Techno-economic and Environmental Impact Assessment of CSP and PV Power Generation for Different Climate Zones

By

Asad Ullah
Reg. No: 00000319325
Session 2019-21

Supervised by
Dr. Mariam Mahmood

A Thesis Submitted to the U.S.-Pakistan Centre for Advanced Studies in Energy in partial fulfillment of the requirements of the degree of

MASTER of SCIENCE in
THERMAL ENERGY ENGINEERING

U.S.-Pakistan Centre for Advanced Studies in Energy (USPCAS-E)
National University of Sciences and Technology (NUST)

H-12, Islamabad 44000, Pakistan

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THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by **Mr. Asad Ullah** (Registration No. **00000319325**), of U.S.-Pakistan Centre for Advanced Studies in Energy has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is within the similarity indices limit and accepted as partial fulfillment for the award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

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This thesis is dedicated to my beloved parents and siblings, who have been a constant source of inspiration and strength and continuously provided their moral, spiritual, and emotional support. I would gladly like to make a special mention of my dear brother, whose words of advice, encouragement, moral and financial support motivated me to move forward throughout my academic years.

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Abstract

In this study, cleaner energy production through two main solar energy technologies is compared from technical, economical, and environmental perspectives. The impact of solar multiple, thermal storage size, and cooling system for CSP, while module type and tracking system for PV is investigated to evaluate the techno-economic performance of power plant. Technical performance is evaluated on energy generation and capacity factors metrics, while economic performance is evaluated on levelized cost, payback period, and net present value metrics. In addition, environmental metrics such as GHG emissions reduction, fossil fuel saved, and life cycle water consumption are evaluated. Initially, 50 MW CSP power plant is modeled and simulated at four selected locations, then the most feasible location for CSP based power plant is compared with a solar PV plant of the same capacity.

From the result, it is concluded that CSP based power plant located at Quetta is technically and economically viable and has a very good potential to mitigate the adverse impacts of climate change by producing clean energy. The capacity factor of the CSP plant is 36.6% as compared to 19.8% for the PV plant, while the solar to electrical efficiency of CSP plant is 14.2% as compared to 20.8% for the PV plant. The land area required to generate energy is 2.77 acres/GWh for CSP and 2.33 acres/GWh for PV plant, while the net capital cost for CSP is 5 times higher than that of PV plant. The optimization of different design parameters is performed to obtain the minimized levelized cost of energy (LCOE) for both CSP and PV plants. Simulation results for CSP and PV plants in Quetta indicate that LCOE can be minimized to 11.57 cents/kWh and 4.69 cents/kWh, respectively. CSP plant has superior annual energy production and capacity factor in comparison to PV plant, while PV plant is superior in terms of project capital cost and levelized cost of energy. Thus, the CSP plant performs better from a technical perspective while the PV plant performs better from an economic perspective.

Keywords: solar power technology, techno-economic evaluation, environmental sustainability, sensitivity analysis, comparative analysis, feasibility study

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List of Abbreviations

AEP	Annual energy production
CF	Capacity factor
CSP	Concentrated solar power
CSTPP	Concentrated solar thermal power plant
DHI	Diffused horizontal irradiance
DNI	Direct normal irradiance
ESMAP	Energy sector management assistance program
GHG	Greenhouse gas
GHI	Global horizontal irradiance
HOMER	Hybrid optimization of multiple energy resources
HTF	Heat transfer fluid
IEA	International Energy Agency
IGCEP	Indicative generation capacity expansion plan
LCOE	Levelized cost of energy
LCC	Life cycle cost
LPG	Liquified petroleum gas
NEPRA	National electric regulatory authority
NPV	Net present value
NASA	National aeronautics and space administration
NREL	National renewable energy laboratory
NSRDB	National solar radiation database
NTDC	National transmission and dispatch company
NOCT	Normal operating cell temperature
PBP	Payback period
PTC	Parabolic trough collector
PV	Photovoltaic
PBS	Pakistan bureau of statistics
PMD	Pakistan meteorological department
SDGs	Sustainable development goals
SAM	System Advisor Model
SEE	Solar-to-electricity efficiency
SM	Solar Multiple

STC	Standard test conditions
tCO_2	tons of CO_2
TES	Thermal Energy Storage
TMY	Typical meteorological year

List of Publications

Journal Papers

Techno-Economic and Environmental Impact Assessment of Concentrated Solar Thermal and PV Systems for Different Climate Zones

Asad Ullah; Mariam Mahmood; Sheeraz Iqbal; Muhammad Bilal Sajid; Zohaib Hassan; Kareem M. AboRasc; Hossam Kotb; Mokhtar Shouran; Bdereddin Abdul Samad

Journal: Energy Reports

Submitted: November 19, 2022

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Chapter 1

Introduction

1.1 Background

Energy is considered the primary driving force of the world's economy and its demand is increasing day by day with the growing population[1] and industrialization. Global energy consumption piled up at a rate of 1.7% per annum in the last decade as shown in Figure 1-1, whereas its demand fell by 4.5% in 2020 due to the impacts of the Covid-19 pandemic [2]. Fossil fuels still remain major energy sources, but they are constantly depleting at a rapid rate. As of 2020, oil continues to hold the largest share of 31.2% of the global energy mix, followed by coal (27.2%), and natural gas (24.7%), whereas renewables have a share of 5.7% of primary energy consumption. The rapid depletion rate and price surge in fossil fuels have led to a worldwide growing trend in adopting renewable energy resources. Thus, it is imperative to expand renewable energy to make certain a robust rebound in global energy demand.

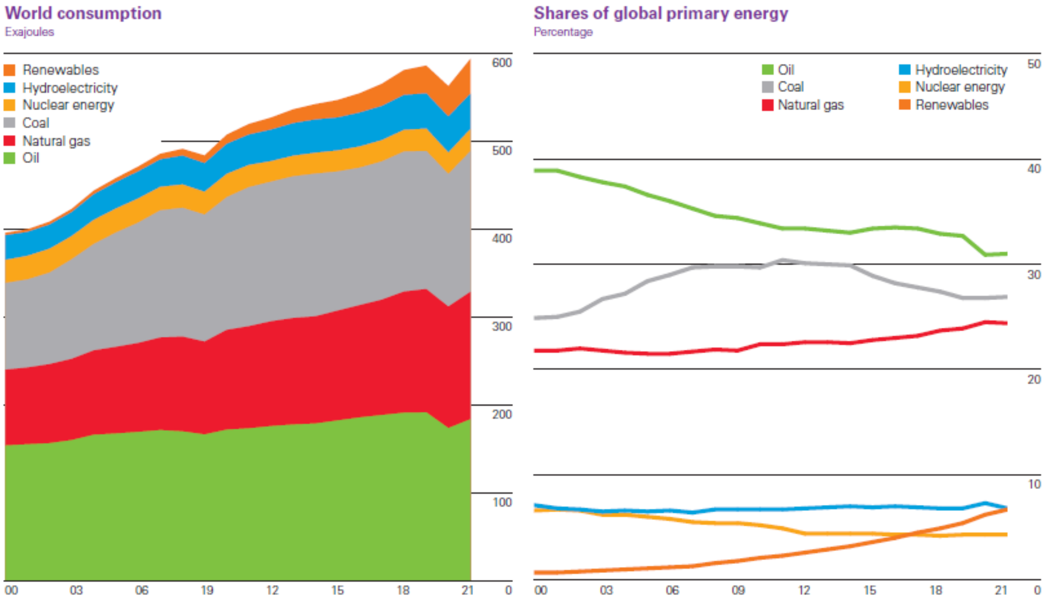

Figure 1-1: World energy consumption and share by primary source [2]

It is also to be noted that as the world plans to move toward a decarbonized transport system to meet its target to slash greenhouse gas (GHG) emissions, Electric Vehicles (EVs) will add 5% to global electricity demand by 2050 [3]. To fulfill the 1.5°C pathway, the electricity sector will have to be completely decarbonized by 2050, thus it is the need of the hour to ramp up renewables [4].

On the other hand, the World is facing severe issues like climate change and carbon dioxide emissions are one of the primary causes of global climate change. To avoid the worst impacts of climate change, the world must reduce emissions urgently. The burning of fossil fuels for energy purposes is one of the main reasons for a large amount of CO_2 emissions. According to a report, fossil-fueled thermal power plants emit about 40% of global CO_2 emissions, which needs to be slashed at a swift rate [5]. Therefore, low-carbon energy production is a strategic priority to address climate change. Figure 1-2 shows that emissions stand at 34.8 gigatons of CO_2 ($gtCO_2$) which needs to be slashed at a swift rate to achieve, the roadmap presented by the International Energy Agency (IEA), Net Zero by 2050 to tackle the global climate challenge [6].

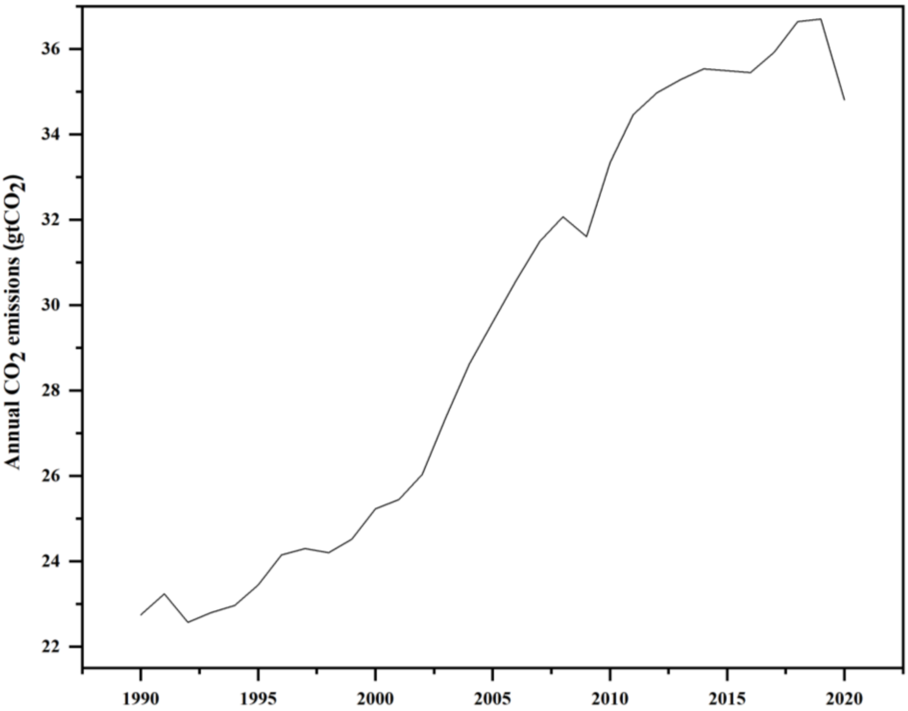

Figure 1-2: Global CO_2 emissions from 1990 to 2020 [7]

Pakistan has figures of 1.08 tons of CO_2 emissions per capita, and its power sector is responsible for 44% of the country's CO_2 emissions [8]. Although these figures are lower than in other south Asian countries, they must be kept low to ensure environmental sustainability. Therefore, it is essential to look for sustainable alternative energy sources to deter climate change and ensure energy security for the world.

