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Techno-Economic Analysis of Concentrated Solar Power with Molten Salt Storage for Gwadar

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ABSTRACT

This study examines the feasibility of implementing a 50 MW parabolic trough Concentrated Solar Power (CSP) system with molten salt storage in Gwadar, an area facing significant energy insecurity due to its isolation from the national grid and dispersed energy demand. Using primarily quantitative and modeling-based methods, the research investigates the technical and financial aspects of CSP technology. The System Advisor Model (SAM) is utilized to simulate the CSP plant's performance, evaluating both technical and financial aspects. The methodology involves a thorough investigation into the viability of CSP plants, focusing on solar resource availability, land suitability, and molten salt availability. The findings suggest the technical feasibility of a CSP system in Gwadar, with optimal solar conditions observed in summer and ample land available in the industrial zone, with potential molten salt sourcing from Balochistan resources and Gwadar's seawater. Simulation results indicate the CSP system's potential to provide consistent and sustainable power generation, even under limited sunlight conditions, achieving a capacity factor of 23.3%, reflecting efficient energy production. Additionally, analysis of thermal energy storage dynamics highlights effective energy production and storage mechanisms, emphasizing the system's potential for renewable energy advancement. However, despite promising outcomes, the estimated Levelized Cost of Energy (LCOE) of $0.2349/kWh presents competitiveness challenges compared to other CSP technologies, necessitating further optimization and cost reduction efforts to enhance economic viability. In conclusion, this research underscores the importance of exploring options for cost reduction to improve the economic feasibility of deploying CSP technology in Gwadar, offering insights for sustainable energy solutions to address the region's energy challenges.

***Keywords**: Concentrated Solar Power, Parabolic Trough, National Solar Radiation Database, Solar Irradiance, Molten Salt Storage, Levelized Cost Of Energy, System Advisor Model.*

Introduction

The technology of concentrating solar thermal power has emerged as a prime choice for large-scale electricity generation. With the ascent of renewable energy resources to new heights, the

sun, as the most abundant energy source has captivated global researchers. They focus on discovering novel methods to harness the utmost potential from this resource. This motivation is the primary incentive for designating this field as a prominent area of research.
This research explores the potential of integrating concentrated solar power (CSP) with molten salt storage to address energy insecurity and promote sustainable energy development in Gwadar, a port city in Balochistan, Pakistan, which faces significant challenges in electricity provision and overall development. Energy insecurity presents a critical challenge in Gwadar, a port city located in the southwestern province of Balochistan, Pakistan. Despite its strategic importance and potential for economic growth, Gwadar faces significant challenges in ensuring reliable access to energy for its residents and businesses.

Figure 1.1 Gwadar Map [2]
Fig 1.1 shows the map of Gwadar city. In recent years, Gwadar has experienced rapid development, through the construction of a deep sea. However, this growth has not been matched by an adequate expansion of the city's energy infrastructure. As a result, Gwadar suffers from frequent power outages and a lack of reliable access to electricity [1] the energy situation in Gwadar is characterized by energy insecurity, the absence of grid connectivity, and resulting challenges. This has led to frequent power outages, high energy costs, and environmental degradation [2].
The primary goal of this research is to conduct a comprehensive techno-economic analysis of integrating concentrated solar power with molten salt storage in Gwadar, with the objectives of addressing energy insecurity, evaluating technical feasibility, and assessing the potential economic and environmental benefits.
1.1 Background of Study
Concentrated solar power is the method to harness sunlight to generate heat, which can then be used to power current conventional thermoelectric systems or potential advanced generation systems. What sets CSP apart is its capacity to store heated substances in a cost-effective and efficient thermal energy storage system. This accumulated thermal energy can be utilized from evening until dawn or during overcast conditions to supply sustainable, on-demand electricity. Beyond electricity generation, CSP techniques are progressively expanding into emerging sectors like process heat, solar fuels, and desalination [3].
The evolution of the "techno-economic analysis of concentrated solar power with molten salt storage" research has been marked by significant stages. Emerging in the early 2000s, CSP

technology harnessed sunlight to generate high temperatures for electricity. The integration of molten salt storage in the following decade addressed solar intermittency, leading to thorough techno-economic analyses and the development of precise modeling tools. These studies gained prominence in the context of evolving renewable energy policies and matured markets, attracting the attention of governments and investors. Additionally, researchers explored the role of CSP with molten salt storage in grid stability, responding to the challenges posed by intermittent solar energy. This ongoing research continues to drive innovation and optimization, fueling the potential of CSP with molten salt storage in global sustainable energy efforts [4].

1.2 Description of the Technology:

In this section, I will explore two primary categories solar photovoltaic (PV) and solar thermal power systems. Solar PV directly converts sunlight into electricity using semiconductor materials, while solar thermal power systems utilize the sun's heat to generate power. Within the latter category, concentrated solar power (CSP) emerges as a key player, employing optical systems to focus sunlight and increase energy intensity. Four notable CSP technologies are solar power towers, parabolic dish type, parabolic troughs, and linear Fresnel reflectors. Additionally, molten salt serves a crucial role in these systems, facilitating thermal energy storage to ensure a consistent and reliable power supply. This concise overview highlights the diverse approaches within the realm of solar technology, with each contributing to the broader goal of sustainable and renewable energy solutions.

1.2.1 Solar PV

The sun holds a lot of energy in the form of light and heat. We can capture this energy with just a bit of effort and put it to good use. There are two ways we get solar energy from the sun: one uses light to make electricity, and the other, which we're focusing on here, collects heat by focusing sunlight onto a spot or line [5]. In Figure 1.2, there's an illustration of a solar panel composed of doped silicon. When sunlight hits the silicon, it generates pairs of electrons and holes in the semiconductor material. These pairs enable the flow of electric current through an external circuit, often connecting to a battery. This technology produces electric power in the form of direct current.

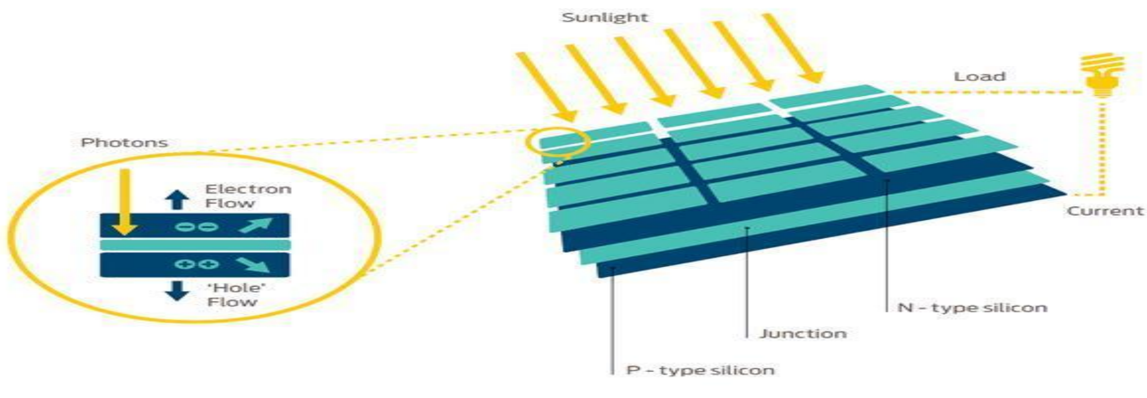


Figure 1. 2 Operation of Photovoltaic cell [5]

1.2.2 Solar Thermal Power Systems

Solar thermal power systems utilize sunlight, concentrating it to create high-temperature heat for generating electricity. These systems include solar collectors with two main parts: mirrors that capture and direct sunlight onto a receiver. In most systems, a fluid is heated in the receiver, creating steam. The steam drives a turbine, which powers a generator to produce electricity. Tracking systems keep sunlight focused on the receiver as the sun moves [6].

These systems might also feature thermal energy storage, allowing the collector to heat a storage system during the day. Later, the stored heat generates electricity when sunlight is lacking. Some solar thermal power plants are hybrids, using other fuels like natural gas alongside solar energy during low sunlight periods [6].

Fig. 1.3. shows how a solar tower power plant with molten salt storage works by using a big area of mirrors called heliostats. These mirrors reflect sunlight and point it towards a tall central tower. Inside the tower, there is a special liquid, usually molten salt. This liquid takes in the heat from the strong sunlight and moves it to a machine that changes the heat. This changed heat is used to make steam, and this steam moves a moving part called a turbine, making electricity. The molten salt can also be kept in big containers. This helps when there's no sunlight, like during the night or when the sky is cloudy. So, the power plant can keep making electricity even when the sun isn't shining [5,6].

