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Modelling and Design of Concentrated Solar Power Plant with Molten Salt Thermal Energy Storage

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Abstract: This research study focuses on the design and development of a 100 MW linear Fresnel molten salt power plant, aiming to harness solar energy for electricity generation. The study investigates various aspects related to the plant's design, including the heliostat field, direct normal irradiance (DNI), solar multiple, receiver thermal power, power cycle, tower and receiver, and thermal storage. Extensive analysis and simulations were conducted to optimize the system's performance and efficiency.The results of the study reveal that the heliostat field design parameters, such as the number of heliostats, dimensions, and reflective area to profile ratio, play a crucial role in achieving accurate sunlight concentration. DNI data specific to the project location was utilized to determine the available solar energy for conversion into electricity. The research concludes that the design and development of a 100 MW linear Fresnel molten salt power plant is a viable and sustainable solution for harnessing solar energy. The study provides valuable insights into the design parameters, system optimization, and operational considerations, contributing to the advancement of concentrated solar power technology. The findings of this study will serve as a foundation for future research and development in the field of renewable energy, paving the way for cleaner and more sustainable power generation.

Introduction

Solar energy is a clean and abundant source of renewable energy that has the potential to play a significant role in meeting the world's growing energy demands while reducing greenhouse gas emissions [1-2]. Concentrated solar power (CSP) technology harnesses the power of sunlight by using mirrors or lenses to concentrate solar radiation onto a receiver, where it is converted into thermal energy [3-5]. This thermal energy can then be stored and used to generate electricity on-demand, even during periods of low solar radiation.

One of the key challenges in CSP technology is the intermittent nature of solar radiation. To overcome this challenge and ensure continuous power generation, thermal energy storage systems are employed [6-7]. Molten salt thermal energy storage is a widely adopted and promising technology in which high-temperature molten salts are used to store thermal energy for later use. This allows CSP plants to provide stable and dispatchable electricity, making them a reliable and flexible renewable energy solution [8-11].

The design and development of a concentrated solar power plant with molten salt thermal energy storage require a comprehensive understanding of various system components, including the heliostat field, receiver, power cycle, thermal storage, and integration with the grid [12-13]. The optimization of these components is crucial for maximizing the overall system efficiency, reducing costs, and ensuring long-term operational reliability [14]. Furthermore, the geofigureical location of the power plant plays a significant role in determining the solar resource availability, ambient conditions, and other environmental factors. Considering the specific location, such as Lahore, Pakistan, allows for the adaptation of the system design to local conditions and optimization for enhanced performance.

Given the importance of CSP technology in the renewable energy landscape, there is a need for continuous research and development to improve the design and operational aspects of concentrated solar power plants. This study aims to contribute to the existing knowledge by investigating the design and development of a 100 MW linear Fresnel molten salt power plant in Lahore, Pakistan. By analyzing parameters such as solar multiple, DNI, ambient temperature, wind velocity, and other system variables, the study seeks to optimize the design, enhance system performance, and provide valuable insights for future CSP projects. The outcomes of this research will contribute to the advancement of concentrated solar power technology, facilitate the transition to a sustainable energy future, and provide valuable information for policymakers, investors, and stakeholders in the renewable energy sector

Modelling and Simulation Techniques for Concentrated Solar Power Plants

Overview of modelling and simulation tools used in CSP research

The study and development of Concentrated Solar Power (CSP) plants heavily relies on modelling and simulation techniques. These tools offer insightful data on the functionality, effectiveness, and optimisation of CSP systems [15-19]. Researchers can evaluate the practicality, economic viability, and environmental impact of various CSP systems by simulating various operating situations and design parameters. We give an overview of the modelling and simulation techniques frequently used in CSP research in this post.

The usage of system-level models is one of the extensively used modelling strategies in CSP. These simulations represent the overall operation of the CSP plant while accounting for the interactions between various parts and systems. System-level models depict the physical and thermodynamic processes taking place within the CSP system using mathematical equations. Solar radiation, heat transmission, fluid transport, and electrical generation are among the things they take into account [20]. Researchers can use these models to analyse CSP plant performance and design under various operating situations.

Computational fluid dynamics (CFD) is a prevalent technique used in CSP modelling. Numerical techniques are used in CFD simulations to solve challenging fluid flow and heat transfer equations. The flow behaviour, heat transfer mechanisms, and thermal performance of certain parts, including solar receivers, heat exchangers, and storage tanks, may all be thoroughly analysed using CFD models [21]. The efficiency of a system can be increased by optimising heat transfer by modelling fluid flow patterns and temperature distributions.

Additionally, ray-tracing models are frequently employed to assess the optical efficiency of CSP systems [22]. These models represent the flow of solar rays from the solar collectors to the incident sunlight while taking into consideration reflection, refraction, and absorption. Researchers can assess the effectiveness of concentration and choose the best placement and orientation for mirrors or heliostats in power tower or parabolic trough systems using ray-tracing techniques. Ray-tracing simulations can increase the concentration of sunlight onto the receivers by optimising the optical design, which will optimise thermal performance and boost energy generation.

CSP research employs a variety of simulation tools, including dynamic models and control system simulations, in addition to system-level models, CFD, and ray-tracing methods. The transient behaviour and responsiveness of CSP plants under various operating situations are captured using dynamic models [23]. These models are crucial for researching the system's dynamic behaviour during startup, shutdown, or shifts in the availability of solar resources. On the other hand, control system simulations concentrate on reviewing the effectiveness of control algorithms and methods for effective operation and optimum power production.

In CSP research, modelling and simulation techniques have many advantages. Before actual implementation, they enable virtual testing and analysis of various design configurations, operational methods, and control schemes. These instruments allow researchers to assess the effects of numerous elements on the general performance of CSP plants, including solar resource fluctuation, thermal losses, component deterioration, and energy storage capacity. By doing so, it is possible to spot potential problems, improve system design, and raise the dependability and cost-effectiveness of CSP technologies [24].

Mathematical models for solar collectors and receivers

In Concentrated Solar Power (CSP) systems, mathematical models are essential for the study and optimisation of solar collectors and receivers.

These models use mathematical formulas to describe the physical and thermal behaviour of the parts, giving important information on their effectiveness [25]. The significance of mathematical models and their applications in the design and optimisation of solar collectors and receivers will be covered in this article.