1.2 Solar Energy

Among all the renewable energy sources, solar energy is a perfect choice for the future world as it is abundant in nature, freely available, easily affordable, gives better output efficiency, and has no harmful impact on the ecosystem [9]. It can be converted into electric energy by two different methods:

- Direct conversion through photovoltaic (PV)
- Indirect conversion through thermodynamic cycles.

Concentrated solar power (CSP) is a method of producing energy by using mirrors to reflect the heat energy of the sun. The sunlight is reflected, focused, and concentrated by the mirrors into a heat collecting area, where it is subsequently turned to heat. The heat is then used to produce steam, which drives the steam turbine to produce electricity. Because CSP technology has the ability to store heat, this process can be repeated continuously and used on days when there is no sunlight, or during the night.

In the global CSP market, Spain and USA comprise almost two-thirds of global CSP capacity as shown in Figure 1-3. Spain retained the global leader in operational capacity with 2.3 GW at the end of 2020, followed by the USA with nearly 1.7 GW commercially operational CSP power plants. China, Morocco, and South Africa are other major contributors to CSP capacity. According to a report by IEA, average annual generation growth of 31% is required to achieve a Net Zero power generation of 204 TWh from CSP in the current decade. This needs attention on an urgent basis to put CSP on right track with Net Zero Emissions by 2050 Scenario.

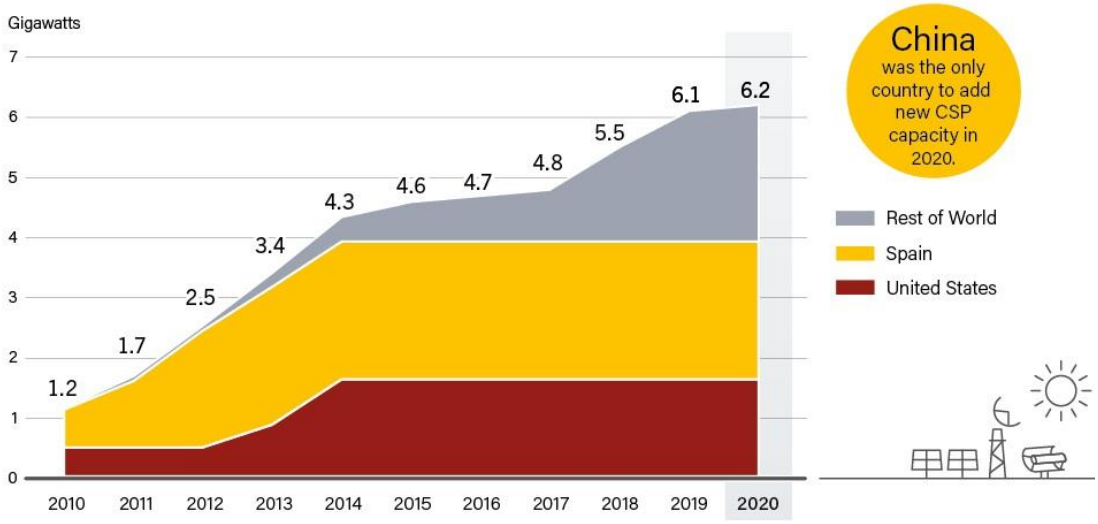

Figure 1-3: Global installed capacity of concentrated solar power (CSP) [10]

Despite the much lower capital cost and other privileges of a PV system, CSP technology has several advantages such as a better capacity factor, equipped with TES to generate electricity during cloudy or after sunset hours, and the capability to integrate with hybrid energy systems. CSP costs fell by 50% during the last decade, and TES equipped CSP systems are installed along PV systems to increase capacity factors and decrease costs [10]. There are four types of CSP technologies that are commercially in use: Parabolic trough collector (PTC), Solar power tower (SPT), Parabolic dish (PD), and Linear fresnel reflector (LFR). Among these, PTC is considered the most mature technology and completely dominates the CSP market. So, parabolic trough technology is selected in this study to evaluate the performance of CSP plants.

The brief introduction of both solar technologies is given below.

1.2.1 Parabolic Trough Collector (PTC) Systems

A parabolic trough is a linear focus solar collector. It consists of a reflector that reflects the incoming solar radiations onto a receiver deployed along the focal line of reflector. The receiver is filled with a heat transfer fluid (HTF) usually molten salt or thermal oil. The reflector follows the sun by mechanism of solar tracking system to maximize the power yield. The diagrammatic representation of parabolic trough collector is shown in Figure 1-4.

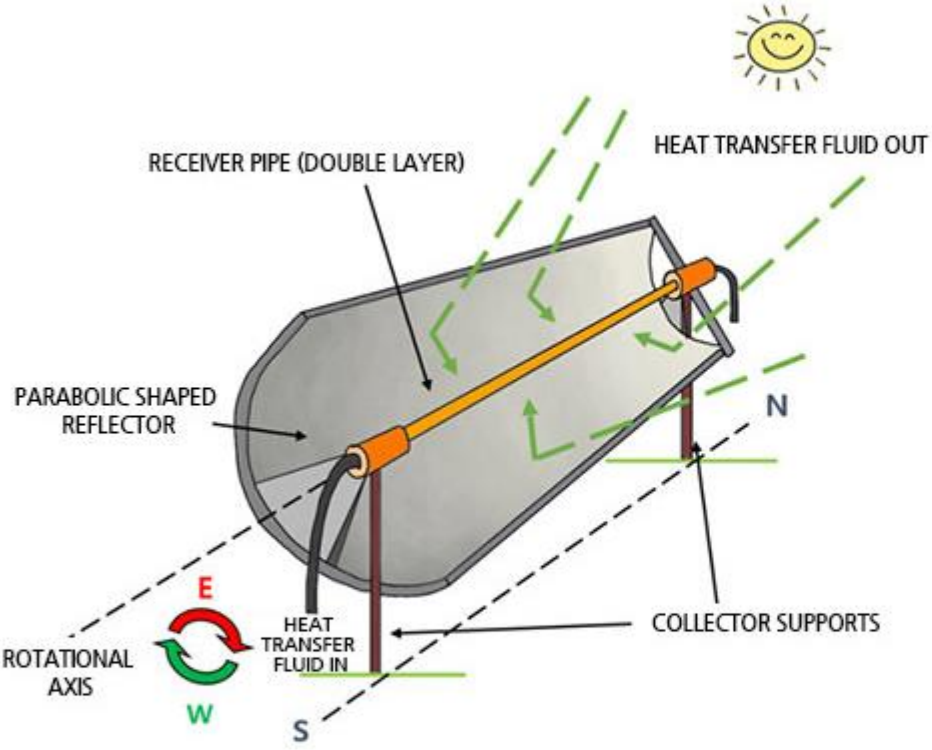

Figure 1-4: Parabolic trough collector system [11]

1.2.2 Solar Photovoltaic (PV) Systems

A solar cell, also known as photovoltaic cell, uses photovoltaic effect to transform sunlight into electrical energy. Photovoltaic modules, also known as solar panels, are made up of these individual solar cells The vast majority of solar cells is made of silicon material as it ranges from non-crystalline to crystalline form.

Solar cell is basically a P-N junction diode that is made up of one or two layers of semiconducting material. When sunlight falls on it, an electric field is created across the layers causing the electricity to flow. The flow of electricity depends upon the intensity of sunlight falling on the cell. The diagrammatic representation of solar photovoltaic plant is shown in Figure 1-5.

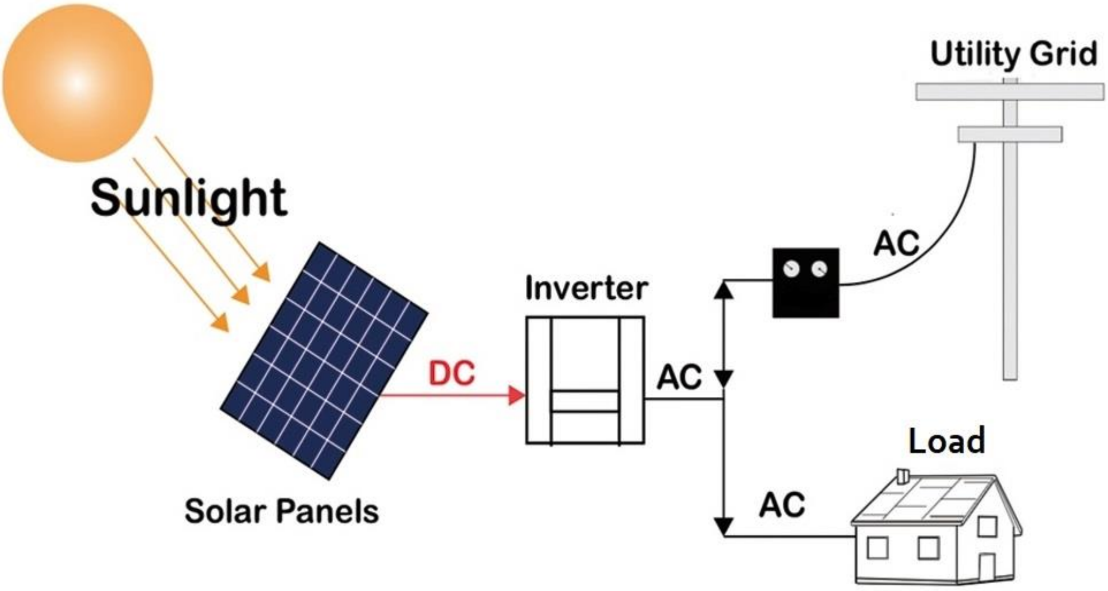

Figure 1-5: Solar photovoltaic (PV) system [12]

1.3 Aims and Motivation

Pakistan is a developing country, where most of its energy demand is met by fossil fuel-based power plants. As an emerging economy, its electricity demand is increasing day by day at a rapid rate. Almost half of the energy is consumed by domestic users while the energy consumption share by the industrial sector is one-fourth as shown in Figure 1-6.