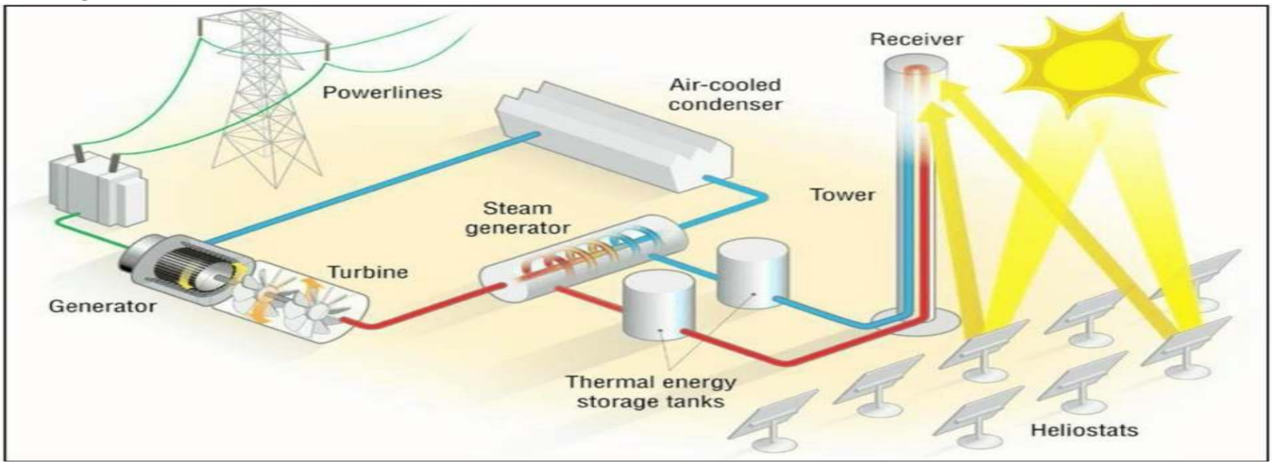


Figure 1.3 Working principle of concentrated solar power tower [6]

The process of producing energy from concentrated solar power in a plant is shown in Figure 1.4. Solar collectors that concentrate sunlight into a tiny area are used to start the process. To exchange heat, the heat is generated and transmitted to a fluid. Steam is produced as the heated fluid flows through a mechanism that heats water. To generate electricity, a generator is driven by a turbine that is propelled by steam. The voltage of the power is then adjusted before it is sent into the grid for distribution.

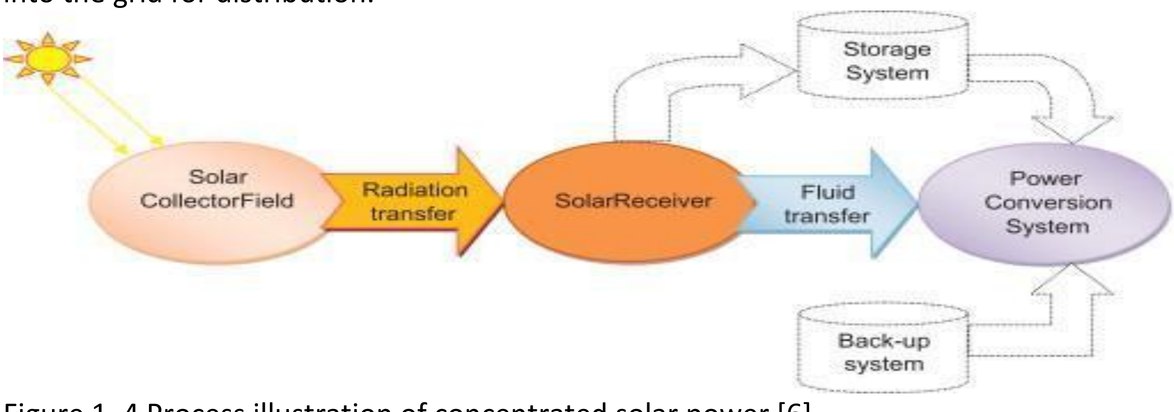


Figure 1. 4 Process illustration of concentrated solar power [6]

1.3 Concentrated Solar Thermal Power

As explained briefly in the previous section, these systems generate electricity using mirrors and are of the following four types.

- Solar power tower
- Parabolic dish type
- Linear Fresnel reflectors
- Parabolic trough

These technologies have been described comprehensively in the succeeding sections.

1.3.1 Solar Power Tower

The system uses numerous large mirrors that are tracked along two axes and pointed in the direction of the sun. To collect the heat, the sunlight is reflected by the mirrors onto a central receiver, which is typically a tall tower. Steam turbines or other heat engine components are used to convert the heat that has been collected into electrical power [7]. The solar tower with a mirror is shown in Fig. 1.5. Further characteristics of solar power tower systems are presented in Table 1.1.

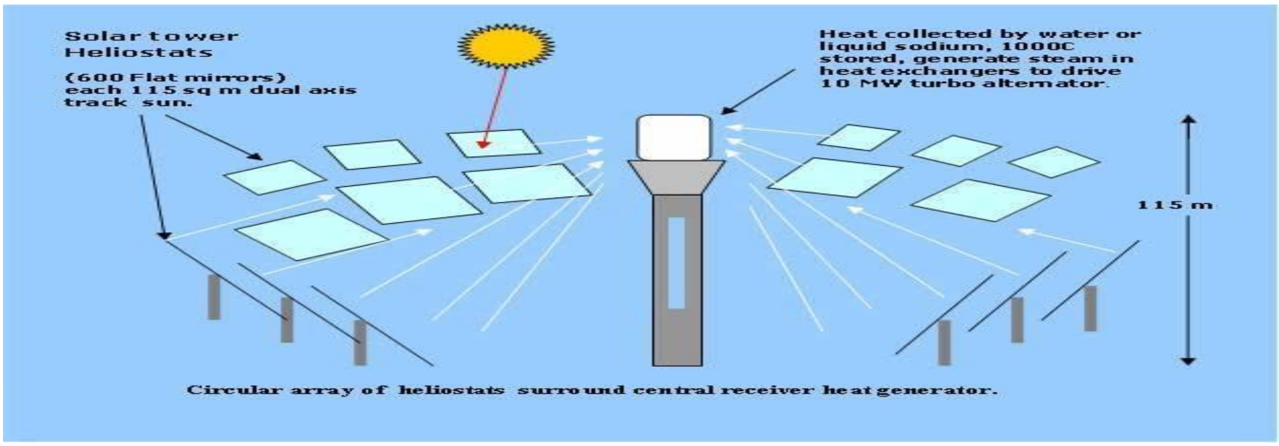


Figure 1. 5 Solar tower system [7]

1.3.2 Parabolic Dish Type

This technology is known as a "parabolic dish collector" because it resembles the trigonometric parabola, a curved shape in mathematics. It employs cutting-edge techniques and a computer-guided system to track the sun as it moves throughout the day, just like contemporary solar devices. Mirrors are used by the dish-type solar collector to collect sunlight and direct it to a specific location. The sterling engine, a type of heat engine, is connected to a receiver and used to generate electricity. These systems are useful for converting sunlight into electricity on a small scale because they can operate at temperatures of up to 1000°C. [7].

The parabolic shape of this collector greatly influences how well it performs. A poor shape will result in an imperfect reflection of light onto the central receiver. Fig. 1.6 shows a schematic diagram of the parabolic dish system. Furthermore, a summary of the characteristics of PD systems is presented in Table 1.1.

[7] In Simple Words a parabolic is like a giant and shiny satellite dish following the Sun. the dish collects sunlight and focuses it into a super-hot in the middle at the hot spot. we have something that gets hot that heats into electricity. so, it looks like a big fancy way of turning into power. The

system with a medium size capacity ranging from 5 to 25MW capacity .it stands out with a remarkable optical efficiency of 94% for converting sunlight into electricity making an effective renewable energy system solution.

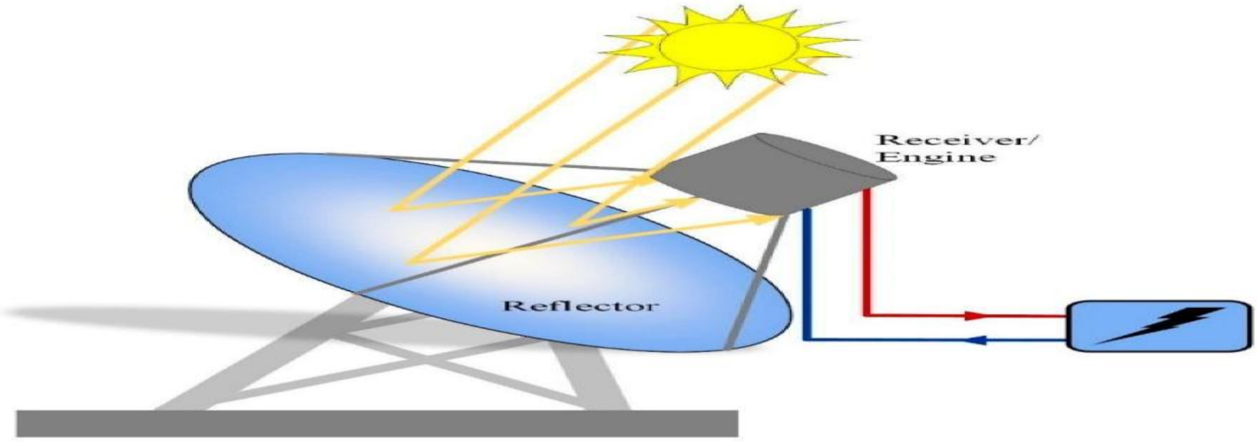


Figure 1. 6 schematic diagram of the parabolic dish system. [8]

1.3.3 Linear Fresnel Reflectors:

A linear Fresnel reflector (LFR) system is a type of solar power system. It uses a bunch of mirrors to focus sunlight onto a central receiver. LFR is shown in Fig. 1.7 The mirrors are mostly flat or a little curved. Unlike PT systems, the receiver is not right next to the mirrors. This means LFR systems use less material and don't need things that spin fast. Also, LFR systems take up less land. because the mirrors are simple, they cost less to make, and they don't need as much land. but because the mirrors are simple, they aren't super good at using all the sunlight. That's why there aren't many big LFR plants around the world. Further characteristics of LFR systems are summarized in Table 1.1.