Researchers and engineers can learn about and predict how heat moves through solar collectors and antennas with the help of mathematical models [26]. These simulations take into account variables including solar radiation, absorber plate characteristics, fluid flow parameters, and thermal losses. Researchers can learn vital details, such as the temperature distribution, heat transfer rates, and general thermal efficiency of the collector or receiver, by resolving the governing equations.

The energy balance equation is a popular mathematical model for solar collectors. The absorbed solar radiation, convective and radiative heat losses, and the thermal energy held within the collector are all taken into consideration by this equation [27]. The energy balance equation can offer important insights into the thermal performance of the collector by taking into account factors including the shape of the collector, optical qualities, and fluid flow characteristics. This knowledge is essential for enhancing the collector's overall efficiency, choosing the best materials, and optimising its design.

The heat transfer equation is yet another crucial mathematical representation for solar collectors. This equation considers conduction, convection, and radiation to describe the heat transfer processes taking place inside the collector [28]. Researchers can calculate the heat transfer rates between the absorber plate and fluid, the convective heat losses to the surroundings, and the temperature distribution inside the collector by resolving the heat transfer equation. These findings support boosting heat transfer effectiveness, lowering thermal losses, and optimising the collector's design.

Mathematical models are also used to analyse and optimise solar receivers, which are critical components in CSP systems. The concentrated solar radiation must be taken in by receivers in order to be transformed into thermal energy. Receivers are modelled mathematically taking into account the geometry, composition, solar concentration, and heat transmission mechanisms. For instance, the heat transfer via the receiver tube and the fluid flowing inside it would both be taken into account in a mathematical model for a receiver in a parabolic trough system. Convective heat transmission from the fluid to the receiver, radiative heat losses, and solar radiation absorption by the receiver would all be considered in the model [29]. Researchers can analyse the thermal behaviour of the receiver, optimise its design parameters, and enhance its overall performance by solving the pertinent equations.

The performance of these parts in CSP systems can be designed, optimised, and assessed using mathematical models for solar collectors and receivers. They shed light on the collectors' and receivers' overall efficiency as well as their thermal behaviour and heat transfer processes. Researchers and engineers can improve the performance and dependability of solar collectors and receivers in CSP applications by using these models to make educated decisions about design revisions, material selection, and operating conditions.

Simulation approaches for thermal energy storage systems

The analysis and optimisation of thermal energy storage (TES) systems in many applications, such as concentrated solar power (CSP) facilities, rely heavily on simulation methods. These methods give scientists and engineers the ability to comprehend the behaviour of TES systems, forecast how well they will operate under various operating scenarios, and assess the effects of design changes. In this post, we'll talk about the value of simulation methods for TES systems and look at a few standard methods.

The creation of mathematical models that characterise the thermal behaviour of the storage medium, heat transfer procedures, and the overall dynamics of the system is a necessary step in simulation approaches for TES systems. The performance of the system is then learned by solving these models using numerical techniques.

The finite difference method is a popular simulation technique for TES systems. This method discretizes the governing equations for heat transport and energy conservation and solves them repeatedly. The TES system is divided into a grid of discrete cells. This technique offers comprehensive information on the temperature distribution, heat transfer rates, and overall system performance while allowing for the depiction of complex geometries like the storage tank and heat exchangers.

The finite element method (FEM) is the foundation for another simulation strategy. The TES system is divided into finite elements by FEM, and each element is represented by a group of equations that characterise the system's regional behaviour. Particularly for complicated geometries and boundary conditions, FEM offers a more realistic description of the system's behaviour by solving these equations. The thermal behaviour of TES systems with complex designs and complex heat transfer mechanisms is frequently studied using FEM [30].

TES systems frequently use simulations of computational fluid dynamics (CFD). The interaction between the heat transfer fluid and the storage medium is modelled using CFD. CFD simulations offer thorough information about the flow patterns, heat transfer coefficients, and thermal stratification within the TES system through the solution of the Navier-Stokes equations and the incorporation of the relevant turbulence models. This method is very helpful for examining the fluid dynamics and heat transfer processes in TES systems, such as phase change materials or molten salt storage tanks.

Empirical and semi-empirical models are occasionally employed for simulation in addition to these numerical methods. These models are based on experimental data and correlations discovered through research studies or observations made in the field. They offer a condensed illustration of the TES system and offer short evaluations of its functionality [31]. Empirical models might need to be calibrated for certain TES setups and may have limits in their ability to capture complicated processes.

The design, optimisation, and assessment of TES systems in CSP plants heavily rely on simulation methods. They make it possible to comprehend thermal behaviour, heat transfer procedures, and system performance more thoroughly. Researchers and engineers can analyse various design alternatives, consider the effects of operational conditions, and find ways to increase the effectiveness and dependability of TES systems in CSP applications by employing simulation approaches.

Performance Analysis and Optimization of Concentrated Solar Power Plants

Performance analysis and optimization are essential aspects of Concentrated Solar Power (CSP) plants to ensure their efficient operation and maximize energy production. Evaluating system performance metrics provides valuable insights into the effectiveness and productivity of the plant. In this article, we will discuss the evaluation of key performance metrics such as efficiency and capacity factor and explore methods for optimizing the performance of CSP plants [32].

Evaluation of system performance metrics: efficiency, capacity factor, etc.

Evaluation of performance metrics is crucial for assessing the efficiency and effectiveness of Concentrated Solar Power (CSP) systems. Various performance metrics are used to measure different aspects of the system's performance. In this article, we will discuss the evaluation of key performance metrics, including efficiency, capacity factor, and other relevant metrics for evaluating CSP system performance.

Efficiency is one of the primary performance metrics used to assess the effectiveness of a CSP system. It represents the ratio of the useful output energy, such as electricity or heat, to the input energy from the solar resource. In the case of electricity generation, the efficiency is typically measured as the ratio of the electrical power output to the solar power incident on the solar collectors [33]. Higher efficiency indicates better utilization of the available solar energy. Evaluating and optimizing the efficiency of a CSP system involves analyzing the performance of individual components, such as the solar collectors, thermal energy storage, and power conversion systems. By optimizing each component's efficiency and minimizing energy losses, the overall system efficiency can be improved.

The capacity factor is another important performance metric for CSP systems. It measures the actual energy output of the system compared to its maximum potential output. The capacity factor takes into account various factors, such as the availability of the system, maintenance downtime, and periods of low solar irradiation. A higher capacity factor indicates a more efficient utilization of the system's installed capacity. Evaluating the capacity factor helps identify operational issues, maintenance requirements, and opportunities for improving the system's availability and productivity.

