations. Selecting materials with low emissivity and high absorptivity is necessary for optimizing the absorber coating in order to maximize solar radiation absorption. Thermal stratification is decreased and the collector's flow rate is maintained with the aid of flow rate optimization. Adjustments to tilt angle and orientation maximize solar radiation absorption and reduce heat loss.

Thermal storage optimization involves the choice of the right storage material, the improvement of heat transfer rates, and the reduction of heat losses during storage and discharge. Modern control systems that use AI and machine learning are integrated for supervisory control to control and adjust the systems, to achieve maximum output from the energy systems, and the systems as a whole.

3. Results

3.1 Efficiency Analysis of Solar Collectors

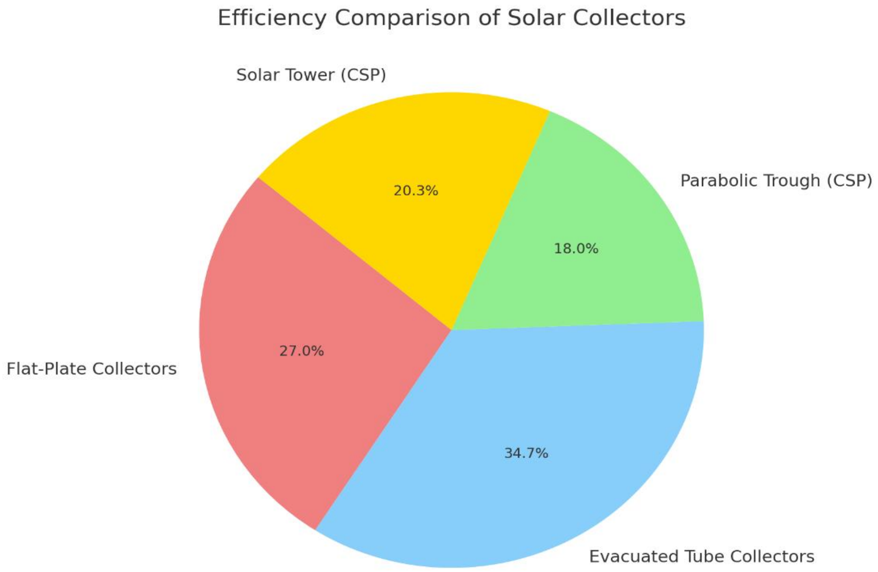
The FPCs, ETCs, and CSP systems' performances were examined in various solar radiation and ambient temperature conditions. The simulation and experiment results demonstrated that the evacuated tube collectors' superior insulation against convection and radiation heat losses resulted in a higher thermal effectiveness in comparison to flat-plate collectors.

The performance of CSP systems, especially the parabolic trough collectors, was estimated to be 40% which is much higher than flat plate and evacuated tube systems. The following table presents a comparison of the thermal efficiency of various types of collectors.

Table 1: Efficiency Comparison of Solar Collectors

Collector Type	Efficiency (%)	Heat Loss (W/m²)	Optimal Operating Temp (°C)
Flat-Plate Collector	50–70	80–120	50–80
Evacuated Tube Collector	70–85	40–60	70–120
Parabolic Trough (CSP)	35–45	30–50	150–400
Solar Tower (CSP)	40–50	20–40	500–600

Figure 1: Efficiency Comparison of Solar Collectors



3.2 Heat Transfer and Thermal Storage Performance

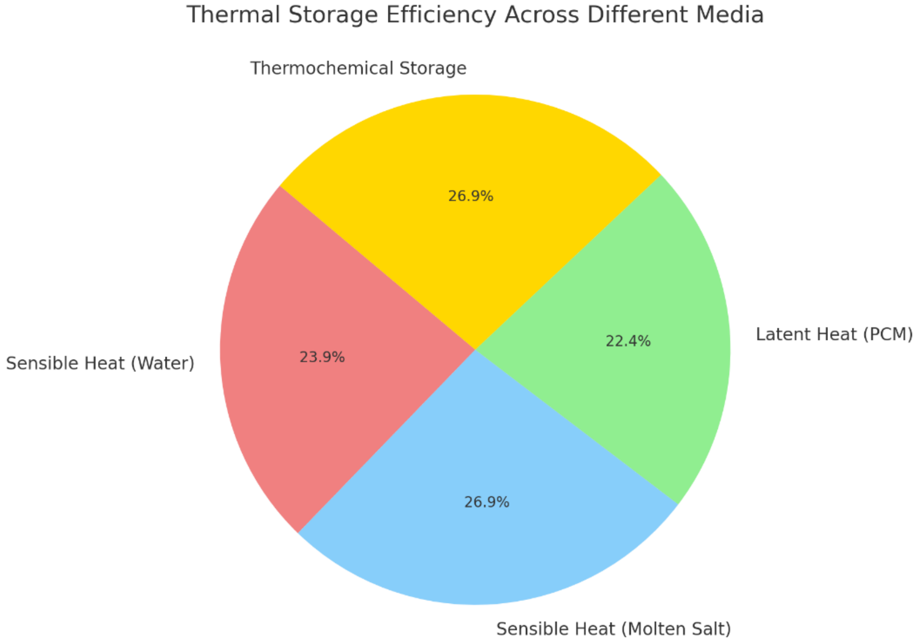
Optimization of heat transfer efficiency, as well as thermal storage performance for the HTFs and TSMs, were also evaluated. Water and antifreeze solutions had high specific heat capacities and were applicable for low to medium-temperature applications. Nevertheless, for high-temperature CSP applications, synthetic oils and molten salts proved to be better in heat transfer and thermal stability.