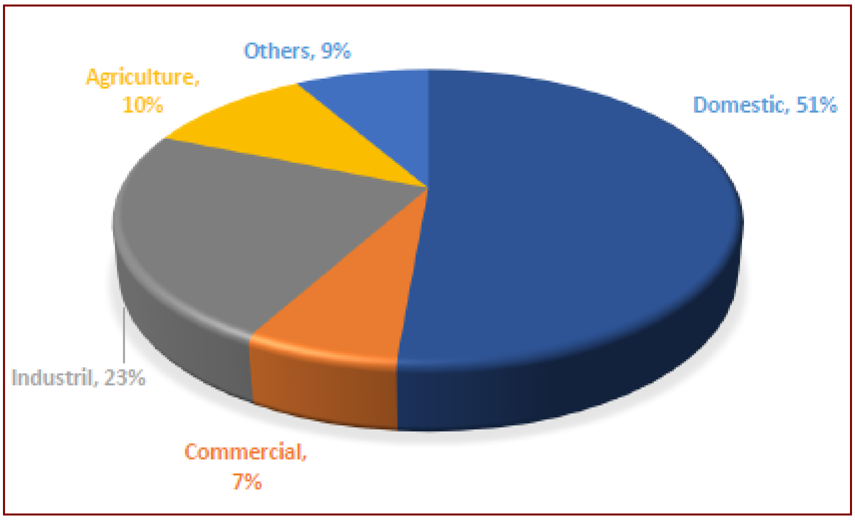

Figure 1-6: Percentage mix category-wise sale of electricity [13]

By the mid of 2021, the total installed capacity of the country reached 34,500 MW of which 66% consists of thermal power plants which comprise local coal, imported coal, natural gas, RLNG, and RFO based technologies as shown in Figure 1-7 [13]**.** A significant proportion of revenue is spent on importing petroleum products for natural gas, coal, RFO, and RLNG based thermal plants. This imported fuel based expensive energy is affecting the progress of various sectors and thus impeding economic growth.

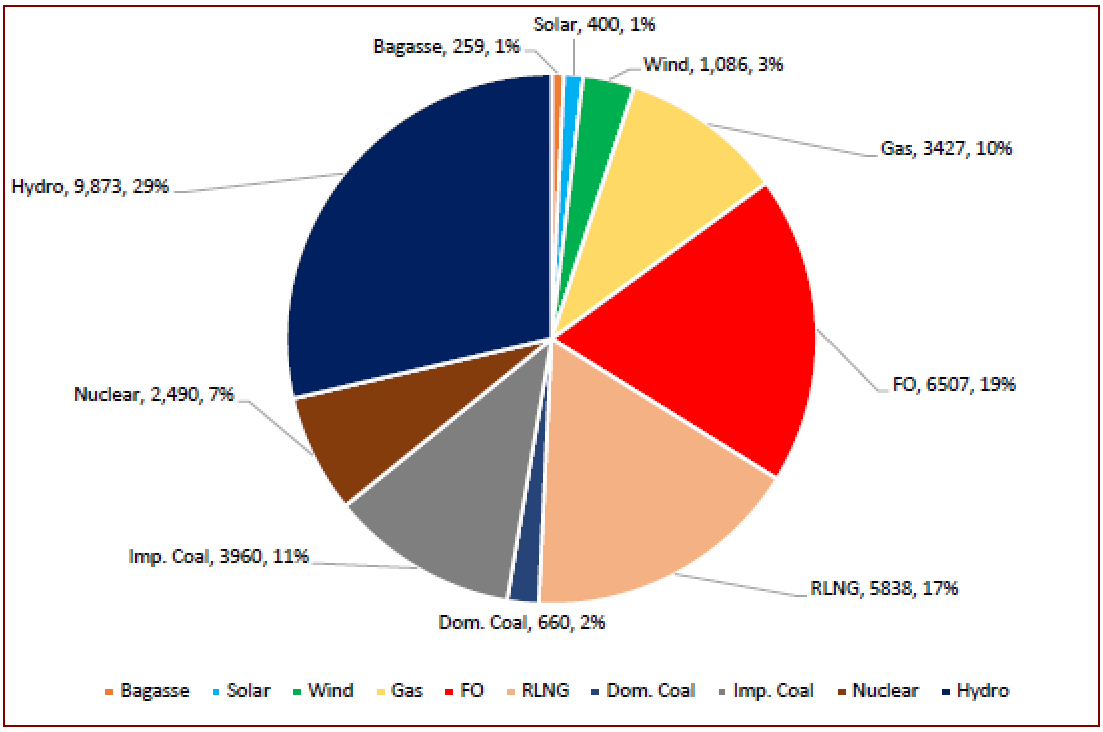

Figure 1-7: Installed capacity of Pakistan as of May 2021 [13]

The energy generation is contributed by approximately 57% by fossil fuels based thermal plants, 32% by hydroelectric plants, 8% by nuclear energy plants, and only 3% by renewable energy projects as shown in Figure 1-8 [13].

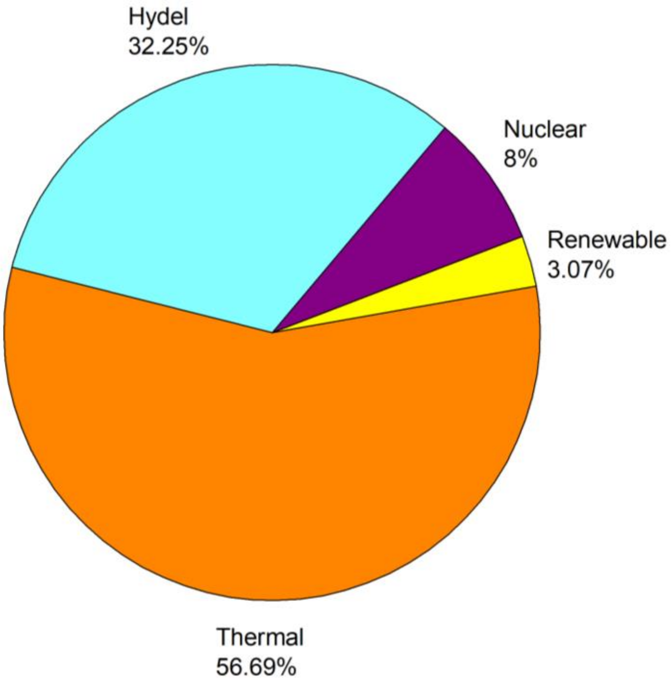

Figure 1-8: The energy-mix scenario of Pakistan [13]

The energy crisis due to dependence on imported petroleum products for power generation and a recent hike in fuel prices in the global oil market has worsened the situation to an extreme extent. To address shortages of fuels and petroleum products along with rising energy prices, the government of Pakistan is attempting to reduce power usage by implementing a five-day work week and limiting the operation hours of large commercial businesses. These steps may be very helpful in reducing energy consumption. However, they have a negative impact on the already sinking economy. Therefore, it is very essential to move towards sustainable alternative energy sources to tackle this issue. So, it is the need of the hour to inject a significant proportion of renewable energy into the country's energy mix. Alternative Energy Development Board (AEDB) proposed an Alternative and Renewable Energy policy (2019) to enhance the share of renewable energy by up to 30% by 2030 [14]. The installation of utility-scale CSP and PV technology will be a momentous milestone to boost the renewable energy sector. It is therefore of vital importance for Pakistan to exploit solar resource potential for power generation purposes.

1.4 Research Objectives

This study aims to evaluate the techno-economic performance and environmental analysis of solar power plants. It carries out parametric optimization to determine minimized LCOE and optimum TES size against each SM with accurate solar field sizing and design point input variables according to reference location. An optimal TES size against each SM is determined on the basis of minimized LCOE. Furthermore, an extensive economic analysis based on realistic cost values, and a financial model considering all kinds of taxes and incentives is presented. Moreover, Environmental analysis is performed on RETScreen to predict GHG reduction and crude oil saved to determine its impact on the environment. In the end, a precise comparison between CSP and PV systems based on performance, financial and environmental perspectives, is drawn to create a baseline scenario and find the pros and cons of both technologies comprehensively.

The main objectives of this research work are:

- To model and simulate 50 MW parabolic trough based CSP plant under different climate zones of Pakistan.
- To evaluate the techno-economic and environmental impact assessment of CSP and PV systems for a suitable location.
- To optimize the different design parameters to minimize the LCOE for both CSP and PV plants.
- To perform a comparative analysis between CSP and PV plants on the basis of various technical, economic, and environmental parameters.

1.5 Organization of thesis

This 1st chapter comprises of introduction about the global energy scenario, share and potential of solar energy, and the aim of this research. Chapter 2 comprises of literature review of both solar technologies from the global and local perspectives. The research methodology for the proposed study is described in detail in Chapter 3. It discusses all the meteorological parameters for site selection and design point technical parameters for system modeling. Furthermore, system cost and financial parameters are discussed in detail for economic analysis. Results analysis and discussion is presented in Chapter 4. In this chapter, an extensive techno-economic evaluation, environmental analysis, sensitivity analysis, and comparative analysis of two solar technologies is described. The last chapter comprises of conclusions and future recommendations.

Summary

Energy is pivotal for accomplishing social, economic, and environmental goals of sustainable human development. The progress of any country relies on the availability of reliable and affordable power to all the people of that country, which is essential for human welfare and economic development. It is a key input for economic development; hence the power industry is an essential part of any economy's infrastructure. Pakistan is dragged into energy crisis due to its huge dependence on fossil fuel-based power plants. Therefore, there is a need to look for alternative and renewable energy sources and solar energy can be considered a potential solution to this energy crisis. The goal of this research is to carry out a techno-economic and environmental assessment and comparative analysis of the two major solar technologies.

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Chapter 2

Literature Review

This chapter discusses the literature and theoretical background of both CSP and PV technologies. It presents a comprehensive review of research previously carried on the topic. This review covers all aspects from meteorological, technical, economical, and environmental perspective. The impact of meteorological and design point parameters on the technical and economic performance of solar technology is studied in detail. Furthermore, environmental analysis is carried out to assess the environmental impact of proposed CSP and PV plants in comparison to conventional fuel-based plants. This is carried out in three folds: concentrated solar power, solar photovoltaic, and studies from perspective of Pakistan.

2.1 CSP Technology

Since parabolic trough is chosen CSP technology in this research because it is the most mature and clearly dominant in CSP global market. So, the literature of CSP technology mostly linked to parabolic trough is studied.

A case study is conducted a decade ago on the use of solar field thermal energy in various low temperature industrial applications to increase efficiency and decrease GHG emissions [1]. However, intermittent behavior of thermal energy is a major challenge to the true potential of solar thermal systems.

Kalogirou [2] thoroughly carried a research study on the receiver thermal model of the parabolic trough collector. He discussed the mechanism of heat transfer and heat losses through the receiver part of parabolic trough system in details. This mathematical model is then solved in an equation solving program named Engineering Equation Solver (EES) and the resulted are validated by well-known performance of collectors tested at Sandia National Laboratories.

A closed-form analytical expressions based mathematical model is formulated on International Energy Agency (IEA) roadmap to determine present LCOE and its future evolution of solar PV and CSP for energy planning policies and future strategies [3]. It is found that solar PV technology should be preferred for medium to high latitude regions while CSP technology is preferable for arid regions with relatively low latitude.