Other performance metrics that are commonly evaluated in CSP systems include:

Solar-to-electricity conversion efficiency: This metric specifically measures the efficiency of converting solar energy into electrical energy. It considers losses in the solar collectors, thermal energy storage, and power conversion systems.

Thermal efficiency: For CSP systems that generate thermal energy, the thermal efficiency measures the efficiency of converting solar energy into usable heat. It accounts for losses in the solar collectors and heat transfer systems.

Dispatchability: Dispatchability refers to the system's ability to provide power on demand. It is a critical metric for CSP systems with thermal energy storage. Evaluating dispatchability involves analyzing the system's capability to store and release thermal energy when needed, allowing for continuous power generation even during periods of low solar irradiation.

Reliability and availability: These metrics assess the system's ability to operate reliably and consistently over time. They consider factors such as maintenance downtime, system failures, and scheduled maintenance activities [34].

To evaluate these performance metrics, advanced modeling and simulation tools are often utilized. These tools enable the analysis of system performance under various operating conditions and help identify areas for improvement. Additionally, real-time monitoring and data analysis can provide insights into the system's performance and facilitate continuous optimization.

Factors affecting the performance of CSP plants

The performance of Concentrated Solar Power (CSP) plants can be influenced by various factors. Understanding these factors is crucial for optimizing the plant's efficiency and overall performance. Some key factors that affect CSP plant performance are:

Solar Resource Availability: The performance of CSP plants is significantly influenced by the availability of solar resources, such as direct normal irradiance (DNI). High sun radiation areas are better suited for CSP systems because they can produce more power there. The output of the plant may vary depending on the availability of solar resources at different times of the day and throughout the year [35].

Design and Configuration: The size, quantity, and configuration of solar collectors, as well as the capacity for thermal energy storage, can all have a big impact on how well a CSP plant performs. Examples of these technologies include parabolic troughs, power towers, and dish systems. For the plant to operate as efficiently as possible, proper design optimisation that takes into account site-specific characteristics and operational requirements is crucial.

Optical and thermal losses: The performance of the CSP system can be impacted by optical and thermal losses. Solar radiation is reflected, absorbed, and scattered, which results in optical losses. These losses can be reduced with the use of techniques like anti-reflective coatings, better mirror design, and precise tracking systems. Thermal losses can happen during heat transfer procedures, like in the receiver, or when thermal energy is stored. For minimising these losses, effective insulation and thermal management techniques are essential [36].

Heat Transfer Efficiency: For the CSP system to maximise energy conversion and overall plant performance, efficient heat transfer is essential. The heat transmission efficiency is influenced by things like receiver design, heat transfer fluid choice, and thermal energy storage medium. By reducing energy losses and enhancing thermal conversion, these factors can be optimised to improve the plant's performance.

Optimization techniques for improving CSP plant performance

Different optimisation strategies can be used to improve the performance of CSP plants. These methods are designed to increase the system's overall energy output, capacity factor, and efficiency. In CSP plants, common optimisation methods include:

- Advanced tracking and control systems can be used to position solar collectors or heliostats in the best orientation to catch the most solar energy possible throughout the day. The device can track the sun's movement and maintain ideal alignment by dynamically altering the mirror angles, which enhances energy gathering [37].
- Advanced Heat Transfer Fluids: The use of high-performance heat transfer fluids can improve the system's overall

performance and the efficiency of heat transfer. Improved thermal properties in modern fluids, such as larger specific heat capacities or lower viscosities, can improve energy transmission and lessen thermal losses [38].

- Optimisation of Thermal Energy Storage: CSP plants' operational hours and capacity factor can be increased by using effective thermal energy storage (TES) systems. Improved plant performance can be attained by optimising the TES system's architecture, which includes the choice of the storage media, thermal insulation, and charging/discharge techniques.
- Integration with Hybrid Technologies: By combining CSP plants with other hybrid energy technologies, such as wind power or photovoltaics (PV), the system's overall performance and dependability can be increased. By combining the use of several energy sources, hybrid systems allow for better energy management, an increase in capacity factor, and improved grid integration.
- Real-time monitoring, problem detection, and performance optimisation are made possible by the use of modern control and monitoring systems [39]. These systems offer useful information on system performance, enabling quick modifications and maintenance, improving efficiency, and reducing downtime.

Environmental and Economic Considerations of Concentrated Solar Power

CSP technology is a desirable renewable energy source because it has several economic and environmental advantages. For the development of decisions and policies, it is essential to comprehend the environmental effects and financial viability of CSP plants [40]. This section compares CSP systems to various renewable energy sources and addresses the environmental effect assessment, cost analysis, and economic viability of CSP systems.

CSP Plant Environmental Impact Assessment:

Compared to conventional power production sources, CSP facilities have the potential to considerably cut greenhouse gas emissions and minimise environmental impact. They do, however, also have some environmental implications that should be evaluated. Several significant environmental features of CSP plants include:

1. Land Use: The installation of solar collectors, power block infrastructure, and thermal energy storage devices for CSP facilities necessitates a sizeable quantity of land. The environmental impact assessment assesses the need for more land and takes into account variables including land accessibility, habitat disruption, and land-use disputes [41].
2. Water Use: The cooling process in some CSP technologies, including parabolic troughs, requires the use of water. The evaluation looks at the plant's water usage while taking into account issues including water shortages, potential effects on regional water supplies, and the adoption of alternate cooling systems.
3. Impacts on Local species and Ecosystems: The development and operation of CSP facilities may have an effect on nearby species and ecosystems. Environmental evaluations detect possible threats to migratory pathways, protected species, and biodiversity, and they recommend mitigation strategies to lessen these effects.
4. Aesthetics & Visual Impact: CSP plants may alter the appearance of the surrounding area. In order to minimise visual disruption through thoughtful plant design and site selection, assessments take into account the visual aesthetics, cultural history, and potential visual impacts on surrounding residents.

Cost Analysis and Economic Feasibility of CSP Systems

The economic feasibility of CSP systems is a critical factor in their widespread deployment. Cost analysis evaluates the capital costs, operational costs, and levelized cost of electricity (LCOE) of CSP plants. Key considerations in cost analysis include:

1. Capital Costs: Capital costs include the costs related to building a plant, buying land, installing solar collectors, installing thermal energy storage, building the infrastructure for a power block, and interconnecting to the grid. To identify the initial expenditure needed for CSP initiatives, assessments examine capital costs.
2. Costs of Operation and Maintenance: Costs of operation include recurring expenses including labour, upkeep, repairs, and replacements. Analysing these expenses provide information about the

long-term financial feasibility and sustainability of CSP systems.