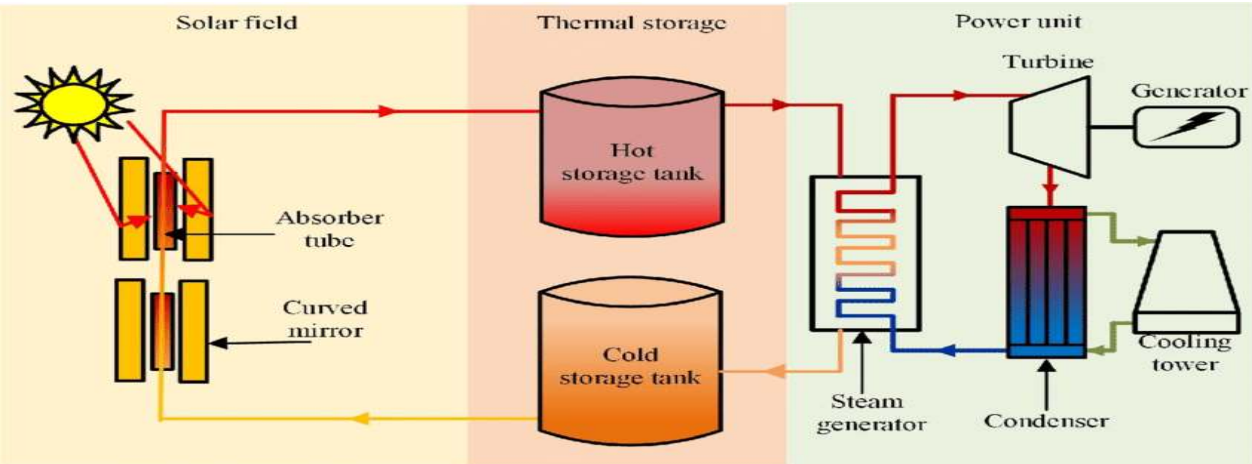


Figure 1. 7 Schematic diagram of a linear Fresnel reflector system. [7]

1.3.4 Parabolic trough

Figure 1.8 provides a visual representation of the PT (parabolic trough) plant under consideration. The initial unit within this setup is the PT solar field, characterized by parabolic-shaped reflectors, absorber tubes, and solar field piping. Incident sunlight is focused onto a focal point along the absorber tube through the parabolic reflector. To harness the thermal energy, a heat transfer fluid (HTF) circulates within the absorber tubes. Subsequently, it is directed into the second unit,

referred to as the thermal storage unit. This unit comprises two distinct tanks: hot storage tanks and cold storage tanks. It is noteworthy that the utilization of these two storage tanks is a prevalent practice in commercial concentrating solar power plants [7,8].
The HTF flows from the hot storage tank to the cold storage tank via a steam generator, where it undergoes a heat exchange process. The thermal storage unit fulfills two primary functions: first, it reserves any surplus thermal energy, and second, it supplies the heat required for the operation of the third unit, namely, the power unit [8]. Further characteristics of PT systems are summarized in Table 1.1.

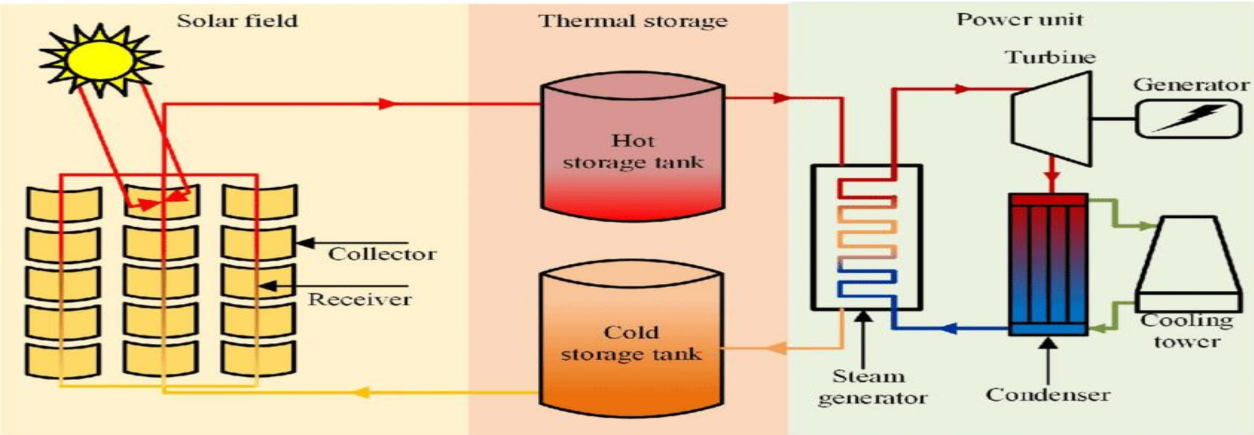


Figure 1. 8 Schematic diagram of a parabolic trough (PT) plant. [7]
A parabolic trough system is like a giant curved mirror that focuses sunlight into a single point. This focused sunlight gets very hot and it is used to generate electric power, like a magnifying glass to create a powerful beam of sunlight that can on a large scale. the curved shape helps to gather the concentrated sunlight in a good way, turning it into a clean and renewable source of energy.
Table 1.1 Characteristics of CSP technologies [5,6,7,8]

Characteristic	Unit	Parabolic trough collectors	Solar power tower	Linear Fresnel reflectors	Parabolic dish
Plant Capacity	MW	30-300	100-200	1-100	5-25
Capacity Factor	%	23-55	20-77	20-25	24-25
Cycle Temp. (Max)	°C	300-400	585	150-500	800
Concertation ratio	-	70-80	300-100	25-100	1000-3000
Optical efficiency	%	80	73	65-75	94

1.4 Molten Salt for Thermal Energy Storage
Thermal energy storage (TES) represents an indispensable technology for energy provisioning, particularly concerning the variable generation of CSP technology [9]. Within CSP installations, molten salt, serving as the HTF in parabolic trough solar fields, assumes a pivotal role in augmenting system performance [10].The maximum operating temperature for the molten salt circuit and storage pegged at 565 °c, primarily derives from the thermal stability inherent to molten salt [9]. Given the elevated risk of salt solidification within lengthy pipeline systems,

contemporary parabolic trough CSP plants persist in the utilization of thermal oils as heat-transfer mediums [10].

2. Literature Review

2. 1 Concentrated solar power (CSP)

Concentrated solar power (CSP) employs the concentration of solar energy to generate heat for electricity. It is enhanced by the utilization of molten salt storage to ensure a consistent energy supply. This technology's importance for Gwadar, Balochistan is rooted in its solar potential and advantageous coastal location. This study's focal point is the evaluation of CSP feasibility and its impact on molten salt storage in Gwadar. The study objectives encompass technical assessment, economic analysis, evaluation of environmental advantages, and exploration of socioeconomic implications. Ultimately, this research seeks to provide insights into sustainable energy adoption, yielding benefits for Gwadar while stimulating analogous global initiatives.

The research evaluates the feasibility and economic viability of concentrated solar power (CSP) with molten salt storage in Gwadar. CSP offers reliable and renewable energy generation by storing excess solar energy. It reduces greenhouse gas emissions, enhances energy security, and allows for customized solutions to meet different energy needs [11]. CSP technology is a promising renewable energy solution, but it faces challenges. This review study summarizes and compares 143 global CSP projects, addressing factors like capacity, technology, efficiency, and challenges. It discusses issues with HTF, ES technologies, cooling, water management, and LCOE. It explores hybridization with other renewables and identifies leading countries, technologies, and efficient approaches. The study's analysis informs the future of CSP and its impact on reducing global warming potential [12].

2.2 Advancements in Concentrated Solar Power

The literature offers valuable insights into the technical aspects of CSP technology, including its utilization of concentrated solar rays for electricity generation. In Concentrated Solar Power (CSP) technology, the solar radiation focuses directly on a Heat Transfer Fluid (HTF). This fluid then flows through a sequence of thermal exchangers to generate highly heated vapor. The vapor is subsequently transformed into electric power using a conventional steam turbine. Moreover, a fraction of the thermal energy is stored in specific liquid or solid mediums (such as molten salts) to ensure uninterrupted turbine operation during periods of limited sunlight, such as nighttime [13]. Optical concentrators are employed in operational thermodynamic solar systems to harness the power of direct sunlight. What sets CSP technology apart from other renewable energy conversion systems is its unique characteristic—a thermal storage mechanism. This innovative feature allows the system to generate electrical power even during instances of cloudy skies or when the sun has set [14].

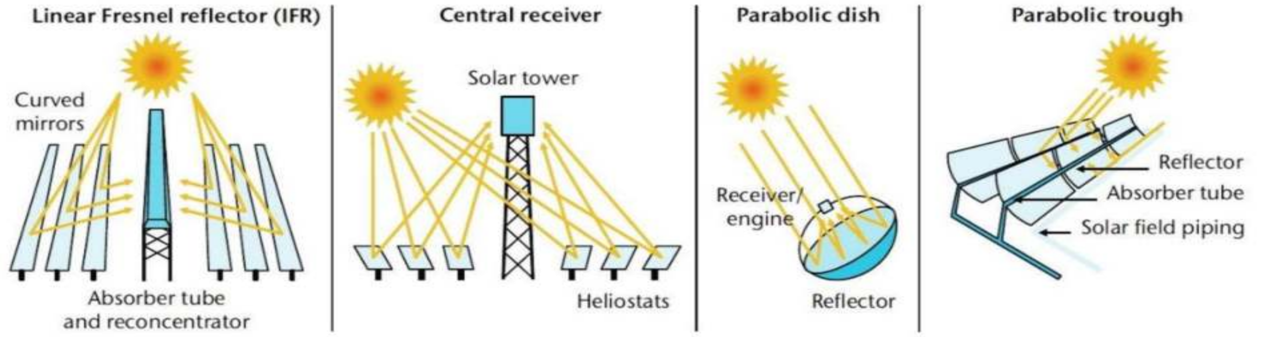


Figure 2.1 Primary CSP Technologies [15]

In Fig.2.1 CSP technologies can be classified into four types. One of them is called the parabolic trough system, which uses curved reflectors to concentrate sunlight onto a pipe filled with thermal oil. The heated oil is then used to produce electricity in a steam generator. A crucial technology in Concentrated Solar Power (CSP) plants is the parabolic trough system [15]. This system utilizes curved reflectors to concentrate sunlight onto a receiver pipe. Inside the pipe, a heat transfer fluid, such as thermal oil, absorbs the concentrated solar energy and undergoes heating. This heated fluid is then utilized in a thermal power unit, where it generates steam that powers a turbine, ultimately producing electricity. [16]. The Solar Parabolic-Dish (SPD) system uses a curved dish to reflect sunlight onto a receiver placed at the center. This system has concentrators that can move in two directions to track the sun's movement. At the center, there is a setup that converts the sunlight into electricity. [17]. Solar power tower (SPT) systems use large mirrors to reflect sunlight onto a receiver at the top of a tower. The receiver, made of stable materials like ceramics or metals, reaches high temperatures. This heat produces steam, driving a turbine to generate electricity. [18].