Boukelia et al. [4] performed the optimization of the Parabolic Trough Solar Thermal Power Plants (PTSTPP) in Algeria integrated with Thermal Energy Storage (TES) and fossil fuel backup system (FBS) on two parameters Solar Multiple (SM) and a full load of thermal energy storage (TES), with an objective of minimized LCOE and maximized annual energy yield. A 4E (energy, exergy, economic, and environmental) comparative study alongside Andasol-1 as reference plant is chosen to find the viability of solar thermal plants in different sites of Algeria. The molten salt solar thermal power plants are found to be feasible for semi-arid and arid Algerian locations. A study on the impact of meteorological parameters on the performance of a 50 MW CSP power plant with both (dry and wet) cooling and TES, is carried out under climatic conditions of Tunisia. The highly accurate meteorological data measured from ground station is used for simulation runs and performance is compared with reference plant "Andasol-1" in Spain [5]. The comparative study showed excellent results for both economic and technical parameters of power plant "Andasol-1" if it is shifted to desert region of Tunisia.

In neighboring India, a study is carried out to evaluate the techno-economic potential of CSP systems on the basis of solar and land resource assessment across the country to identify suitable locations for CSP projects [6]. The terrain features, solar resource data and wind power density of under study geographic area were considered decisive parameters to assess the potential of CSP systems. It is found that geographic areas with annual DNI exceeding 1800 kWh/m^2 are economically feasible for deploying CSP technologies. Bishoyi & Sudhakar [7] modelled a 100 MW parabolic trough solar thermal power plant with thermal energy storage in SAM and carried simulation to analyze its performance to determine the economic viability of the project. The simulation results provided a hint to assess the performance and potential of solar thermal power plants.

Kassem et al. [8] conducted an extensive SWOT analysis for each CSP technology in the context of Saudi Arabia and incorporated the analysis outcomes to assess the technical and financial performance of potential CSP scenarios. These potential scenarios were created by altering collection technology, solar thermal receivers, loop configuration, heat transfer fluids, thermal storage size and plant capacity. The analysis disclosed that CSP is most mature and widely adopted in CSP projects around the globe. Belgasim et al. [9] discussed the potential of different types of CSP technologies from socio-economic perspective and energy scenario of Libya. He evaluated the impact of various site parameters such as solar resource data, land topography, water resources and grid connectivity on the thermos-economic performance and implementation of parabolic trough plant.

A small-scale version of the Solana power plant is emulated and analyzed for two different locations of Jordan in System Advisor Model (SAM), and results are validated from the measured data of existing plants [10]. The location with suitable combination of DNI, dry bulb temperature and relative humidity throughout the year performed better in terms of energy generation.

Crespi et al. [11] analyzed the impact of pressure ratio and turbine inlet temperature on thermal efficiency and work output of the supercritical carbon dioxide (sCO_2) power cycle to assess its potential for CSP applications. These sCO_2 power cycles have the ability to achieve higher thermal efficiency at intermediate temperature.

2.2 PV Technology

Since the regions that lie near the equator contain huge potential of solar energy technologies. However, the relevant authorities need to introduce tax incentives to encourage handsome investment in energy sector. The targeted subsidies and consumer friendly policies can change the viewpoint of power sector investors towards the alternative and renewable energy resources [12].

Mukisa et al. [13] proposed a technique to determine the rooftop area preferable for solar PV installation and its orientation, moreover, he investigated the impact of loan period and loan share on grid connected solar PV project feasibility. The findings indicate that if loan period is relatively shorter then the loan share can be higher for the project to stay in economically feasible range. Akhter et al. [14] evaluated the performance characteristics of a composite PV system based on three different PV technologies (m-Si, p-Si, and a-Si) for tropical climate regions. The comprehensive analysis of various performance parameters showed that p-si based PV modules performed better in terms of energy yield and degradation rate. Alshare et al. [15]

compared the actual performance with simulated results of a 5 MW photovoltaic system to correlate its performance parameters to the climatic conditions such as solar irradiance, ambient temperature and wind speed of a particular geographic area in Jordan.

An analysis is conducted on 10 kW polycrystalline silicon PV system to assess its potential and evaluate its performance for two remote islands [16]. The PV system was considered feasible for the locations with daily global horizontal irradiance of 5.07-5.30 kWh/m^2 and its LCOE was found to be much lower than diesel generator system. Oloya et al. [17] analyzed the performance of utility-scale solar PV system for Uganda and determined the economic viability of the projet though different feed-in-tariff scenarios. The results suggested that relatively lower discount rate paves a way to the economic viability of the PV project. Agyekum [18] presented a detailed techno-economic comparative analysis of two different solar PV systems with tracking systems under three different climatic conditions of Ghana. The sensitivity analysis indicted that tracking system had significant impact on the performance of PV systems.

2.3 Solar Technology from perspective of Pakistan

Pakistan has an enormous potential for solar power due to its geographic location as it lies near the equator. Even though there are plenty of studies are already carried out for renewable energy systems but there are still vital areas to investigate the system performance in context of Pakistan. In a study to assess the wind and solar potential in the region of Multan, the electrical energy output of a typical wind system is found to be very low compared to both PV and PTC systems [19], whereas PTC and PV systems are found to be feasible based on the calculated LCOE. Besides that, east-west tracking system showed better performance than north-south tracking for solar resources.

Soomro et al. [20] investigated the potential, performance, and economic evaluation of all four types of CSP technologies for different locations in Pakistan. Potential assessment is undertaken on the basis of solar resource data, land topography, and availability of water resources. Parabolic trough and solar power tower were found to be feasible among all the CSP technologies and their performance was extraordinary during summer season.

Tahir et al. [21] performed a techno-economic analysis of concentrated solar thermal power for different potential sites with the objective function of minimized LCOE and presented a policy framework to address the major potential barriers to its implementation in detail. These potential sites were chosen on the basis of feasible infrastructure required for CSP plants.

Due to the recent decrease in solar Photovoltaic (PV) costs, Pakistan is moving towards solar power solutions for both on-grid and off-grid systems. Shabbir et al. [22] carried out a study on the solar irradiance behavior and computation of the PV module’s optimum tilt angle for maximum energy yield in Pakistan. The study also covered the economic analysis of domestic PV systems and its impact on national grid. Khalid & Junaidi [23] assessed the feasibility of photovoltaic (PV) based power plants for eight dfferent sites and Quetta emerged as potential site for PV based power plant in Pakistan through the outcome of this study. He modeled a 10 MW PV plant at potential site and performed the sensitivity analysis to assess the economic viability of the plant with different modes of array orientation.

Ali & Khan [24] simulated two 42 kW PV rooftop systems and compared their techno-economic performance with actual measured data of installed systems. The study indicates that lowering cost of PV systems makes it commercially viable for Pakistan. Ahmed et al. [25] evaluated the techno-economic performance of PV plants for different climatic zones of Pakistan. It is found that PV power plants were feasible from technical and economic perspective in all climatic zones and Quetta was most feasible site to set up a PV plant due to its high solar potential.

Summary

This chapter includes literature review about the working and performance of solar technology. The overview of previously published work on solar PV and CSP is presented in this chapter. All the constraints need to be considered for modeling a solar technology plant and their effect on the feasibility of project is studied in detail from published work.

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Chapter 3

Research Methodology

The methodology framework for the techno-economic analysis and environment sustainability assessment of CSP and PV plants at selected sites is described in this chapter. For this purpose, power plants modeling and simulation is performed on System Advisor Model (SAM).

SAM is an hourly based simulation tool that determines energy output, tariff, and cash flow based on performance, cost, and financial model interaction. SAM presents a framework that can be used to analyze and compare the performance and cost of power systems for a variety of renewable technologies and markets. Many engineers, technology researchers, project managers, and policy analysts avail themselves of this software to make decisions regarding the feasibility and viability of renewable energy projects.

In this study, CSP based power plant is modeled on SAM. Initially, four different locations are selected on basis of climate zones. CSP based power plant is designed, modeled, and simulated for a period of one year. Parametric analysis is done on the basis of various input parameters such as SM, TES, loop inlet/outlet temperature, and turbine output fraction to get maximized AEP with minimized LCOE. The most feasible location for CSP based power plant is compared with PV system of same capacity. In the end, CSP and PV plants for most feasible site are compared from technical, economic, and environmental perspective. Figure 3-1 shows the framework of approach that has been adopted in this research work.

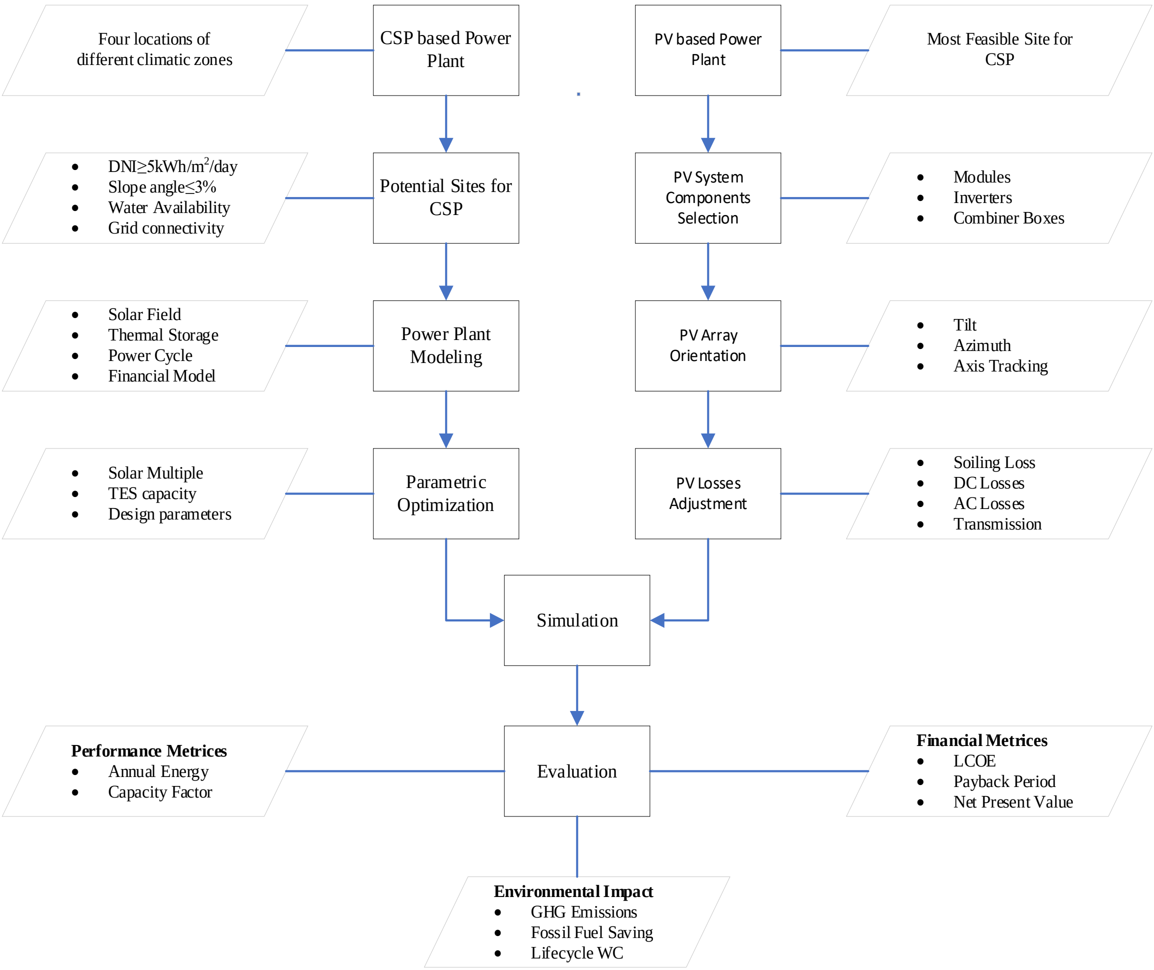

Figure 3-1: Research methodology flowchart for CSP and PV plants deployment

3.1 CSP Modeling

Three main components of concentrated solar thermal power plants as shown in Figure 3.2 are solar field, thermal storage, and power block. The design point parameters of these components are discussed in the following sections, while all the remaining technical parameters are described in **Error! Reference source not found.**-5. The s tep-by-step plant modeling procedure to simulate it for one year to analyze its performance is shown in the Figure 3-3.