3. Levelized Cost of Electricity (LCOE): LCOE is a crucial indicator for assessing how competitively priced various energy technologies are. It indicates the typical cost of power production during the course of the project. To determine if CSP facilities are economically viable, cost analysis measures their LCOE and compares it to that of alternative energy sources.

Comparison with Other Renewable Energy Technologies

CSP technology has distinct advantages and disadvantages compared to other renewable energy technologies [42]. A comparative analysis helps in understanding the strengths and limitations of CSP systems. Some points of comparison include:

Table 1 Comparison with Other Renewable Energy Technologies

Factors	Description
Efficiency and Capacity Factor	CSP plants incorporate thermal energy storage, enabling continuous power generation even during non-sunlight hours. This improves their capacity factor compared to intermittent renewable sources.
Grid Integration and Stability	CSP plants with thermal energy storage offer dispatchability, providing stable and reliable power supply. This distinguishes them from variable renewable sources dependent on weather conditions.
Resource Availability	CSP plants require direct sunlight for optimal performance, making them suitable for regions with high solar radiation. In areas with limited solar resources, other renewable technologies may be more viable.
Cost Competitiveness	While initial capital costs are relatively higher, advancements in technology and economies of scale have contributed to cost reductions. CSP is becoming more competitive with conventional and other renewable energy sources.
Environmental Impact	CSP plants produce clean and renewable energy without greenhouse gas emissions, air pollution, or water contamination associated with conventional power plants. They contribute to reducing carbon dioxide emissions and mitigating climate change impacts.
Local Job Creation and Economic Development	CSP projects stimulate local economies by creating job opportunities. Construction and operation require a skilled workforce, contributing to employment generation. Procurement from local suppliers can boost the regional economy.
Technology Innovation and R&D	Ongoing research and development efforts drive advancements in CSP technology. R&D initiatives focus on improving system efficiency, reducing costs, and enhancing overall performance through innovation in materials, receiver design, thermal energy storage, and control systems.

This table 1provides a concise overview of the factors affecting the performance and viability of CSP plants, including their benefits, economic aspects, and ongoing innovation in the field.

To maximize the environmental and economic benefits of CSP systems, ongoing efforts are directed towards further improving the technology, optimizing system performance, and reducing costs. Policy support, financial incentives, and favorable regulatory frameworks play a vital role in promoting the adoption and deployment of CSP technology. Continued research, innovation, and collaboration among industry, academia, and government entities are essential for the growth and sustainability of the CSP sector [42].

Methodology

The utilization of solar energy as a renewable and sustainable power source has gained significant attention in recent years. Solar Concentrated Power (CSP) plants, particularly those incorporating molten salt thermal storage, have emerged as a promising solution for efficient and reliable electricity generation. The design and modeling of such CSP plants require a comprehensive understanding of various components, including the heliostat field, tower and receiver, thermal storage system, electrical HTF heater, and power cycle. This chapter presents the methodology employed in the modeling and design of a solar concentrated power plant with molten salt thermal storage, with the objective of maximizing energy output and overall system efficiency. By exploring the interlinkages between these components and their respective parameters, this research aims to contribute to the advancement of CSP technology and its integration into the global energy landscape.

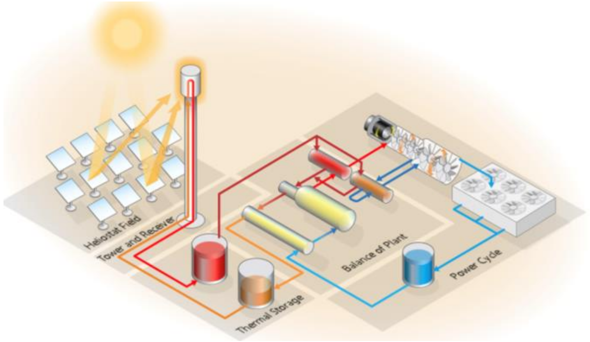


Figure 1 CSP plant with thermal storage

Design System

The design of a solar concentrated power plant involves various components and parameters that need to be carefully considered. These include the heliostat field, direct normal irradiance (DNI), solar multiple, receiver thermal power, power cycle, and thermal storage.

1. Heliostat Field: The heliostat field is a crucial component of a solar concentrated power plant. It consists of a large array of heliostats that reflect and concentrate sunlight onto a central receiver. The design of the heliostat field involves determining the number of heliostats, their dimensions, the reflective area to profile ratio, the single heliostat area, image error, and the number of heliostat facets in the X and Y directions. These parameters are essential for achieving accurate sunlight concentration and optimizing the overall system performance.
2. DNI (Direct Normal Irradiance): DNI represents the solar radiation intensity received from direct sunlight. It is a key parameter in designing a solar concentrated power plant as it determines the available solar energy for conversion into electricity. The design of the system requires accurate DNI data specific to the project location, which can be obtained from historical weather data or solar resource assessments.
3. Solar Multiple: The solar multiple is the ratio of the thermal power absorbed by the receiver to the thermal power produced by the power cycle. It represents the degree of concentration achieved by the heliostat field and influences the overall system performance. The solar multiple is determined based on the desired power output and the design of the heliostat field.
4. Receiver Thermal Power: The receiver thermal power is the amount of thermal energy absorbed by the receiver from the concentrated sunlight. It depends on factors such as the DNI, solar multiple, and the receiver's thermal efficiency. The receiver's design is crucial in maximizing the absorption and conversion of solar energy into thermal energy.
5. Power Cycle: The power cycle converts the thermal energy from the receiver into electricity. The design of the power cycle involves determining the design turbine gross output, estimated net output at

design, and cycle thermal efficiency. The turbine gross output represents the maximum power output of the turbine, while the net output is the actual power output after accounting for losses. The cycle thermal efficiency is a measure of the efficiency of the power cycle in converting thermal energy to electrical energy.

6. Tower and Receiver: The tower and receiver play a critical role in the solar concentrated power plant. The design parameters include the hot temperature of the heat transfer fluid (HTF) entering the power cycle, typically around 600°C, and the cold temperature of the HTF leaving the power cycle, typically around 350°C. These temperatures determine the temperature difference across the power cycle and influence its efficiency.
7. Thermal Storage: Thermal storage is an essential component of a solar concentrated power plant, allowing energy to be stored for use during periods of low sunlight or high electricity demand. The design parameters for thermal storage include the full load hours of storage, which represents the duration of operation at full load without additional solar input, and the solar field hours of storage, which indicates the number of hours the solar field can provide thermal energy to the storage system.