Molten salt TES is widely used in commercial (CSP) systems. However, there is a need for more affordable and efficient TES systems. Phase change materials (PCM) are being explored as potential solutions due to their low cost and ability to store large amounts of energy. A new idea of using PCM for storing energy in solar power plants has been introduced. This concept focuses on improving the design of collectors, materials used, heat transfer processes, and energy production and storage [19].

2.3 Evaluating the Feasibility of Advanced Solar Energy Technologies

Researchers have also developed a method that uses multiple factors to evaluate CSP technologies and measure their performance [20]. In Tanzania, the practicality of CSP technology has been assessed by using computer models to simulate Parabolic Trough and Solar Tower CSP technologies, developed by the U.S. National Renewable Energy Laboratory [21]. The performance of different methods of generating electricity, such as solar panels and concentrated solar power systems, has been studied in various locations in Saudi Arabia [22]. Two approaches to utilizing solar energy and storing it have been proposed and analyzed: upgrading existing CSP plants with more efficient equipment and designing new hybrid plants that can both store and release energy using a specific process [23]. The current situation, challenges, and prospects of thermal energy storage technology, with a focus on improving materials and chemical reactors, have been examined [24]. Hybrid solar desalination systems driven by curved-shaped troughs and rounded-shaped dish CSP technologies have been studied. These systems have been categorized and assessed in terms of their energy efficiency and cost-effectiveness [25]. A framework combining computer mapping and decision-making methods has been presented to identify suitable locations and evaluate the technical potential of large-scale solar panels and CSP plants [26]. Studying Concentrated Solar Power (CSP) with molten salt storage for Gwadar, Balochistan is crucial for several reasons. Firstly, it ensures a reliable and secure energy supply for the growing industrial and residential sectors in Gwadar by reducing dependence on traditional energy sources. Secondly, adopting CSP with molten salt storage promotes environmental sustainability by reducing greenhouse gas emissions and mitigating the environmental impact of fossil fuel-based power generation. Thirdly, implementing CSP with molten salt storage in Gwadar fosters economic development, creating job opportunities and stimulating the local economy. Lastly, CSP with molten salt storage contributes to grid stability and integration, addressing the intermittent nature of solar power and supporting the seamless integration of renewable energy into the existing power grid. Overall, studying and implementing CSP with molten salt storage in Gwadar, Balochistan offers benefits such as a reliable energy supply, environmental friendliness, economic growth, and enhanced grid stability [27]. The mounting requirement for electricity and the necessity to decrease greenhouse gas emissions have paved the way to develop sustainable energy and renewable technologies such as solar power. Concentrated Solar Power (CSP) plants have emerged as an important technology that can provide reliable renewable energy. CSP plants can generate electricity even during periods of low solar radiation by storing collected thermal energy. Among the various thermal storage systems, molten salt storage has gained significant attention because of its capability to store large amounts of thermal energy at a high temperature. Numerous studies have investigated the performance of CSP plants with molten salt storage [28].According to Musi et al, “the study highlights that the LCOE of CSP is decreasing and has the potential to meet the SunShot target of 6$/kWh by 2020. However, the CSP market is influenced by factors such as location and level of industrial cooperation, as well as learning effects at the country and technology levels” [29]. Sanz conducted a technical and efficiency evaluation of a 100-MW class central receiver system that uses a thermocline hybrid thermal energy storage system; and compared it to the standard dual-tank thermal storage system [30].Mukeshimana et al conducted a technical and economic assessment of CSP in Rwanda. The study involved modeling two CSP technologies: a solar concentration tower plant and a parabolic collector solar plant to evaluate their feasibility and economic viability [31]. Agyekum compared the technical and economic potentiality of photovoltaic (PV) and PV-battery photovoltaic power plants in three separate atmospheric situations in Ghana. The study highlights the current research and development efforts on CSP systems, with an emphasis on their techno-economic feasibility and barriers to deployment in various regions [32]. “Middelhoff conducted a study on the design and evaluation of the techno-financial and environmental performance of a hybrid concentrated solar biomass power plant for electricity generation in Australia’s Riverina-Murray area. The study highlights the potential for the deployment of plants in the region due to its abundant solar and biomass resources”[33]. “Liaqat performed a study on the simulation and modeling of a 100 MW CSP thermal power plant in Pakistan, using a parabolic trough collector by system advisor model” [34]. Aly evaluated the technical and economic feasibility analysis of CSP in Tanzania by using the system advisor model of the National Renewable Energy Laboratory to model solar towers and parabolic troughs [35].

3. Research Methodology

The research design in this study is primarily quantitative and modeling-based, focusing on concentrated solar power. This approach from NERL [36] involves collecting and analyzing numerical data related to the technical and financial aspects of CSP technology. The rationale for this choice is rooted in the complexity of CSP, requiring detailed technical and financial analysis. The use of the system advisor model (SAM) software further supports the quantitative approach as it is designed for simulating the costs and efficiency of renewable energy systems, offering valuable insights into technical (monthly, and annual energy output and financial performance [37]. This research design aligns with the need for data-driven decision-making, allowing researchers to assess costs, efficiency, and performance metrics through simulations and numerical results, essential for informed decision-making in renewable energy project planning.

The research design for evaluating the feasibility of concentrated solar power in Gwadar is a meticulously planned framework that encompasses various crucial elements. The initial phase will involve a comprehensive site assessment, emphasizing solar irradiance, land availability, water sources, and molten salt availability. The solar irradiance assessment from reputable sources aims to understand the solar energy potential in Gwadar. Specifically, the analysis of direct normal irradiance (DNI) values throughout the year provides a nuanced understanding of variations and patterns. [38] land availability is assessed through data obtained from local authorities, ensuring the suitability of identified areas for CSP plants. Google Maps will be utilized for mapping and visualization, enhancing the spatial understanding of selected sites. Water availability, both fresh and seawater, is evaluated to estimate the water demand for CSP plant operations. [39] the research will also explore the potential use of seawater as molten salt, presenting a holistic view of sustainable water-sourcing options. Additionally, the study will investigate molten salt sources, considering local availability and the feasibility of creating molten salt from indigenous mineral resources.

The research design for this study is centered on modeling and simulating a parabolic trough system, with a specific focus on analyzing its performance metrics, annual energy production, power generation patterns, and thermal energy storage efficiency. To achieve this, the research will employ the system advisor model (SAM) version, a sophisticated tool designed for system analysis. [40] the initial step involves acquiring pertinent parameters for CSP system design from SAM, encompassing solar field characteristics, power cycle specifications, and thermal energy storage details. Weather data crucial for the Gwadar region, including solar irradiance, will be sourced from reputable databases such as the National Solar Radiation Database and the Pakistan Meteorological Department. Site-specific data, including geographical coordinates, solar irradiance, wind speed, and equipment details, will be meticulously collected. The National Renewable Energy Laboratory (NERL) and the Meteorological Department of Pakistan are integral sources of comprehensive weather data. Utilizing scrub, which provides a detailed collection of hourly and half-hourly solar radiation values of a year, ensures capturing seasonal fluctuations in solar irradiance. [40,41] The simulation process will entail using SAM to simulate the system's performance, considering hourly intervals and key weather parameters. SAM-generated data will be analyzed to extract annual performance metrics, including AC energy production, capacity factor, gross electrical output, and net output at design conditions. Monthly and annual power generation patterns will be scrutinized, and an in-depth analysis of thermal energy storage TES parameters, such as charge state and charge thermal power, will be conducted. The research will culminate in visual representations, such as graphs and charts, to effectively communicate key findings regarding monthly and annual energy production, power generation patterns, and efficiency. This comprehensive research design ensures a systematic and thorough investigation into the performance and efficiency of parabolic trough systems, contributing valuable insights to the field of renewable energy optimization.