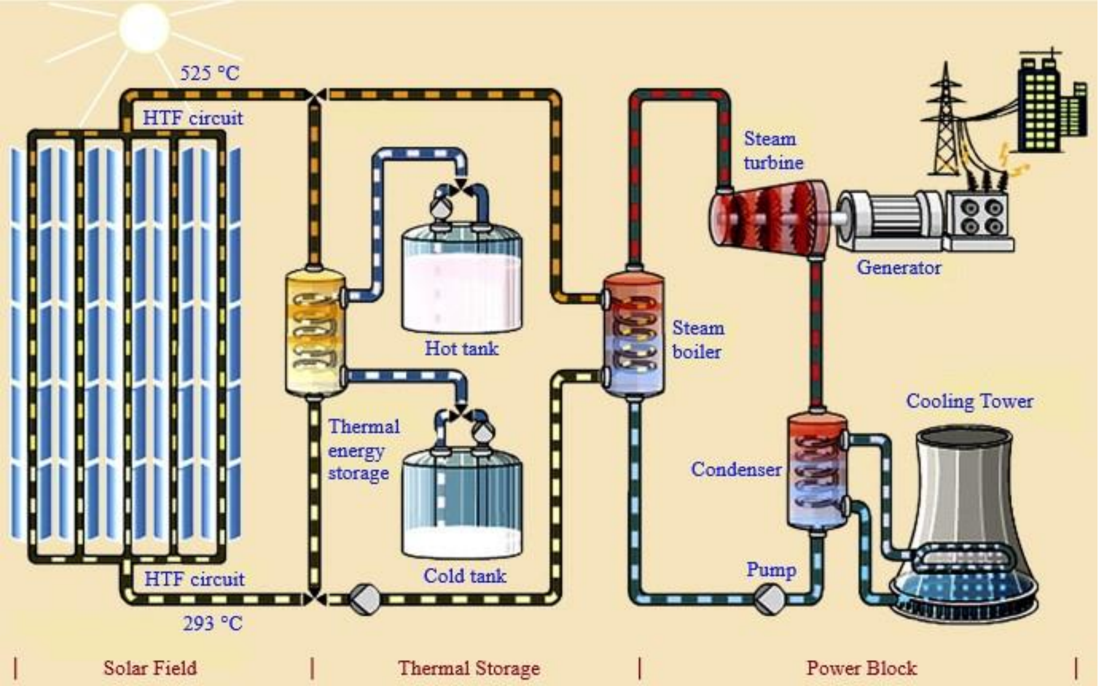

Figure 3-2: Structure of a concentrated solar power plant [1]

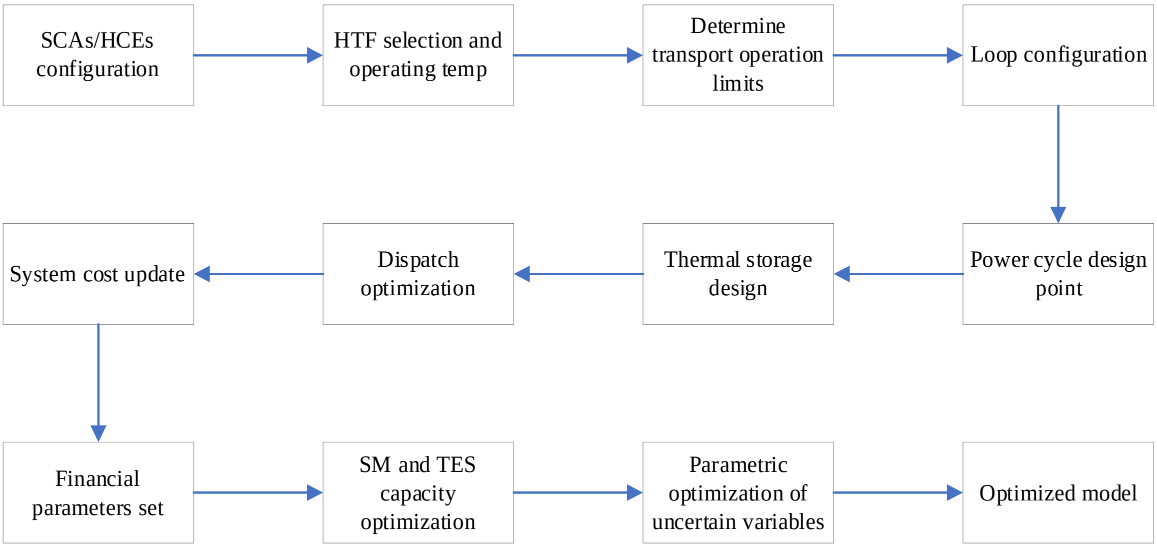

Figure 3-3: CSP plant modeling procedure in SAM

3.1.1 Meteorological Data

The climatic conditions play pivotal role in the performance of solar thermal power plants. The required meteorological data to analyze and simulate the performance of solar thermal power plants are solar irradiation, ambient temperature, wind speed, air pressure, and relative humidity. Moreover, dry-bulb and wet-bulb temperatures data is required to model and compare the performance of dry and wet cooling systems for CSP power plants. Air-cooled condensers work on dry-bulb temperature while evaporative condensers work on wet-bulb temperature The solar energy that is incident on horizontal surface, can also be referred as Global Horizontal Irradiance (GHI), comprises of direct normal irradiance (DNI) and diffused horizontal irradiance (DHI). DNI is essentially focused by CSP technology to produce thermal energy while GHI is focused by PV technology to generate electricity. Hence, reliable solar resource data across the country is essential for evaluating the feasibility of concentrated solar thermal plants. The National Renewable Energy Laboratory (NREL) created satellite based solar resource mapping for Pakistan under South Asia Regional Initiative for Energy Integration. The Energy Sector Management Assistance Program (ESMAP) also developed solar resource mapping of country, however this data is validated by ground measurements. These both resources indicate that Pakistan has high potential of deploying CSP technology across the country, especially in northwestern Baluchistan. Figure 3-4 and Figure 3-5 show the average monthly variation in DNI and number of sunshine hours of selected sites for CSP deployment, respectively. While Figure 3-7 and Figure 3-8 show the monthly variation in ambient temperature and wind speed for four selected sites The remaining essential meteorological data is obtained from Pakistan Meteorological Department (PMD).