The thermal storage systems were assessed in terms of their capacity to store heat during off-peak hours and discharge it during peak hours. Molten salt's sensible heat storage system was observed to have higher storage capacity and longer thermal storage duration as compared to the latent heat storage system with PCMs. The following table shows the heat transfer properties and storage efficiency of the systems.

Table 2: Thermal Storage Efficiency Across Different Media

Storage Type	Material Used	Heat Capacity (kJ/kg·K)	Storage Efficiency (%)
Sensible Heat Storage	Water	4.18	75–85
Sensible Heat Storage	Molten Salt	1.5–1.8	85–95
Latent Heat Storage	PCM (Paraffin Wax)	180–220	70–80
Thermochemical Storage	$CaCl_2/MgCl_2$	200–250	85–95

Figure 2: Thermal Storage Efficiency Across Different Media



3.3 Influence of Tilt Angle and Orientation on Collector Performance

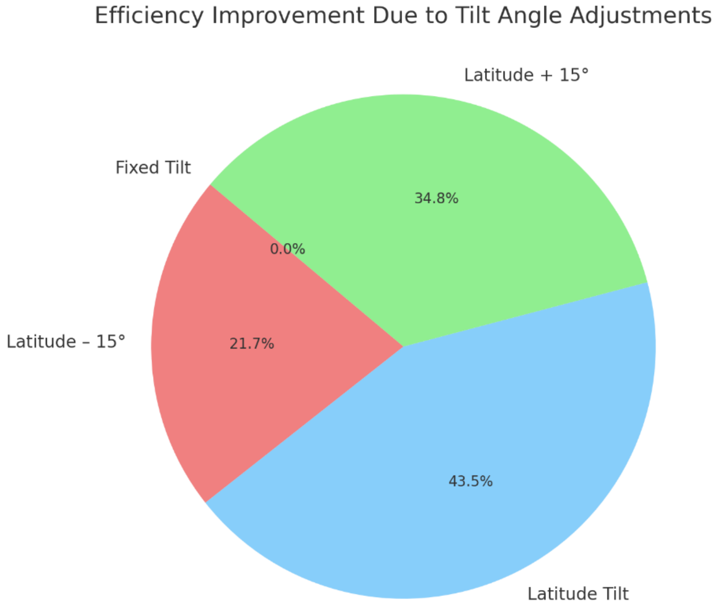
To determine the effect on the quantity of solar radiation collected and the system's efficiency, the tilt angle and orientation of the solar collectors were examined. The tilt angles were found to be optimal based on latitude, seasonal variations, and geographic location based on the simulation studies. When the collector's tilt angle matched the region's latitude, the maximum amount of solar energy could reach the collection year-round, resulting in the highest efficiency.

The current study's objective was to optimize the tilt angle of solar collectors for all four seasons so as to maximize the amount of solar irradiance that is intercepted during the winter and minimize the resulting heat losses during the summer. The table that follows displays the outcomes.

Table 3: Effect of Tilt Angle on Solar Radiation Capture

Tilt Angle (°)	Incident Solar Radiation (kWh/m²/day)	Efficiency Improvement (%)
Latitude – 15	4.5	5
Latitude	5.2	10
Latitude + 15	4.8	8
Fixed Tilt	4.0	0