The research design for a comprehensive cost analysis of a parabolic trough solar plant, specifically focusing on the fixed-charge rate levelized cost of electricity (LCOE) method using the system advisor model SAM. [41] the study will involve gathering quantitative financial data for the parabolic trough solar plant from SAM, encompassing key parameters such as system capacity, capital costs, fixed operating costs, variable operating costs, and financial assumptions. The primary goal is to calculate the LCOE, a critical metric for assessing the economic feasibility of the solar plant. The research will commence by utilizing SAM to input relevant financial parameters into the LCOE formula [41]. [41,42] This includes the fixed charge rate, total capital cost, fixed operating cost, annual energy production, and variable operating cost. Subsequently, data will be obtained from the National Renewable Energy Laboratory's annual technology baseline (NERLATB) to enrich the analysis. We will not only compare the calculated LCOE of the proposed parabolic trough design with global LCOE values provided by NERLATB for concentrated solar power (CSP) plants but will also delve into the NERLATB provisions for adjusting technology details. This investigation aims to ensure alignment between the researched parabolic trough design and the industry standards represented by NERLATB global data, providing valuable insights into the economic viability and competitiveness of the proposed solar plant design. Figure 3.1 shows other overall methodology sections for research.

To Summarize the research methodology, the research is a Modeling and quantitative based research, the key data is Direct normal irradiance which is taken for one year from Gwadar on an hourly basis which are series of 8,760 hourly values that signifies the system's electricity production throughout the year National renewable energy and base and local station of Pakistan Meteorological department. The Excel sheet data is imported for the system advisor model. The system parameters for the system are entered, and financial parameters are taken by default from the system advisor model updated version for cost analysis. After setting and entering all the parameters into the simulation software, then the simulation for the system performance and efficiency is done by me. The system advisor model provides results in different types of graphs and charts as well as statistical data provided by the computer-based software which is one of the important features. For viability and site assessment, the data was taken from local authorities and previously published research work. Results for the proposed objective are generated from simulation-based tools in graphs which. SAM played the key role as a software used in the analysis of solar resources efficiency, generated output power and thermal energy storage for proposed CSP system assessment in Gwadar city

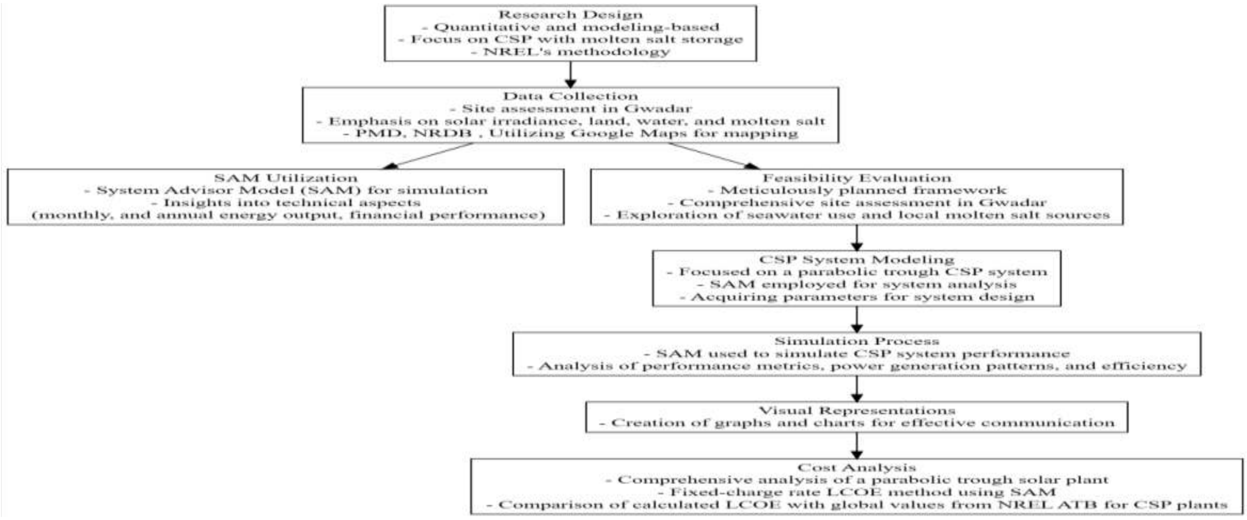


Figure 3.1 Block diagram of research methodology section

3.1 Data Collection Method:

The data collection method for the viability and site assessment of concentrated solar power plants in Gwadar, Balochistan, was a systematic process that involved gathering observations and measurements from various sources. The data collection section of the study was divided into several parts. The first part of the study discussed the availability of solar resources in the area. The first step involved collecting solar irradiance data to accurately represent the regional solar irradiance climate in Gwadar Balochistan. Solar irradiance data was obtained from reliable sources of the National Solar Radiation Database and the Pakistan Meteorological Department on an hourly basis for the year 2022-2023[43,44]. The second part of the study focused on the availability of land for the potential establishment of a CSP plant. For land availability, Google Maps and existing data were obtained from past research papers, local administration, relevant government agencies, reports, and databases. The third part of the study was further divided into two sub-sections: one discussed the availability of fresh water, and the other explored the potential use of seawater. Data on water consumption by CSP plants and comparisons with other power generation methods were collected from past research papers, local administration, and existing literature. The fourth part of the study discussed the availability of molten salt, a crucial component for CSP plants. Availability of molten salt data was obtained from past research papers, local administration, existing literature, official reports, and documentation. This section was further divided into a sub-section, which explored the possibility of using seawater as a source of molten salt. Figure 3.2 shows the data collection method for viability and site assessment of CSP with molten salt storage in Gwadar.

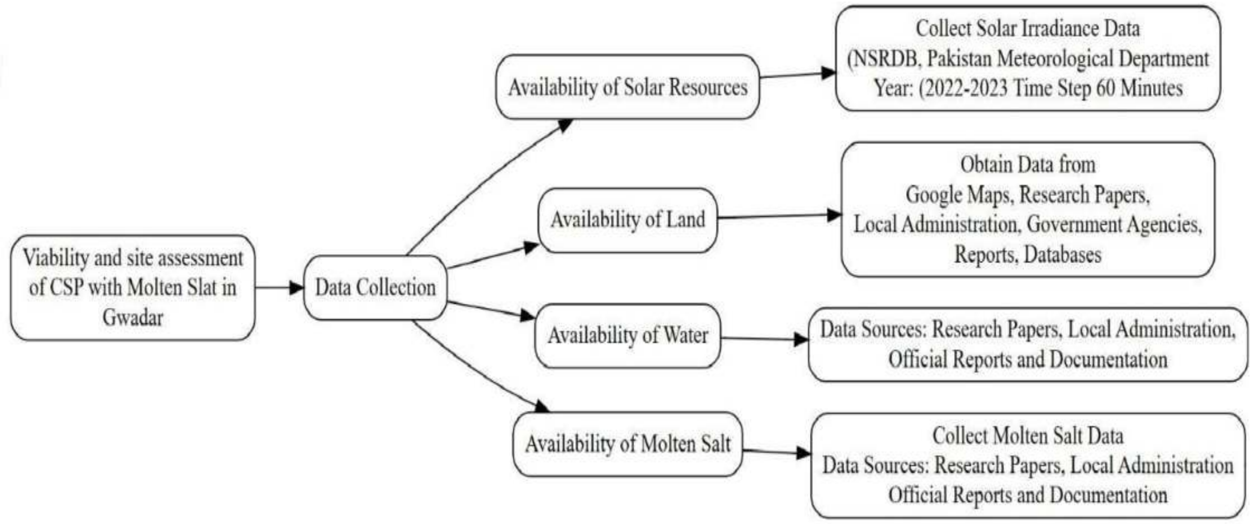


Figure 3.2 Data collection block diagram for CSP plant viability assessment

For modeling and simulating a parabolic trough using the system advisor model (SAM) for Gwadar City, we carefully gathered information. We started by getting important details like where the system will be, what resources are available, and specific information about the solar field, power cycle, and thermal energy storage [44]. We got this information from the latest SAM software, known as SAM 2021.12.02. This software is well-known for studying and simulating renewable energy systems. We also collected hourly weather data, which is important for our simulation work. We got this data from two main sources the National Solar Radiation Database and the Pakistan Meteorological Department [43,44]. This weather information, collected every 60 minutes, covers the years 2022-2023 and helps us understand the detailed weather conditions needed for accurate simulations. data collection plan combines information from SAM, weather data, and details about the location. This solid foundation helps us effectively model and simulate the parabolic trough in Gwadar city. Figure 3.3 shows the data collection details for modeling and simulation.

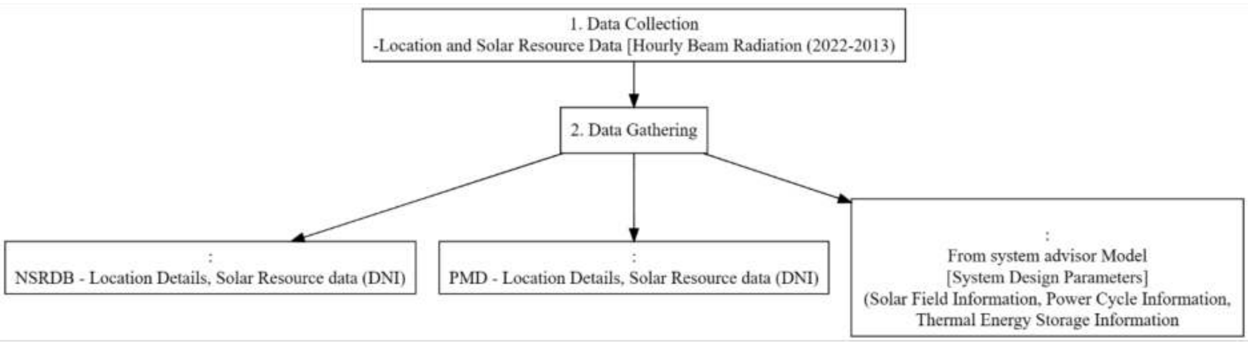


Figure 3. 3 Data collection for system design

The data collection method for calculating the levelized cost of electricity in the proposed parabolic trough project involved utilizing the simple fixed-charge rate (method within the system advisor model Leveraging SAM's advanced simulation capabilities, essential financial data was extracted from the latest version of, encompassing parameters crucial for comprehensive cost analysis. These parameters, including capital cost (TCC), fixed annual operating cost variable operating cost per kWh fixed charge rate, and annual electricity production were systematically gathered to ensure a thorough evaluation of both initial setup costs and ongoing operational expenses associated with the parabolic trough system. This methodological approach aimed to provide a precise and comprehensive assessment of the project's economic viability, considering diverse factors influencing the levelized cost of electricity [45]. Figure 3.4 shows the simple fixed charge-rate LCOE method for cost analysis.