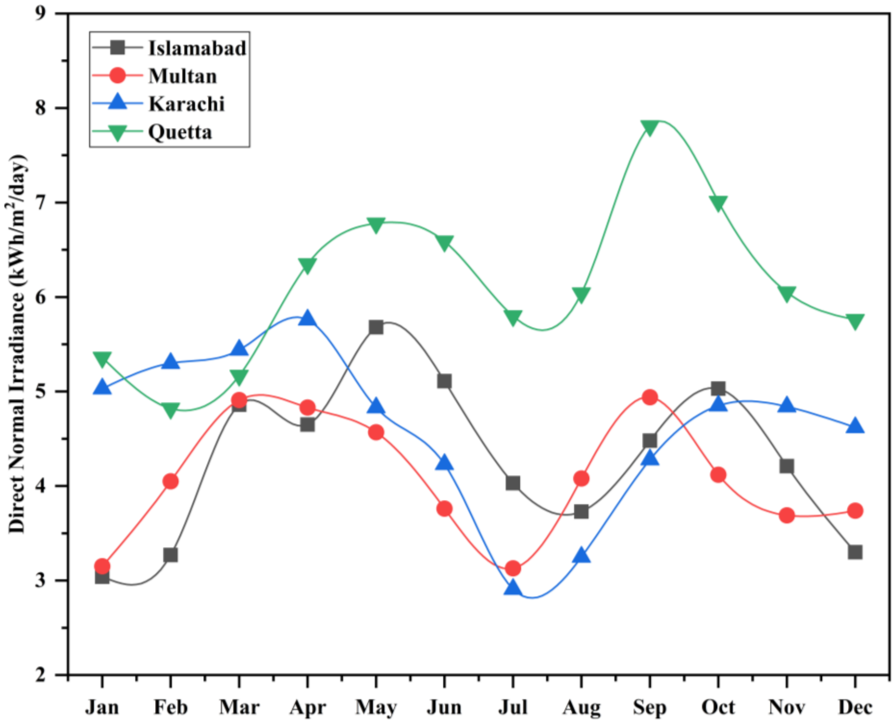

Figure 3-4: Monthly average direct normal irradiance (DNI) of selected sites

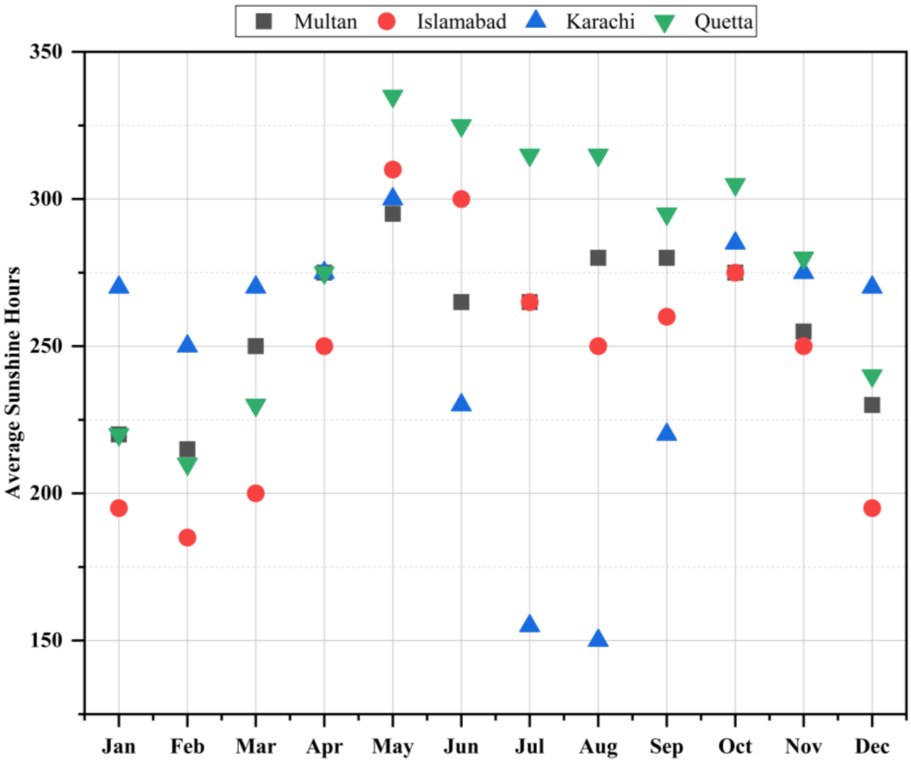

Figure 3-5: Monthly average sunshine hours of selected sites

3.1.2 Site Selection

The first step towards building a CSP based power plant is site selection. Literature suggests that CSP based power generation is technically and economically feasible for locations receiving DNI greater than 1800 kWh/m^2/year (DNI ≥ 5 kWh/m^2/day). World Bank launched ESMAP to help developing countries to alleviate poverty and boost growth rate via sustainable energy solutions. Under this program, Renewable Energy Resource Mapping Initiative is launched to map renewable energy resources of Pakistan. This mapping indicates that 83% area of the country exceeds DNI threshold of 2000 kWh/m^2/year, while peak DNI values, surpassing 2700 kWh/m^2/year, can be observed in northwestern part of Baluchistan [2] as shown in Figure 3-6. Secondly, there should be vast barren land with no or less than 3% slope angle as it has a significant impact on output of CSP based power generation system. Through collection of the National Solar Radiation Database (NSRDB), A Typical Meteorological Year (TMY) data of the selected site is used to evaluate the performance of concentrated solar thermal power plants (CSTPP). TMY file contains hourly meteorological data of one year that perfectly represents median weather conditions over a longer period. These selected sites receive 7–11 sunshine hours throughout the year. The coordinates and climate description of selected sites is described in Table 3-1. There are lots of other considerable factors such as appropriate infrastructure, water availability and grid connectivity.

Table 3-1

Coordinates and climate description of selected sites

Location	Latitude	Longitude	Annual DNI (kWh/m^2)	Ambient temp (°C)	Climate zone
Islamabad	33.65° N	73.05° E	1565.41	23.8	Sub-mountains with mild cold climate
Multan	30.15° N	71.45° E	1488.98	29.1	Dry and hot region with arid climate
Karachi	24.85 °N	67.05° E	1681.19	27.6	Coastal area with warm humid sub-tropical climate
Quetta	30.15 °N	67.01 °E	2238.94	18.9	High elevation with cold semi-arid climate

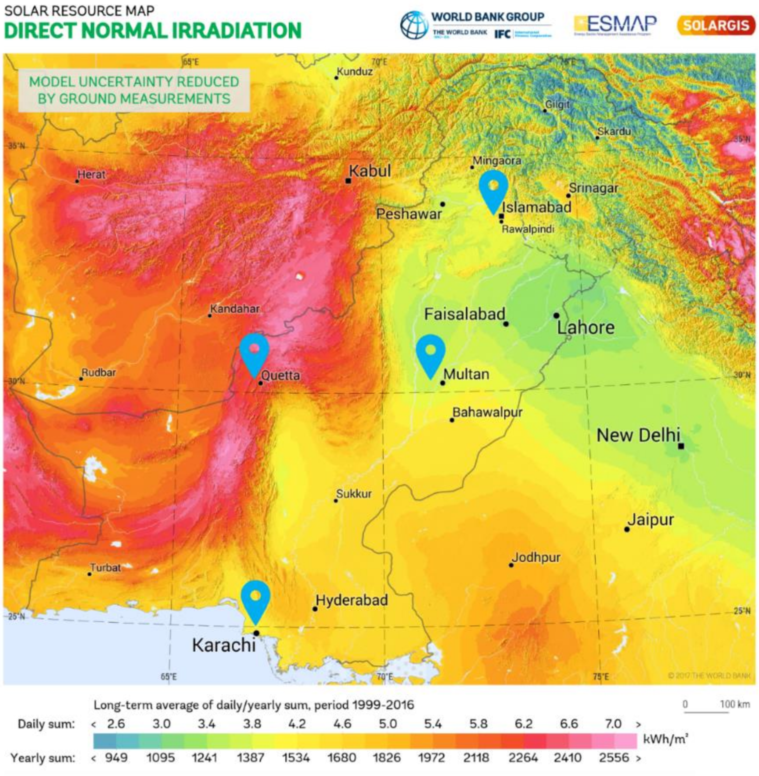

Figure 3-6: Direct Normal Irradiance (DNI) solar map of Pakistan [3]

3.1.3 Solar Field Sizing

The solar field is the heat-collecting section of the plant that comprises of parallel loops of solar collector assemblies (SCAs) that focus the sunlight onto heat collection elements (HCEs). A common header pipe supplies each loop with an equal amount of flow rate of HTF, and another header pipe collects the hot HTF to deliver it either directly to the power cycle for power generation or to the TES system for later use. The solar field is usually divided into multiple sections to minimize pumping pressure losses. In this study, SCAs of SkyFuel SkyTrough and HCEs of Schott PTR70 2008 are used for power plant modeling. Each loop consists of 8 SCAs and HCEs. All the SCAs contain same type of collectors and, are assigned same type of receivers with no variation. The properties of collectors are shown in Table 3-2, while optical properties of receiver and glass envelope are shown in Table 3-3.

Table 3-2

Collector geometry and optical parameters

Parameter	Value
Name	SkyFuel SkyTrough
Aperture area	656 m^2
Aperture width	6 m
Length of collector assembly	115 m
Surface-to-focus path length	2.15 m
Assemblies piping distance	1 m
Modules per assembly	8
Tracking error	0.988
Geometry effects	0.952
Mirror reflectance	0.93
Dirt on mirror	0.97

Table 3-3

Receiver and envelope properties

Parameter	Value
Name	Schott PTR70 2008
Absorber tube inner diameter	0.066 m
Absorber tube outer diameter	0.07 m
Glass envelope inner diameter	0.115 m
Glass envelope outer diameter	0.12 m
Absorber material type	304L
Absorber absorptance	0.96
Envelope absorptance	0.02
Envelope emittance	0.86
Envelope transmittance	0.963
Bellows shadowing	0.96
Dirt on receiver	0.98

An optimal solar field size is one that maximizes the time over a year that it generates enough thermal energy to run the power block at its rated capacity, minimizes the capital and operating cost and utilizes the thermal energy storage effectively. Irradiation at design point determines the solar field size. Using too low reference DNI results in excessive dumped energy while using too high results in undersized solar field which is unable to meet the rated capacity of power block most of the time.

3.1.4 HTF Selection

Two most commonly used HTFs in concentrated solar power generation are HITEC Solar Salt and Therminol VP-1. Their properties are described in Table 3.4

Table 3-4

Properties of potential HTFs for concentrated solar thermal power generation [4]

HTF	Min. Temp (°C)	Max. Temp (°C)	Specific Heat (KJ/Kg °C)	Density (Kg/m^3)
Hitec Solar Salt	238	593	1.561	1790.2
Therminol VP-1	12	400	1.532	1067.6

Hitec Solar Salt is a ternary mixture of 53% KNO_3, 40% $NaNO_2$, and 7% $NaNO_3$. Hitec Solar Salt having higher operating temperature and thermal conductivity, being more energy-dense, less viscous, non-toxic, and lower cost than thermal oil makes it suitable for HTF. The HTF with lower freezing temperature causes lower thermal energy losses [5]. Loop outlet temperature is controlled by either HTF mass flow rate, velocity or by varying SCAs in loop. The loop mass flow rate and velocity of HTF are calculated from Eq. (1) and Eq. (2), respectively.

$$\dot{m} = \frac{A_{SCA}\eta_{abs}N_{SCA}I_b}{C_P \Delta T} \tag{1}$$

$$v = \frac{4\dot{m}}{\rho.\pi.{D_{abs}}^2} \tag{2}$$

Where,

$\dot{m}$ = mass flow rate in single loop

v = Velocity of HTF in single loop

A_{SCA} = Reflective area of solar collector

η_{abs} = Absorber efficiency

N_{SCA} = Number of solar collector assemblies

I_b = DNI at design point

C_P = Specific heat

ΔT = Temperature rise across the loop

ρ = Density of fluid

D_{abs} = Absorber inner diameter

3.1.5 TES Design

Renewable energy power plants are subject to weather transitions, this urges the need of energy storage. CSP technology can store energy cost-effectively in TES that can be used during cloudy and peak demand hours. TES is an essential key component of CSP technology to improve its reliability, dispatchability and efficiency. TES consists of three main parts: a storage tank, a storage medium and a heat transfer mechanism. Sensible heat storage (SHS) is most widely used in utility scale CSP plants due to its low cost, straightforward method, reliability, and experimental feedbacks. SAM models two-tank TES system; one to store hot fluid while the other to collect cold fluid. Using same fluid as HTF and storage medium, avoids from complexity of an extra heat exchanger.