Results

System Advisory Modeling (SAM) is a comprehensive software tool used in the field of renewable energy system analysis and design. It provides a platform for engineers, researchers, and policymakers to simulate, analyze, and optimize various aspects of renewable energy systems. SAM offers a user-friendly interface and a wide range of modules to model different renewable energy technologies, including solar, wind, and biomass.The working of SAM involves several key steps. Firstly, the user inputs the relevant parameters and data required for the specific renewable energy system being modeled. For example, in the case of a solar power plant, inputs may include solar resource data, system specifications, cost parameters, and financial assumptions. SAM provides default values based on industry standards, but users can customize these inputs to reflect the specific project requirements. Once the inputs are provided, SAM utilizes mathematical models and algorithms to simulate the performance of the renewable energy system. It considers factors such as weather conditions, system efficiency, component degradation, and energy conversion processes to generate accurate results. SAM employs robust numerical methods and equations to calculate energy generation, costs, financial metrics, and other system performance indicators.The results generated by SAM provide valuable insights into the feasibility, performance, and economics of renewable energy systems. These results help stakeholders make informed decisions regarding project design, financing options, and policy considerations. SAM offers a range of outputs, including energy production profiles, financial metrics (such as net present value and levelized cost of energy), and sensitivity analyses.

The scope of SAM is broad and encompasses various aspects of renewable energy system analysis. It enables users to evaluate the technical and economic viability of renewable energy projects, assess the impact of different design parameters, and optimize system configurations. SAM can be used at different stages of a project, from the initial planning and feasibility assessment to the detailed design and operational optimization.SAM also facilitates scenario analysis by allowing users to modify input parameters and compare the outcomes. This feature helps assess the sensitivity of the system's performance to changes in factors such as technology costs, resource availability, and policy incentives. It enables users to identify the most favorable conditions for project development and optimize the system's performance based on the desired objectives, whether it be maximizing energy production, minimizing costs, or reducing environmental impacts.

One of the key benefits of using SAM for CSP plant design is its ability to model the solar resource and simulate the plant's energy production. SAM incorporates historical weather data, such as direct normal irradiance (DNI), and uses sophisticated algorithms to generate accurate solar resource profiles. By analyzing these profiles, designers can determine the expected energy output of the CSP plant, helping them assess its viability and economic feasibility.SAM also allows for the detailed modeling of CSP plant components, including the heliostat field, receiver, thermal storage, and power cycle. Designers can input specific parameters, such as heliostat dimensions, receiver properties, thermal storage capacity, and power cycle efficiency, to accurately simulate the behavior of these components. SAM's advanced calculations and algorithms then generate performance data, such as thermal power, electricity generation, and system efficiency, providing valuable insights into the plant's operational characteristics. Furthermore, SAM offers financial analysis tools that allow designers to assess the economic viability of the CSP plant. Users can input cost data, financing terms, and incentives to calculate financial metrics like levelized cost of energy (LCOE), net present value (NPV), and payback period. These metrics assist in evaluating the project's profitability and comparing different design configurations or financial scenarios.

Overall, SAM empowers engineers and researchers in the design of CSP plants by providing comprehensive modeling capabilities, accurate energy production estimation, and financial analysis tools. Its user-friendly interface and robust algorithms make it an indispensable tool for optimizing the performance and economics of CSP projects.

Study Area

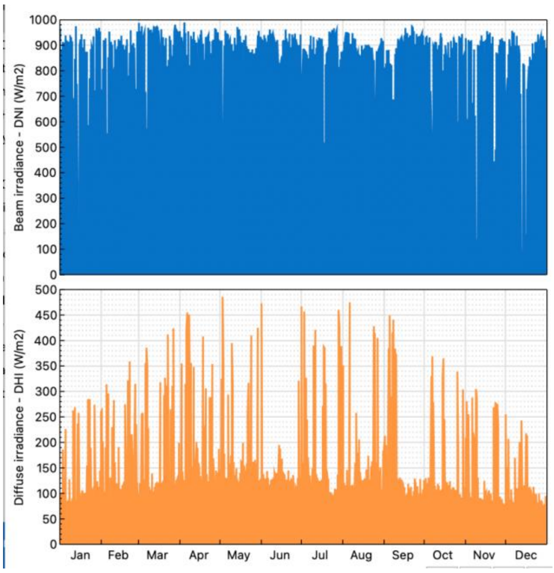
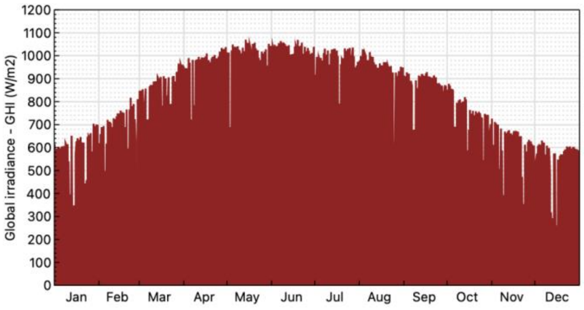


Figure 2 Beam irradiance and Diffuse irradiance

In our simulation using Lahore data, the results for beam irradiance (DNI) indicate a value of 1000 W/m2. This represents the direct solar radiation received on a surface perpendicular to the sun's rays. Additionally, the simulation also shows the diffuse irradiance, which ranges between 100 W/m2 and 500 W/m2. Diffuse irradiance refers to the scattered sunlight that is not directly coming from the sun but is instead scattered by the atmosphere and surrounding objects. These results highlight the solar resource potential in Lahore, with a significant amount of direct solar radiation contributing to the overall energy available for a Concentrated Solar Power (CSP) plant. The high DNI value of 1000 W/m2 indicates favorable conditions for harnessing solar energy using concentrating technologies. Furthermore, the range of diffuse irradiance values between 100 W/m2 and 500 W/m2 suggests the presence of scattered sunlight due to atmospheric conditions and the surrounding environment. This diffuse component contributes to the overall solar energy available for the CSP plant, complementing the direct solar radiation. By understanding and analyzing these simulation results, we can gain valuable insights into the solar resource characteristics in Lahore, which are essential for designing and optimizing CSP plants in the region. The combination of high DNI and significant diffuse irradiance provides a promising foundation for the effective utilization of solar energy in Lahore, supporting the development of sustainable and efficient CSP projects.