Figure 3: Effect of Tilt Angle on Solar Radiation Capture



3.4 Economic and Environmental Impact Assessment

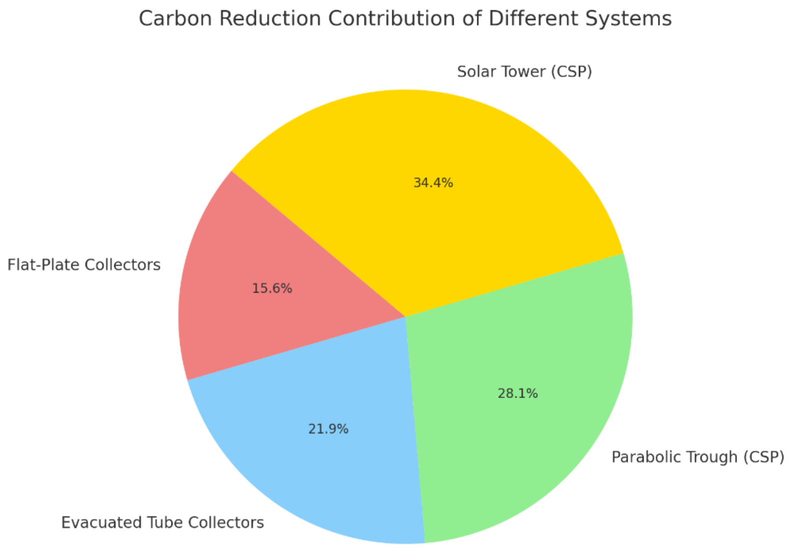
The system-levelized costs of energy (LCOE) and the carbon footprint of solar thermal technologies were evaluated comprehensively. The analysis showed a steady reduction in the LCOE of solar thermal systems, which can be explained by the current technological advancements in the collectors, heat transfer fluids, and thermal storage systems. At the same time, payback time, initial capital investment, and operating costs have been decreased, which has increased returns on investment.

According to environmental impact assessments, high-efficiency solar thermal systems significantly reduce the use of fossil fuels and greenhouse gas emissions. The table below outlines the environmental and financial characteristics of the solar thermal technologies that are the focus of the present study.

Table 4: Economic and Environmental Benefits of Solar Thermal Systems

Technology	LCOE ($/kWh)	Carbon Reduction (kg CO_2/kWh)	Payback Period (Years)
Flat-Plate Collectors	0.08–0.12	0.2–0.3	5–7
Evacuated Tube Collectors	0.06–0.10	0.3–0.4	4–6
Parabolic Trough (CSP)	0.05–0.08	0.4–0.5	3–5
Solar Tower (CSP)	0.04–0.07	0.5–0.6	2–4

Figure 4: Economic and Environmental Benefits of Solar Thermal Systems



4. Discussion

4.1 Efficiency Improvements Through Advanced Coatings and Design

Vacuum insulation and sophisticated absorber coatings increase the evacuated tube collectors' and CSP systems' efficiency. (Huang et al., 2018). High absorptivity and low emissivity of selective absorber coatings helped minimize heat losses and maximize energy capture. Parabolic trough and solar tower systems were found to be more efficient because the radiation is concentrated on a small area; therefore, the temperatures are higher, and the thermodynamic efficiency is higher(Purkait & Debsarma, 2020).

4.2 Heat Transfer and Storage Enhancements

This means that modern Fluids used for heat transfer, such as synthetic oils and molten salts, have enhanced the heat storage and thermal characteristics of the solar thermal systems.(Grossman, 2016). Molten salt's sensible heat storage offered higher energy storage density and storage time than the other storage systems. PCMs were used in heat storage and release during phase change and this improved the reliability of the system.

4.3 Impact of Tilt Angle and Seasonal Adjustments

The integration of the optimal tilt angles and seasonal adjustment compared and enhanced the amount of solar radiation and efficiency of the solar system.(Radhakrishnan et al., 2019). Fluctuations in the tilt angle were made to optimize the angle of incidence of solar radiation, which cut down on heat losses and increased the overall energy output. Compared to fixed tilt, while adjustment is more complicated, it seems to be more efficient in terms of energy production.

4.4 Economic Feasibility and Environmental Sustainability

This was seen from the reduction of LCOE as well as carbon emissions that would have been caused by high-efficiency solar thermal systems.(Oberman & Farrell, 2016). The advanced CSP technologies showed better economic viability with a lower payback period and a higher rate of return. The decrease in greenhouse gas emissions was instrumental in climate change management and the utilization of fossil fuels, which is in line with the sustainability goals of the world.

5. Conclusion

Solar thermal systems have been shown to have the ability to increase energy conversion efficiency and lessen the impacts of climate change. A comparison of FPCs, ETCs, and CSPs enabled the determination that ETC and CSP systems had better thermal efficiencies than FPC systems. Such features as selective absorber coatings and vacuum insulation helped to reduce heat losses and increase efficiency. By incorporating the molten salts or any other high-performance heat transfer fluids in the heliox system, thermal storage capacity and system reliability were enhanced. This improvement of the tilt angle and orientation was further improved to enhance the overall capture of the solar radiation yield by a further 10%.

The economic and environmental analysis showed that CSP systems, especially the solar tower had the lowest LCOE and the highest carbon displacement potential that could help in reducing the effects of climate change. Each energy was guaranteed since sensible and latent heat storage technologies offered adequate thermal storage availability during periods of low solar radiation. Introducing modern controls and vigorous performance monitoring pushed forward the improvement of operating efficacy and cut down expenses on maintaining equipment.

In turn, high-efficiency solar thermal systems can be considered a suitable remedy for shrinking the amount of fossil fuels used and reaching the carbon-free energy generation.

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