3.1.6 Power Block

The power block subsystem converts thermal energy from the solar field into electrical or mechanical energy. It works on superheated steam Rankine cycle with feed water heating and implements statistical design of experiments (DOE) approach to determine the cycle behavior[6]. This power cycle unit can either be stand alone or integrated with combined cycle to either offset fossil fuel usage [7] or boost power [8]. The thermal efficiency of the power block is linked to the inlet temperature of the Rankine cycle. The required mass flow rate of working fluid to run power block at its rated capacity is calculated from Equ. (3)

$$\dot{m} = \frac{Q}{C_P \Delta T} \tag{3}$$

Where,

$\dot{m}$ = Working fluid mass flow rate

Q = Cycle thermal power

C_P = Average specific heat of working fluid

ΔT = Temperature difference between turbine inlet and outlet

Table 3-5

Design point and technical parameters to set up the CSP plant

Parameter	Value	Parameter	Value
Location and Resource		Modules per assembly	8
Location	Quetta	**Receivers (HCEs)**	
Latitude & Longitude	30.18°N,66.98°E	Receivers	Schott PTR70 2008
Average DNI	6.13 kWh/m^2/day	Absorber tube inner diameter	0.066 m
Average Temperature	18.9 °C	Absorber tube outer diameter	0.07 m
System Design		Glass envelope inner diameter	0.115 m
Solar Multiple	2	Glass envelope outer diameter	0.12 m
Cycle thermal power	156 MWt	Internal surface roughness	4.5e-05
Field thermal power	312 MWt	Absorber flow pattern	Tubular flow
Design point DNI	850 W/m^2	Absorber material type	304L
Loop inlet HTF temperature	293 °C	Annulus gas type	Hydrogen
Loop outlet HTF temperature	525 °C	Annulus pressure	0.0001 torr
Solar Field		**Thermal Storage**	
Row spacing	15 m	Storage HTF fluid	Hitec Solar Salt
Stow angle	170°	Full load hours of TES	6
Deploy angle	10°	Storage volume	5241.4 m^3
Water usage for wash	0.7 L/m^2	Parallel tank pairs	1
Washes per year	63	Cold tank heater set point	250 °C
HTF pump efficiency	0.85	Hot tank heater set point	365 °C
Actual number of loops	98	**Power Cycle**	
Single loop aperture area	5248 m^2	Cycle gross output	55.5 MW
Total aperture reflective area	514304 m^2	Gross to net conversion factor	0.9
SCA/HCE assemblies per loop	8	Estimated net output	50 MWe
Total land area	445 acres	Cycle thermal efficiency	0.356
Heat Transfer Fluid (HTF)		HTF hot temperature	525 °C
Heat transfer fluid	Hitec Solar Salt	HTF cold temperature	293 °C
Field HTF min temp.	238 °C	Boiler operating pressure	100 bar
Field HTF max temp.	593 °C	Condenser type	Air-cooled
Freeze protection temp.	150 °C	ITD at design point	16 °C
Min single loop flow rate	1 Kg/s	Min turbine operation	0.2
Max single loop flow rate	12 Kg/s	Max turbine operation	1.25
Header min flow velocity	2 m/s	**Parasitic Losses**	
Header max flow velocity	3 m/s	Piping thermal loss coefficient	0.45 W/m^2-K
Collectors (SCAs)		Wetted loss coefficient	0.4 Wt/m^2-K
Collectors	SkyFuel SkyTrough	Gross power consumed	0.0055 MWe
Reflective aperture area	656 m^2	Balance of plant parasitic	0.02467 MWe
Aperture width	6 m	Aux heater boiler parasitic	0.02273 Mwe

3.2 PV Modeling

Global Horizontal Irradiance (GHI) is considered the one of the major indicators to assess the potential of a site for the installation of PV systems. GHI is the total solar irradiance above a horizontal surface. It is a summation of both direct normal irradiance (DNI), atmospheric diffuse horizontal irradiance (DHI), and ground reflected radiations. The ambient temperature and wind speed play a critical role in the performance of a PV system. The required data for plant modeling such as ambient temperature is shown in Fig. 3.7 and wind speed is shown in Fig. 3.8

Solar photovoltaic system of 50 MW nominal power is modeled in SAM at most feasible location for CSP power plant. It is installed at latitude and longitude of 30.15° N and 67.01° E, respectively. The required GHI data is obtained from NRSDB, while wind speed and ambient temperature are provided by PMD.

The following steps are taken for modeling of PV plant in simulation tool

- Select the location for installation of PV plant
- Import weather data resources such as solar irradiance, ambient temperature, and wind speed
- Select PV system components like modules and inverters according to the requirement of the system.
- Define module tracking and orientation such as type of axis tracking, tilt, and azimuth angles
- Adjust different types of system losses such as shading, soiling, nameplate, mismatch, tracking, wiring and transmission.
- Put all system cost values from direct to indirect capital costs, operation and maintenance costs
- Introduce finanacial parameters such as taxes and incentives

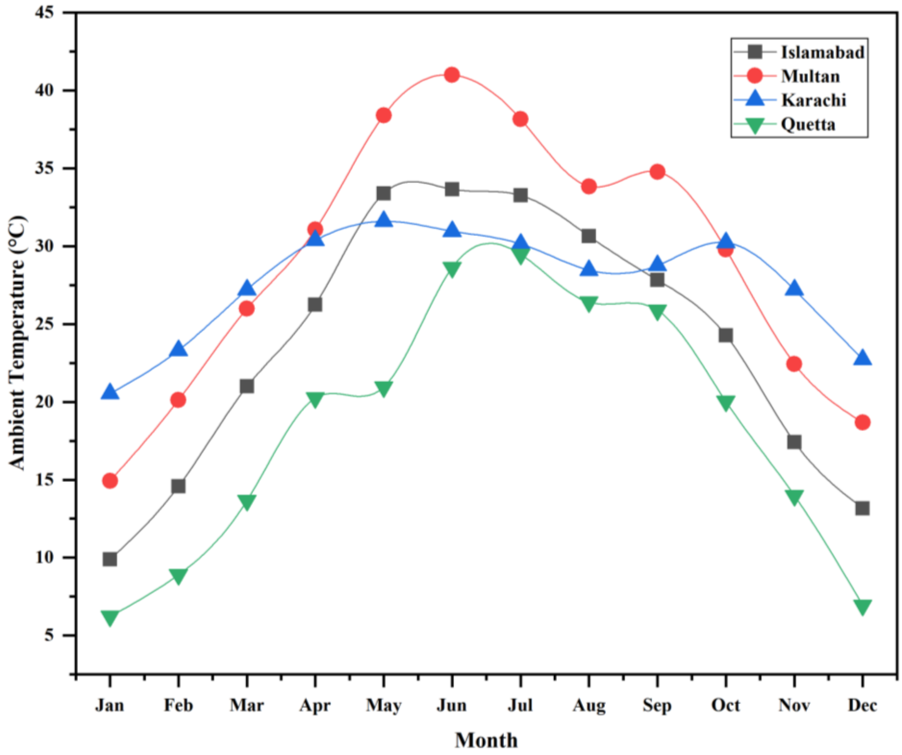

Figure 3-7: Monthly average ambient temperature of selected sites

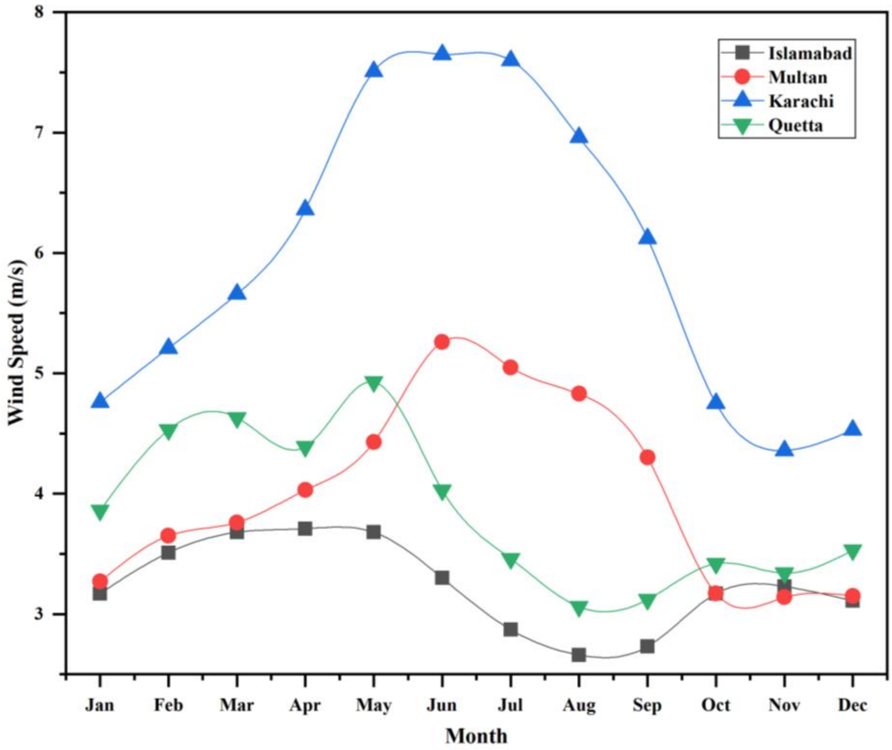

Figure 3-8: Monthly average wind speed of selected sites

3.2.1 PV System Description

PV system consists of 124,896 monocrystalline silicon modules of Jinko solar with each rated power of 400 W_{dc} and 678 inverters of SMA America with each maximum AC power of 62500 W_{ac}. The nominal efficiency of each module is 20.85% at standard test conditions (STC) of 1000 W/m^2 solar irradiance and 25 °C cell temperature, as shown in the IV characteristic curve in Figure 3-9. The weighted efficiency of each inverter is 98.434% and its graph at rapid power output percentage is shown in Figure 3-10. The PV system module and inverter properties are described in Table 3-6 and 3-7, respectively.

Table 3-6

PV plant module properties

Parameter	Value
Jinko Solar Co. Ltd.	JKM400M-72L
Technology	Mono-c-Si
Maximum Power (Pmax)	400.32 W_{dc}
Nominal efficiency	20.85 %
Operating temp	-40°C~+85°C
NOCT	45±2°C
Dimensions	2008 × 1002 ×40 mm
V_{mp}	41.7 V
I_{mp}	9.6 A
V_{oc}	49.8 V
I_{sc}	10.36 A
Temp coefficient at Pmax	-0.406 %/°C
Temp coefficient of Voc	-0.311 %/°C
Temp coefficient of Isc	0.067 %/°C

Table 3-7

PV plant inverter properties

Parameter	Value
SMA America	STP 60-US-10 [480V]
Weighted Efficiency	98.434 %
Maximum AC Power	60000 W_{ac}
Maximum DC Power	60974.6 W_{dc}
Nominal AC voltage	480 Vac

Nominal DC voltage	710 Vdc
Maximum DC voltage	800 Vdc
Maximum DC current	85.879 A_{dc}