In contrast to the selected location of Lahore, the simulation results indicate a global irradiance value of 900 W/m2. Global irradiance represents the total solar radiation received on a horizontal surface, including both direct and diffuse components. In this case, the value of 900 W/m2 suggests a slightly lower solar energy availability compared to Lahore, where the beam irradiance (DNI) was measured at 1000 W/m2.

The lower global irradiance value of 900 W/m2 indicates that the selected location experiences slightly reduced solar radiation intensity. This could be influenced by various factors such as geofigureical location, local climate patterns, and atmospheric conditions. The lower solar radiation levels may have implications for the energy generation potential and efficiency of a Concentrated Solar Power (CSP) plant in this area.

Understanding the global irradiance is crucial for accurately assessing the solar resource and designing CSP systems. Although the global irradiance in this location is lower than in Lahore, it is still a valuable renewable energy resource that can be harnessed through efficient and optimized CSP plant design.

By taking into account the specific solar resource characteristics, such as the global irradiance of 900 W/m2, designers and engineers can tailor the system configuration, heliostat field layout, and other parameters to maximize the utilization of available solar energy. Additionally, implementing advanced tracking and concentrating technologies can further enhance the overall energy capture and improve the performance of the CSP plant in regions with lower solar irradiance levels.

While the global irradiance of 900 W/m2 may present certain challenges in terms of energy generation, it also opens up opportunities for innovative design strategies and system optimization to ensure the efficient utilization of the available solar resource in the selected location.

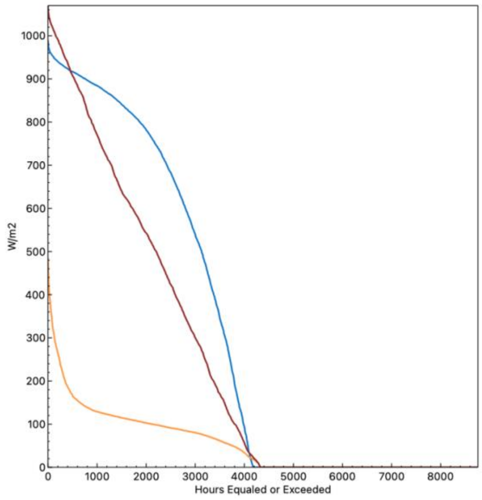


Figure 3 Comparison of irradiances to hours equalled

Overall, the comparison highlights the variations in solar irradiance between Lahore and the selected location. While Lahore enjoys higher beam irradiance and a wider range of diffuse irradiance, the global irradiance at the selected location is slightly lower. However, all three irradiances demonstrate the potential for solar power generation and emphasize the importance of accurately assessing and utilizing the available solar resource to optimize the design and performance of CSP plants.

Wind

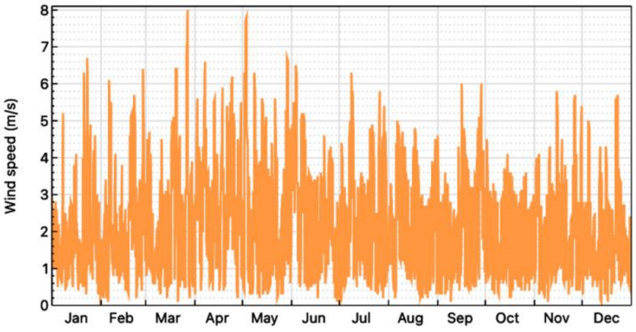


Figure 4 Wind speed figure

Based on the results obtained, the wind speed varies throughout the year. In the month of January, the wind speed ranges from 1 m/s to 3 m/s. This indicates relatively lower wind speeds during this period. As the year progresses, the wind speed gradually increases.By the end of April, specifically on the 30th, the wind speed reaches 8 m/s. This signifies a significant increase in wind velocity compared to the earlier months. This higher wind speed can potentially be advantageous for the operation of the power plant, as it can contribute to increased energy production.

The wind speed remains constant at 8 m/s during the end of May, indicating consistent wind conditions during this period. The stability in wind speed can be beneficial for ensuring a reliable and continuous energy supply from the wind turbines.

It is important to note that the wind speed and its variation throughout the year can have a significant impact on the performance and efficiency of the power plant. The design and operation of the plant should take into account these variations in wind speed to optimize energy production and ensure the stability of the system.

Further analysis and consideration of these wind speed variations in conjunction with other factors, such as solar irradiation and ambient temperature, will help in determining the overall feasibility and effectiveness of the linear Fresnel molten salt power plant design for the specific location in Lahore, Pakistan.

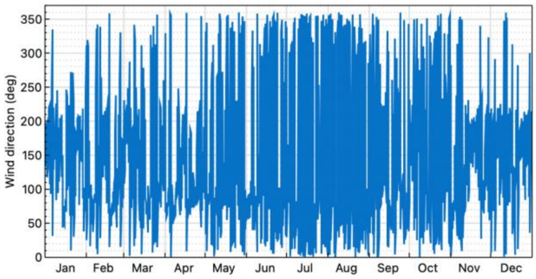


Figure 5 Wind direction in degrees

Based on the results obtained, the wind direction varies throughout the year. In the starting of January, the wind direction ranges from 150 to 200 degrees. This indicates that the prevailing winds during this period are blowing from the south-southeast to the south-southwest direction.As the year progresses, specifically on April 30th, the wind direction varies from 0 to 350 degrees. This indicates a wider range of wind directions, potentially encompassing all directions. The wind direction can shift and come from different angles, providing a more diverse wind pattern during this period.

The wind direction continues to vary until December, implying a dynamic and changing wind pattern throughout the year. The specific wind directions experienced in each month may differ, presenting a range of possibilities for the wind flow at the location. Understanding the wind direction and its variations is crucial for the design and placement of wind turbines in the power plant. By strategically positioning the turbines to align with the prevailing wind direction, optimal energy capture can be achieved. Additionally, considering the variations in wind direction helps in evaluating the overall wind resource availability and its impact on the power plant's performance.

It is important to analyze and interpret these wind direction results in conjunction with other factors, such as wind speed, solar irradiation, and ambient temperature, to assess the suitability and feasibility of the linear Fresnel molten salt power plant design for the specific location in Lahore, Pakistan.