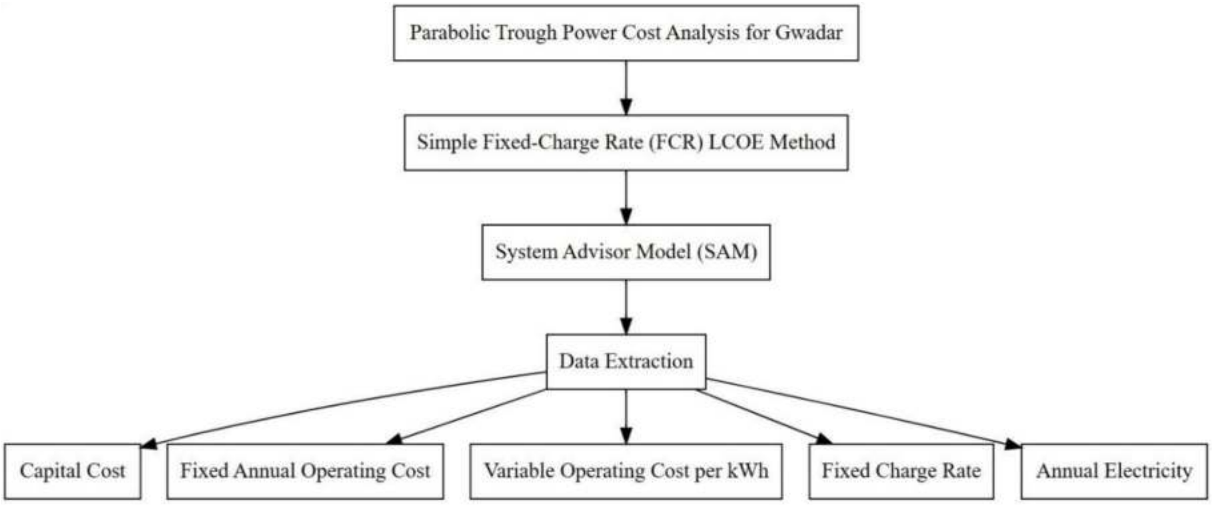


Figure 3.4 Model for fixed charge-rate LCOE method for cost analysis.

3.2 System Advisor Model (SAM)

In this study, the system advisor model (SAM) was used to simulate a concentrated solar power (CSP) plant in Gwadar. Data will be entered of various parameters into SAM, including the plant’s specifications, cost details, and expected performance. Detailed weather data was imported for Gwadar from the National Solar Radiation Database, Google Maps, and Meteorological Department data. The performance model conducts calculations on an hourly basis, producing a series of 8,760 hourly values that signify the system’s electricity production throughout the year [46,47]. Figure 3.5 shows the interface of the system advisor model.

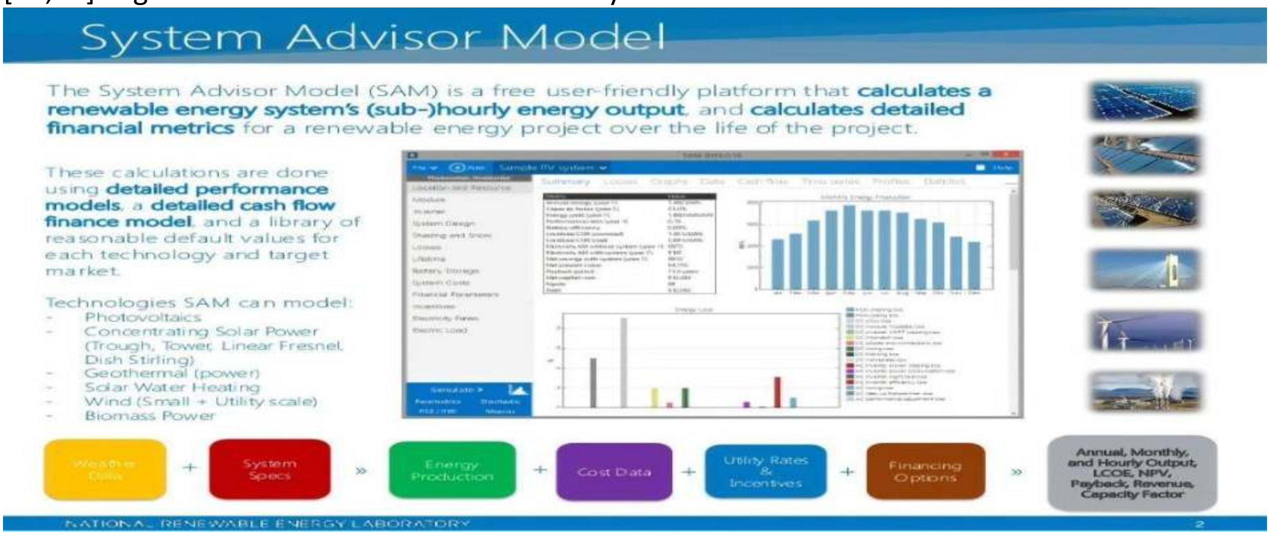


Figure 3.5 System advisor model interface [51]

4. Results and Discussions

4.1 Solar availability

The graph plotted in Figure 4.1 shows the variation of DNI values for each month. It's observed that the DNI values range from a minimum of 2.45833 w/m² to a maximum of 334.042 w/m².

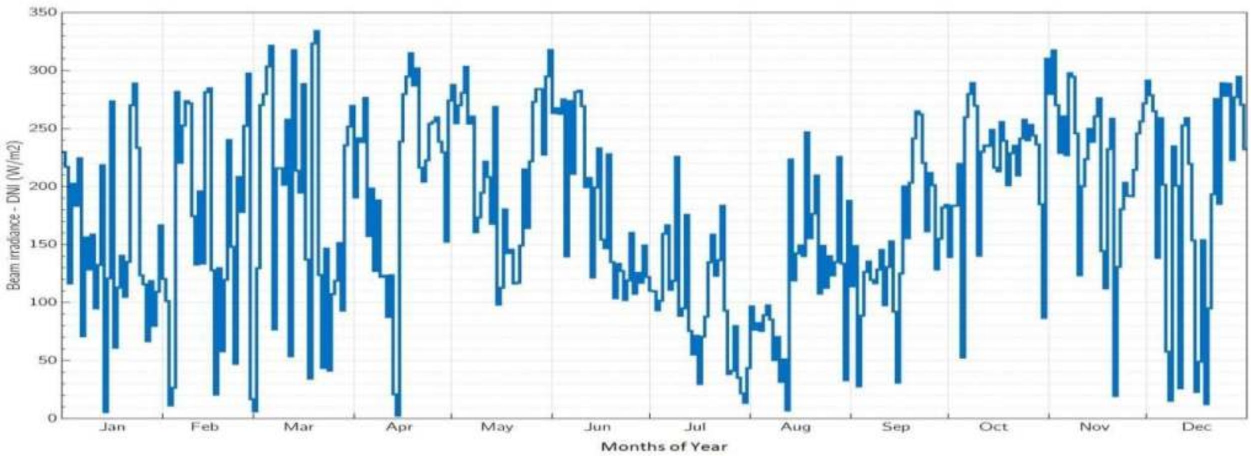


Figure 4.1 Annual direct normal irradiance (DNI) for Gwadar City

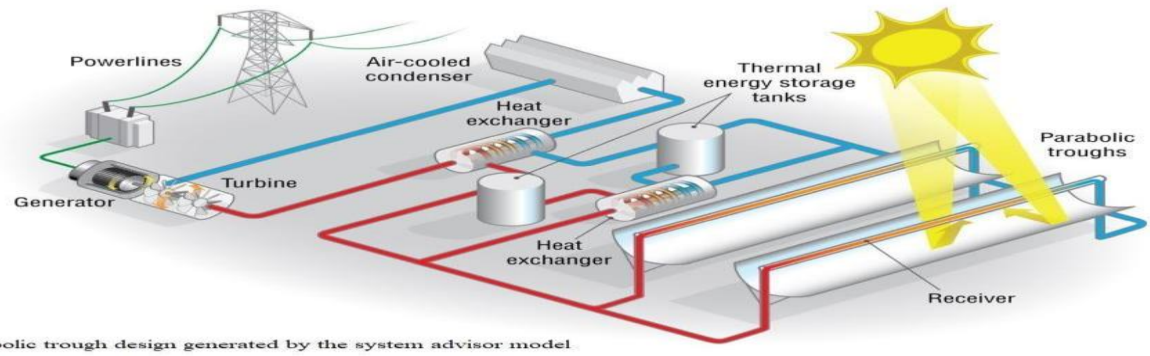
The solar availability for site assessment found that the amount of sunlight in Gwadar city changes throughout the year. The highest amount of sunlight was observed during the summer months, especially in May and June. This is good news for generating concentrated solar power energy. The study also found that the amount of sunlight changes every month. This means that solar energy systems can be designed to work better by adjusting their settings to match the times when the most sunlight is available. The study provides important information for people who want to use concentrated solar power technology in the Gwadar region.

4.2 Land availability

The land availability for site assessment found that the Gwadar industrial zone has enough land to build a 50 MW parabolic trough CSP plant. The land area required for a CSP plant is typically between 5 to 10 acres per MW of capacity. For a 50 MW CSP plant, the expected land needed would be from 250 to 500 acres. The Gwadar industrial zone has a 4,000-hectare area that is only for industrial purposes and it meets the land requirements of a CSP facility. Figure 4.2 shows a map or diagram of the Gwadar industrial zone and the proposed CSP plant location, which shows the strategic position of the CSP plant in the region

Figure 4.2 Map of Gwadar industrial zone and proposed CSP plant location [2]

4.3 Water availability
It indicated that the CSP plant in Gwadar can rely on the region's current freshwater supply of approximately 10 million gallons per day. However, to sustain the plant, which is estimated to generate 106,202,648 kwh-e annually, the water demand varies from 371,708 m^3/year to 26,551 m^3/year based on technology and cooling system choices. To ensure sustainable and efficient operation, it is advised to choose CSP technology with minimal water consumption. The study also suggested utilizing Gwadar seawater for CSP, proposing a two-part system involving freshwater production and seawater use for cooling and potential desalination. This approach provided a practical and sustainable solution for dry regions.
4.4 Molten salt availability
The study found that molten salt has promising potential for a proposed concentrated solar power (CSP) plant in Gwadar. High-quality rock salt in Pakistan, particularly from the Khewra salt mine, and mineral resources in Balochistan could serve as raw materials for molten salt. However, the transformation process requires careful consideration due to its complexity, safety concerns, and the need for specific facilities and expertise. The study also explored the production of molten salt from seawater in Gwadar, which shows promise, leveraging the region's abundant solar radiation and proximity to the Arabian Sea. However, challenges such as significant initial investments, energy consumption, market prices, and fluctuations must be addressed for this technology to become commercially viable. Further research and development efforts are necessary to enhance the efficiency and cost-effectiveness of molten salt production from seawater, ensuring its economic viability for plants. Overall, the study highlighted the technical and economic viability of CSP in Gwadar, contingent on factors like grid connectivity, policy support, and social acceptance.
4.5 Modeling and simulation
The modeling and simulation outcomes indicated that a parabolic trough concentrated solar power (CSP) system, equipped with molten salt storage, designed for Gwadar city with specific parameters (such as solar multiple, field aperture, turbine output, and thermal energy storage) and using Hitec solar salt, is predicted to provide reliable and sustainable power. The system's design allows for continuous power generation, even in the absence of sunlight, enhancing overall efficiency. Further optimization through additional studies and simulations is recommended for improved system design and operation. Figure 4.3 shows the System advisor model generated parabolic trough design. The model's completeness is adaptable to specific project needs, ensuring a tailored approach to CSP plant design.



parabolic trough design generated by the system advisor model

Figure 4. 3 System advisor model generated parabolic trough design

4.6 Annual performance

The simulation of the plant revealed promising results. In its first year of operation, the plant generated a significant amount of electricity (91,720,120 kWh), with a capacity factor of 23.3%, indicating efficient operation at full capacity approximately a quarter of the time. The power cycle demonstrated high efficiency, producing 2,038 kWh of electricity for each kilowatt of capacity. These findings highlight the effectiveness of the plant in harnessing solar energy, showcasing its potential as a clean and renewable energy source for combating climate change and transitioning to sustainable energy. The annual performance metrics of a CSP plant are presented in Table 4.1.

Table 4.1 Annual energy production and capacity factor

Metric	Values
Annual AC energy in Year 1	91,720,120 kWh
Capacity Factor	23.3%
Power Cycle Gross Electrical Output	106,202,648 kWh
First-year kWh/kW	2,038 kWh

4.7 Monthly power generation

The analysis of the system's power generation patterns revealed distinct trends and variations influenced by factors such as time of day, season, and weather conditions. The system consistently exhibited low power output in the early morning and late night, reaching peak generation in the midday or afternoon when sunlight was maximum. Monthly analysis indicated that May and October had the most favorable conditions for solar power generation, while a significant drop in July could be attributed to increased cloud cover or rainfall. The study emphasized the impact of beam radiation, season, and weather conditions on power output, suggesting a need for further investigation to comprehensively understand and optimize the system's performance. Further monthly energy production analysis of the concentrated solar power (CSP) system in Gwadar revealed several patterns. The system consistently generated more electricity than it consumed, with higher production in spring and summer months compared to fall and winter. May shows the highest monthly energy production while July has the lowest due to monsoon weather. The system peaks in power generation at noon, reflecting its reliability as a solar power system. Notably, negative values in the evening suggest power consumption for system operations, requiring further research for optimization. Figure 4.4 shows a monthly graph of the power generated by the system and shows the variation of the system power output over a year.

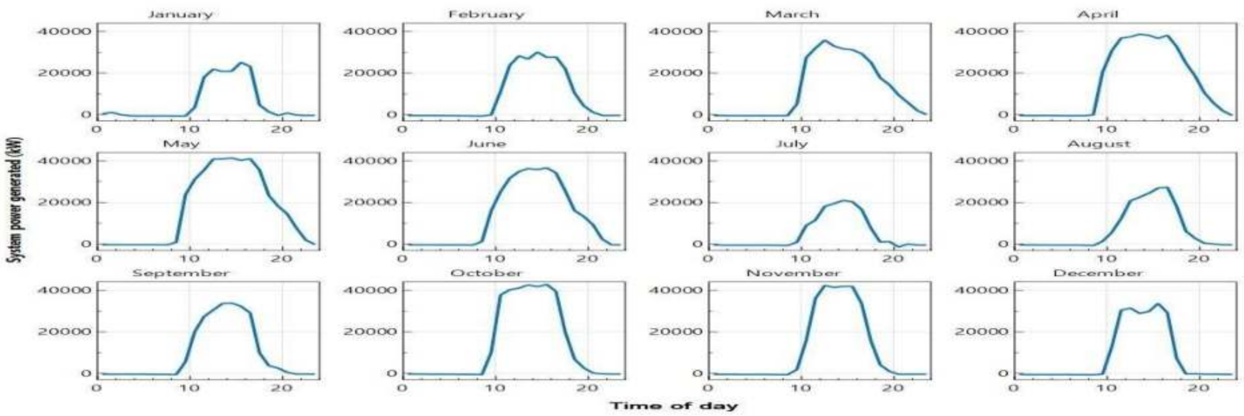


Figure 4.4 Monthly profile for power generation for the CSP system

4.8 Annual system power generation

The annual power generation analysis revealed a consistent daily pattern, with the system consuming more power than it generated in the early hours reaching peak generation around mid-day and gradually decreasing towards the end of the day. Understanding this pattern is crucial for optimizing the operation and efficiency of the solar power system. In the annual power generation analysis, a graph is shown in Figure 4.5 This graph presents the average power output (in kW) of the system for each hour of the day, calculated over a year. This helps us understand the typical daily power generation pattern of the system over a year. The graph has a horizontal axis that shows the time of the day, and a vertical axis that shows the system power output in kilowatts (kW).

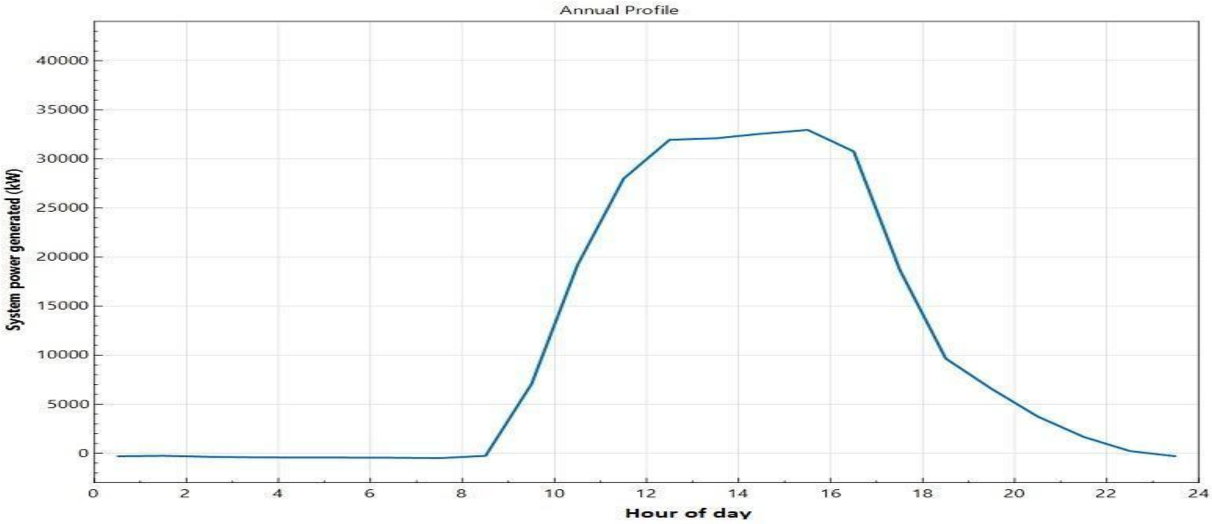


Figure 4.5 Annual System Power Generation Pattern

4.9 Analysis of thermal energy storage

The exploration of concentrated solar power (CSP) with molten salt storage, utilizing Hitec solar salt, demonstrates a sustainable and efficient solution for solar power generation. Analyzing key parameters like thermal energy storage charge state and TES charge thermal power, the system effectively stores solar energy during peak sunlight hours, contributing to renewable energy advancements. The analysis revealed that the system's TES charge state increases throughout the day, peaking around mid-day, showcasing effective energy production and storage. Monthly fluctuations in charge thermal power and system power generated highlight variable power generation, with may exhibiting the highest production. Despite fluctuations, the system maintains an impressive overall power production and storage performance, providing valuable insights into its operational dynamics. Figure 4.6 shows the annual average of days of thermal energy storage charge state as the x-axis represents the time of day and the y-axis shows the thermal energy storage charge state in MWht.