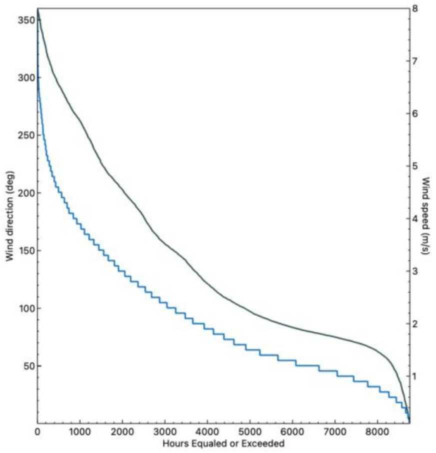


Figure 6 Wind direction and Wind degree

The comparison figure would have the x-axis representing the time period from January to December, indicating the progression of months throughout the year. The y-axis would represent the respective parameters being compared, which in this case are wind speed and wind direction. For the wind speed data, the figure would show a line or a set of data points depicting the values ranging from 1 m/s to 8 m/s. The line or data points would vary in height, indicating the wind speed recorded for each time period. The figure would demonstrate the fluctuations in wind speed from the lower range of 1 m/s in January to the higher range of 8 m/s in April and May, and the subsequent variations throughout the year. On the same figure, the wind direction would be represented by another line or set of data points. The line or data points would show the varying wind direction values ranging from 150 degrees to 350 degrees. The figure would illustrate the changes in wind direction over time, indicating the shift from the range of 150-200 degrees in January to the wider range of 0-350 degrees in April, and the subsequent fluctuations in wind direction throughout the year.

By comparing the two lines or sets of data points on the figure, it would be possible to visually observe any correlations or patterns between wind speed and wind direction. The figure could help identify any trends or relationships between these parameters throughout the year, providing insights into the wind conditions at the specific location in Lahore, Pakistan.

Simulation Results

The system power generated data shows the range of power output from -20,000 kW to 100,000 kW. The power generated represents the electrical energy produced by the solar concentrated power plant during its operation. The figure or visualization would have the y-axis representing the power output in kilowatts (kW), while the x-axis would indicate the time period.In the figure, there would be a line or data points that depict the power generated at different points in time throughout the year. The line or data points would vary in height, indicating the varying power output values. The figure would show the fluctuations in power generation, ranging from -20,000 kW to 100,000 kW, representing periods of low power generation to high power generation. Can be seen in figure

Additionally, the figure would also illustrate a specific period of grid maintenance, which would be represented by a white area on the figure. This white area would indicate the time when the grid maintenance activities are scheduled, during which the power generation is temporarily halted or reduced. It would be visually distinct from the rest of the figure, highlighting the period of grid maintenance and the associated decrease or absence of power generation during that time.

This information would provide insights into the power generation profile of the solar concentrated power plant, showcasing the variability in output and the occurrence of maintenance periods that impact the overall power generation capacity.

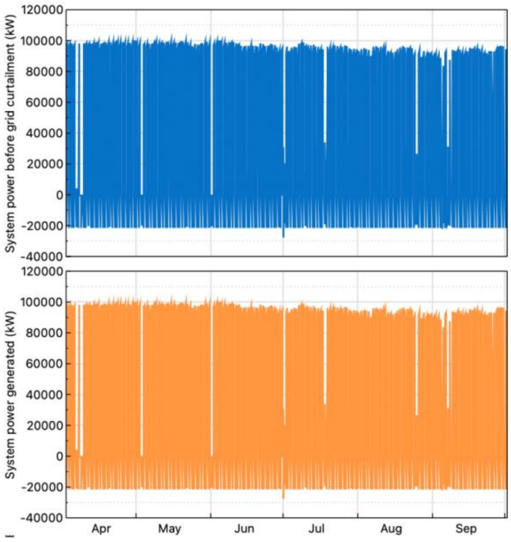


Figure 7 System power generation

The HTF (Hot Thermal Fluid) figure represents the variation in the HTF temperature at the inlet of the solar power plant's thermal system. The figure displays the temperature values on the y-axis and the corresponding time periods on the x-axis.According to the figure, the Hot Thermal Fluid inlet temperature remains relatively constant at 600°C for most of the time, indicating the standard operating temperature at the inlet. This temperature is crucial as it represents the high-temperature HTF entering the power cycle for energy conversion.However, the figure also reveals specific time intervals, such as from 335 to 350°C, where the HTF temperature at the inlet deviates from the standard value. This variation might occur due to certain operational conditions or adjustments in the system. It is important to closely monitor and analyze such temperature variations to ensure the optimal performance and efficiency of the solar power plant.The figure provides a visual representation of the HTF temperature at the inlet, highlighting any deviations from the standard operating conditions. This information aids in identifying potential issues or changes in the HTF system that may impact the overall performance of the solar power plant.

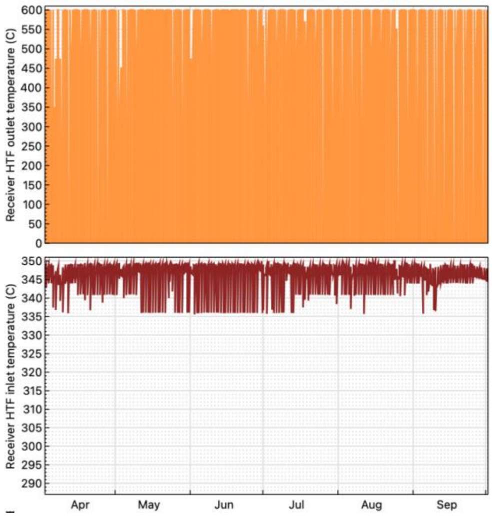


Figure 8 HTF inlet and outlet temperature

The TES (Thermal Energy Storage) figure illustrates the variation in temperature within the TES system of the solar power plant. The figure represents the TES cold temperature and TES hot temperature on the y-axis, while the corresponding time periods are displayed on the x-axis. According to the figure, the TES cold temperature fluctuates between 342°C and 347°C throughout most of the time, indicating the typical operating range for the cold side of the thermal energy storage system. This temperature range represents the lower end of the TES system where thermal energy is stored during periods of excess solar energy or low electricity demand. Similarly, the TES hot temperature exhibits variations between 570°C and 590°C, reflecting the standard operating range for the hot side of the TES system. This range represents the higher temperature level of the thermal energy storage system where thermal energy is stored for subsequent use during periods of low sunlight or high electricity demand. Notably, the figure indicates an occasional deviation from the standard range, with the TES hot temperature dropping to around 560°C once a year. This deviation might be attributed to specific operational conditions or adjustments in the system that influence the TES temperature. By visualizing the TES temperatures over time, the figure provides valuable insights into the behavior and performance of the thermal energy storage system within the solar power plant. Monitoring the TES temperatures helps ensure that the system operates within the desired temperature ranges, optimizing the storage and release of thermal energy for efficient power generation.