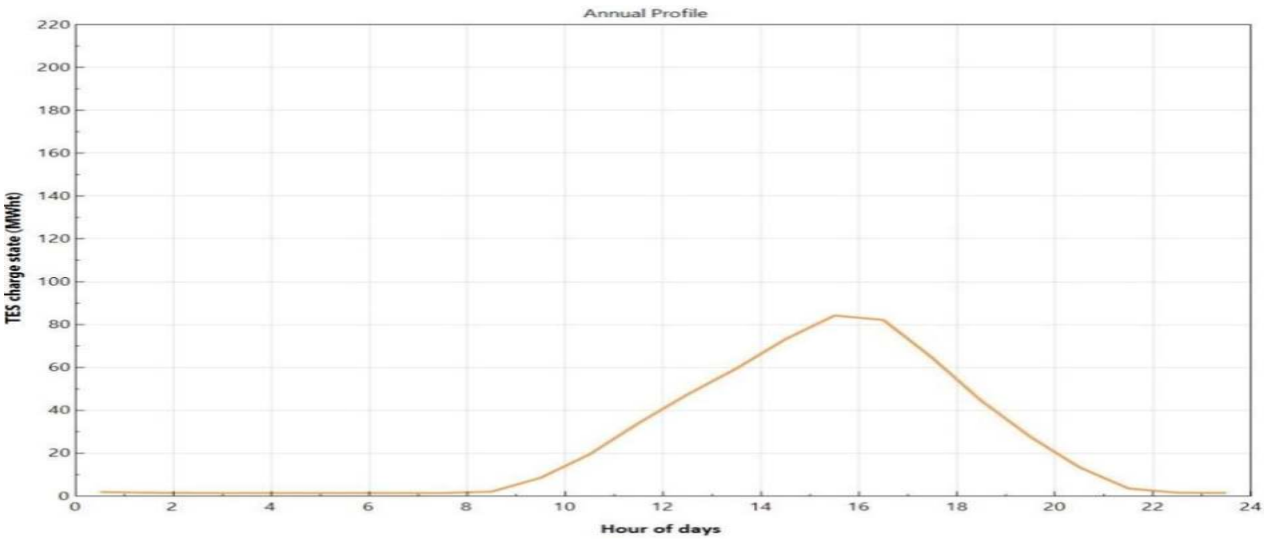


Figure 4.6 Annual Average of Thermal Energy Storage (TES) Charge state

Figure 4.7 illustrates the monthly fluctuations in both TES Charge Thermal Power and System Power Generated. The horizontal axis represents the months of the year, while the vertical axis depicts the TES Charge Thermal Power and System Power Generated. The graph demonstrates the variations in power generation from TES Charge Thermal Power every month.

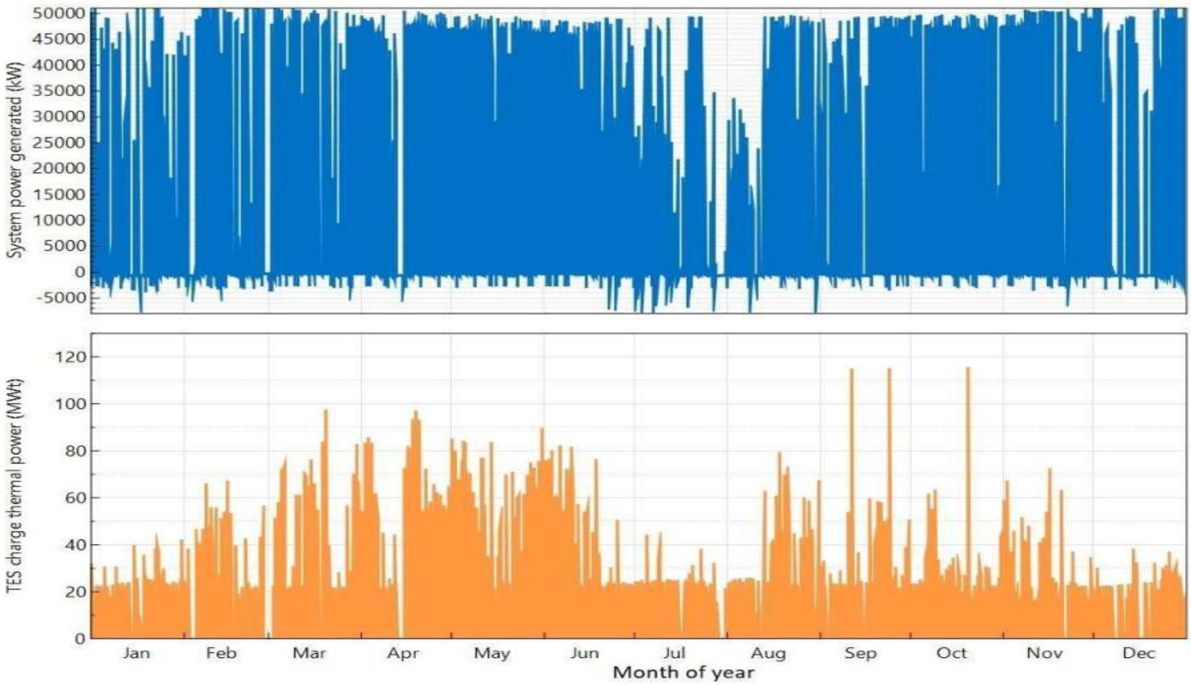


Figure 4.7 Analysis of monthly thermal energy charge power and system power generation

4.10 Cost analysis

The cost analysis of the proposed parabolic trough solar plant using the fixed-charge rate (FCR) levelized cost of electricity method revealed an estimated LCOE of $0.2349/kWh. Comparative analysis with global plant costs from the National Renewable Energy Laboratory (NERL) suggested that the researched parabolic trough design, with 6 hours of thermal storage, may be less cost-competitive compared to other CSP technologies, such as molten-salt power towers with 10 hours

of storage. Further optimization and cost reduction measures are recommended to enhance the competitiveness of the proposed CSP plant within its technology category, as reflected by the relatively higher LCOE.
A notable observation is that the LCOE estimate of the proposed parabolic trough design with 6 hours of thermal storage at $0.2349/kWh appears higher than the global CSP plant LCOE values provided by NERL. This suggests that the researched plant design may be less cost-competitive compared to other CSP technologies, such as the molten-salt power tower with 10 hours of storage.
However, further analysis reveals that NERL also allows for adjusting the technology details to match the parabolic trough with 6 hours of storage, making it more comparable to the researched plant. In this scenario, the LCOE of CSP plants around the world ranges from $0.143/kWh to $0.229/kWh in 2020 and is projected to decrease to a range of $0.101/kWh to $0.162/kWh by 2030. Although these values are closer to the LCOE estimate of the researched plant, they still generally remain lower, indicating that further optimization or cost reduction measures may be needed for the researched CSP plant to be more competitive within the given technology category.

5. Conclusion and Future Work

This research dives into the integration of concentrated solar power with molten salt storage, aiming to tackle energy insecurity and propel sustainable energy development in Gwadar, Balochistan. The study utilized a primarily quantitative and modeling-based research design, focusing on the technical and financial aspects of CSP technology. The methodology involved a meticulous investigation into the viability of plants, emphasizing solar resource availability, land suitability, water access, and molten salt feasibility. Gwadar's abundance of sunlight, especially in summer, positions it favorably for concentrated solar power generation. The assessment confirmed sufficient land in the Gwadar industrial zone and proposed innovative solutions, such as using seawater for cooling and desalination. molten salt, a crucial component, showed potential from local resources and seawater, though challenges warrant further research. Modeling and simulation using the system advisor model predicted a reliable and sustainable system for Gwadar, ensuring continuous power generation. The annual performance analysis demonstrated efficient electricity generation, with a capacity factor of 23.3%. monthly and annual power generation patterns revealed distinct trends influenced by sunlight, seasons, and weather conditions, highlighting the system's reliability. The study also emphasized effective thermal energy storage, contributing to renewable energy advancements. In the final phase, the research will conduct a cost analysis using the fixed-charge rate levelized cost of electricity method, estimating an LCOE of $0.2349/kWh. Comparative analysis suggests opportunities for optimization to enhance competitiveness within the realm of CSP technologies. In essence, this study contributes valuable insights into Gwadar's energy landscape, providing a comprehensive understanding of the technical, economic, and environmental aspects of integrating CSP with molten salt storage. As Gwadar navigates its challenges in electricity provision and overall development, this research sets the stage for informed decision-making and the pursuit of sustainable energy solutions.
Future research for the molten salt-based CSP plant in Gwadar should focus on a detailed study covering the whole process of making molten salt from rock salt and minerals in Balochistan. This study needs to look closely at safety, costs, and environmental impact. Researchers should also explore challenges in making more molten salt, considering safety, special facilities, and expertise for big operations. Making seawater-based molten salt should keep getting better, solving

problems like cost, energy use, and market changes. If it makes economic sense, including costs, salt prices, and help from the government, is a must. Talking with people in Gwadar and Balochistan, solving worries, and getting them on board, plus connecting the CSP plant with the local power system and thinking about policies will help the project succeed.

6 .References

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