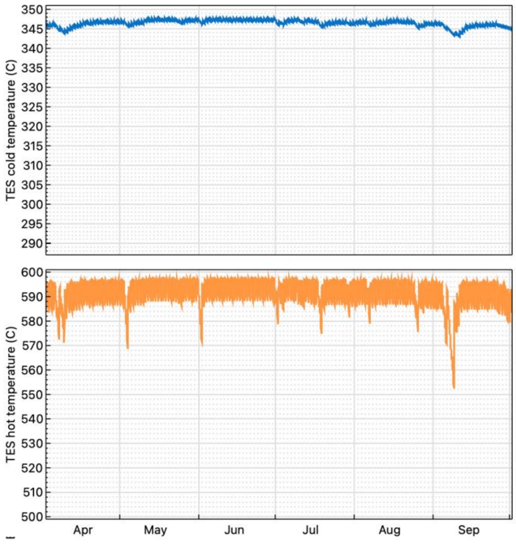


Figure 9 TES hot and cold temperature

The resource solar zenith and solar azimuth angles play a significant role in determining the availability and intensity of solar radiation received at a specific location. These angles are crucial factors in the design and operation of a solar power plant. The figure illustrates the variation of the resource solar zenith and solar azimuth angles over time.According to the figure, the resource solar zenith angle ranges between 30 degrees and 140 degrees. The solar zenith angle represents the angle between the vertical direction and the line connecting the sun and the observer. A lower solar zenith angle indicates that the sun is closer to the overhead position, resulting in more direct and intense solar radiation. As the solar zenith angle increases, the sun's position shifts towards the horizon, leading to a lower intensity of solar radiation. Similarly, the resource solar azimuth angle ranges between 30 degrees and 350 degrees. The solar azimuth angle represents the angle between the north direction and the projection of the line connecting the sun and the observer onto the horizontal plane. The solar azimuth angle determines the orientation of the sun relative to the observer's position. It affects the angle at which solar radiation strikes the solar panels or heliostats in a solar power plant. By monitoring the resource solar zenith and solar azimuth angles, operators and designers of solar power plants can assess the availability and intensity of solar radiation throughout the year. These angles help optimize the alignment and orientation of solar panels or heliostats to capture the maximum amount of solar energy. Additionally, the variations in these angles over time can provide insights into seasonal changes in solar radiation patterns and assist in the planning and operation of the solar power plant.

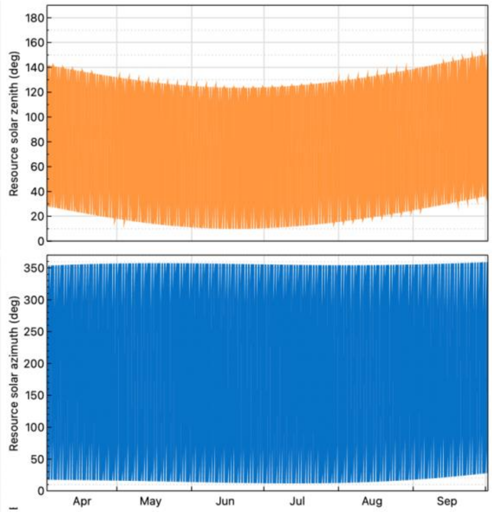


Figure 10 solar zenith and azimuth

The total thermal losses of a solar power plant refer to the amount of thermal energy that is lost during the process of harnessing solar radiation and converting it into usable energy. These losses can occur due to various factors such as conduction, convection, radiation, and heat transfer inefficiencies within the system. The figure shows the variation of total thermal losses over time, ranging from 0.88 MWt to 0.98 MWt. Maintaining low thermal losses is crucial for maximizing the overall efficiency and performance of the solar power plant. Higher thermal losses indicate a greater amount of wasted thermal energy, which reduces the net output and efficiency of the system.

By monitoring and analyzing the total thermal losses, operators and designers can identify areas of improvement and implement strategies to minimize these losses. To reduce thermal losses, several measures can be taken, such as improving insulation, optimizing heat transfer mechanisms, reducing heat leaks, and enhancing the overall system design. By implementing these measures, the solar power plant can minimize energy wastage and increase the overall thermal efficiency, leading to higher energy output and improved economic viability.

Continuous monitoring and analysis of total thermal losses are essential to ensure the effective operation and performance of the solar power plant. By understanding the factors contributing to these losses and implementing appropriate mitigation strategies, operators can optimize the plant's thermal efficiency and enhance its overall energy generation capabilities.

Conclusion

In conclusion, this paper focused on the design and development of a concentrated solar power plant with molten salt thermal energy storage. The research aimed to optimize the performance and efficiency of the power plant by considering various parameters and design aspects.The heliostat field, which consisted of a large array of heliostats, was carefully designed to accurately concentrate sunlight onto a central receiver. Factors such as the number of heliostats, their dimensions, reflective area to profile ratio, and image error were taken into account to ensure optimal sunlight concentration and system performance.The solar multiple, which represented the degree of concentration achieved by the heliostat field, was determined based on the desired power output and the design of the heliostat field. This parameter played a crucial role in optimizing the overall system performance.

The receiver, responsible for absorbing thermal energy from the concentrated sunlight, was designed to maximize the absorption and conversion of solar energy into thermal energy. Factors such as the Direct Normal Irradiance (DNI), solar multiple, and receiver's thermal efficiency influenced the receiver's thermal power.The power cycle, which converted the thermal energy into electricity, was designed with considerations for turbine gross output, net output, and cycle thermal efficiency. These design parameters ensured efficient conversion of thermal energy into electrical energy.The tower and receiver temperatures were carefully determined to optimize the temperature difference across the power cycle and enhance its efficiency.

Thermal storage was incorporated into the design to enable energy storage for periods of low sunlight or high electricity demand. Full load hours of storage and solar field hours of storage were taken into account to ensure reliable operation and continuous energy supply. The analysis of wind velocity, HTF temperature, TES temperature, resource solar zenith, solar azimuth, and total thermal losses provided valuable insights into the system's performance and variations over time.

Overall, the research and design of the concentrated solar power plant with molten salt thermal energy storage aimed to optimize energy generation, improve system efficiency, and enhance the economic viability of the plant. The findings and results presented in this paper contribute to the knowledge and understanding of solar power plant design and provide valuable insights for future research and development in the field of renewable energy.

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