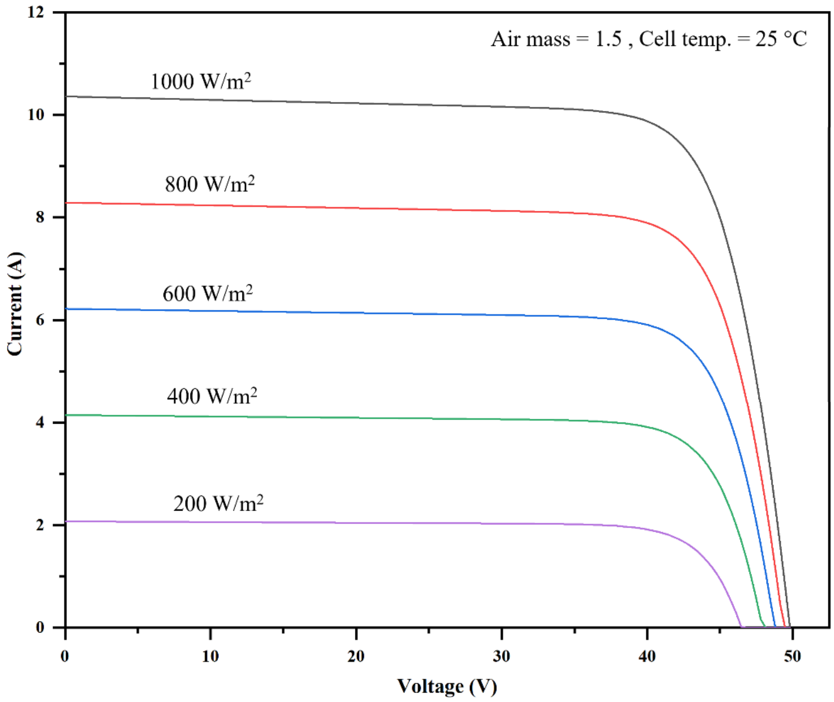

Figure 3-9: Module IV characteristic curve at STC

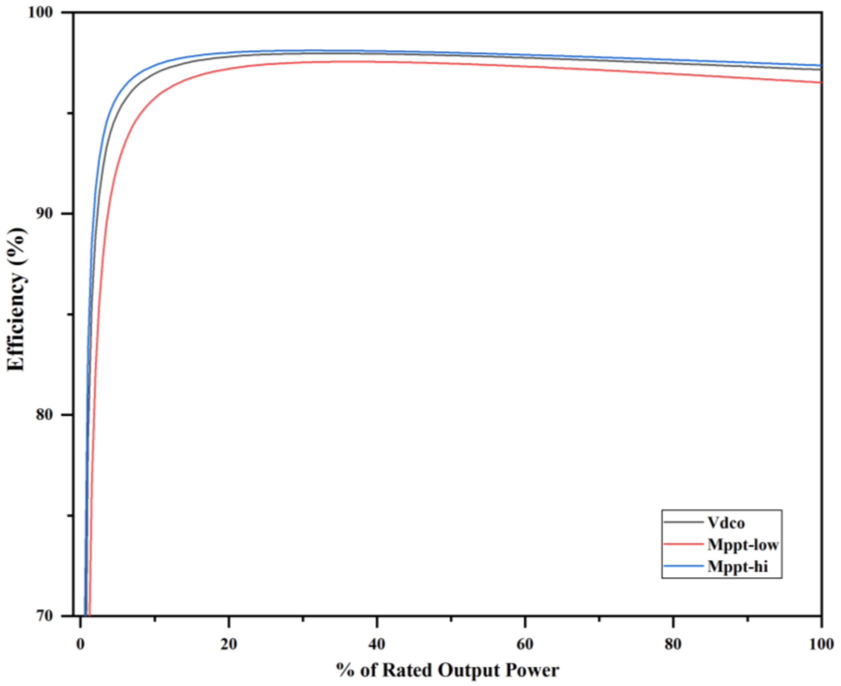

Figure 3-10: Inverter efficiency at rated power output percentage

3.2.2 PV Field Description

There are 7,806 strings in parallel with each string consists of 16 modules. Modules are connected in series to increase the voltage up to minimum operating requirement while strings are connected in parallel using a combiner box to meet the current requirement. As Pakistan is located in the northern hemisphere, the parallel PV arrays are placed in east-west orientation with due south facing (Azimuth 180°) at which PV systems have maximum annual energy yield. The parametric simulation is run to find the optimum tilt angle for PV field. The azimuth angle of 180° for facing true south and tilt angle of 31° are selected to evaluate the performance of PV system. In case of tracking system, EW tracking performs better than NS tracking for solar irradiance in Pakistan [9].

3.2.3 PV Performance Parameters

International Energy Agency (IEA) has established PV system performance parameters, which are described in IEC standard 61724, are utilized in this study to evaluate the operational and reliability performance of grid-connected PV system. These parameters include energy output, energy yields, system efficiency, array capture loss, capacity factor (CF), and performance ratio (PR). These parameters provide a way to assess system performance under different operating conditions. All the concerning PV system performance parameters are defined in Table 3-8.

The output of PV module depends on solar irradiance and temperature, is calculated from Equ. (4)

$$P_{PV,out} = P_{NP} f_{PV} \times \left(\frac{G_T}{1000}\right) \times [1 + \alpha(T_C - T_{STC})] \tag{4}$$

Where,

P_{NP} = Nameplate capacity

f_{PV} = Derating factor

G_T = Incident solar irradiance

α = Temperature coefficient

T_C = Cell temperature

T_{STC} = Cell temperature at STC

Table 3-8

PV system performance parameters [10] [11] [12]

Parameter	Definition	Equation	Units
Array yield (Y_a)	The ratio of DC energy output to the rated power of the PV system for a specific period	$Y_a = E_{dc}/P_{rated}$	kWh/kW
Final yield (Y_f)	The ratio of AC output energy to the rated power of PV system at standard test conditions (STC) for a specific period	$Y_f = E_{ac}/P_{rated}$	kWh/kW
Reference yield (Y_r)	The ratio of total in-plane solar radiation (kWh/m^2) to the reference solar irradiance (1 kW/m^2) over a given period	$Y_r = H_t/G_r$	kWh/kW
Performance ratio (PR)	The ratio of final yield to reference yield	$PR = Y_f/Y_r$	%
Capacity Factor (CF)	The ratio of the energy output of the PV system to the energy output when the system is running at its maximum capacity over a period	$CF = \frac{E_{ac}}{P_{rated} * 8760}$	%
Module efficiency	The ratio of energy converted by photovoltaic module to the solar radiation	$\eta_{pv} = \frac{E_{dc}}{H_t * A_m}$	%
Inverter efficiency	The ratio of AC power generated by inverter to the DC power produced by PV array	$\eta_{inv} = \frac{P_{ac}}{P_{dc}}$	%
System efficiency	The product of module efficiency and inverter efficiency	$\eta_{sys} = \eta_{pv} * \eta_{inv}$	%

3.2.4 PV System Losses

The losses occur in different components of PV system during the energy conversion process. These losses can be divided into these two categories.

I. Array losses (L_a)

The losses in PV array during conversion of solar energy into DC energy

$$L_a = Y_r - Y_a \tag{5}$$

These losses have following two types.

a) Thermal capture losses (L_{CT}): These losses occur due to higher cell temperature than STC.

b) Miscellaneous capture losses (L_{CM}): These losses occur due to mismatching, wiring, shading, soling, string diodes, MPPT errors

II. System losses (L_S)

System losses are defined by the difference between array yield and final yield. These losses occur during conversion of DC energy into AC energy by inverter

$$L_s = Y_a - Y_f \tag{6}$$

3.3 Economic Analysis

This section provides an insight into different economic parameters to determine the financial viability of the project. All the financial values are in US dollars ($) as it is default currency in SAM. Shown in Table 3-9 are system cost parameters for both solar technologies while Table 3-10 demonstrates the financing cost and other financial parameters of the project. It is assumed that net capital cost is borrowed, so debt fraction is 100% for loan term of 10 years with loan rate of 5% per annum. The analysis period is covered for 25 years since it is generic project life of renewable energy systems.

System cost includes all the direct and indirect capital costs that covers installation, operating, and maintenance cost of the project.

Table 3-9

Various system cost parameters [12] [13] [14] [15] [16]

Parameter	Value	Parameter	Value
CSP		**PV**	
Solar Field	150 $\$/m^2$	Module	0.41 $\$/W_{dc}$
HTF	60 $\$/m^2$	Inverter	0.12 $\$/W_{dc}$
TES	62 $\$/m^2$	Balance of system	0.21 $\$/W_{dc}$
Power Plant	1010 $\$/kW_e$	Installation labor	0.15 $\$/W_{dc}$

3.3.1 Commercial Projects

The renewable energy projects buy and sell electrical power at retail rates in residential and commercial financial models of SAM. SAM assumes that the customer owns and operates the project which may be financed with a loan. Debt percent, loan term and rate are specified in project term debt section. Power generated by the project slashes the electricity bill by offsetting the electricity consumption from the relevant power distribution company. These projects recoup their investments by selling excessive electricity to the grid at specified rates by power distribution company.

For the distributed generation financial model, it is assumed that the renewable project reduces grid power purchases to meet the required electric load of a building or facility. “No Load” option is available in SAM if power distribution company is going to purchase all of the electricity by the project. If there is no load, then all the system generated power is considered excess power generation that is either credited for net metering or sold for “buy all/sell all” by the project. In “buy all/sell all” mode of metering and billing, all the electrical power generated by the project is sold to the grid at specified rates and all the electrical power required to meet if any electric load, is purchased from the grid at specified rates.

3.3.2 Financial Model

Financial model calculates financial metrics for CSP, and PV systems based on variations in cash flows of power project over an analysis period. The analysis period is specified in financial model and typically equals to project life. This model makes use of system electrical power output projected by technical parameters to calculate annual cash flow.

Government of Pakistan offers plenty of incentives to encourage investment in renewable energy sector, such as income and sales tax exemption, and premium tariff rates. So, tax depreciation of any kind is not included in this economic model. Moreover, tariff paid to independent power producers (IPPs) is at upward trend. In last decade, electricity prices continued an upward hike. So, electricity bill escalation rate of 10% per year is chosen for this project.

Table 3-10

Financial parameters for solar energy projects

Parameter	Value
Analysis period	25 years
Inflation rate	2.5 %
Nominal discount rate	9.06 %
Debt percent	100 %
Loan term	10 years
Loan rate	5 %
Depreciation	Straight line
Grid curtailment	No
Degradation rate	0.5% /Year
Metering and billing	Buy all / Sell all

Financial evaluation is done on basis of following three metrices:

3.3.2.1 Levelized Cost of Energy (LCOE)

LCOE determines the total project lifecycle cost per kilowatt-hour ($/kWh). It is the minimum cost at which electricity can be sold over the lifetime of the project to achieve break-even point.

$$LCOE = \frac{-C_0 - \frac{\sum_{n=1}^{N} C_n}{(1 + d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1 + d_{real})^n}} \tag{7}$$

Where,

C_0 = Equity investment of the project

C_n = Project cost in year *n*

Q_n = System electricity generated in year *n*

$d_{nominal}$ = The nominal discount rate

d_{real} = The real discount rate

N = Analysis period in years

3.3.2.2 Net Present Value (NPV)

NPV is the present value of the after-tax cash flow discounted at year one of the renewable project. It determines the economic feasibility of the project based on assessments of both revenues and costs. A positive NPV indicates that the project is feasible.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1 + d_{nominal})^n} \tag{8}$$

Where,

C_n = After-tax cash flow in year *n*

$d_{nominal}$ = The nominal discount rate

N = Analysis period in year n

3.3.2.3 Payback Period (PB)

Payback period is the time taken by project to regain the initial investment, from the revenue it produces.

$$PB = \frac{Initial\ Investment\ Cost}{Annual\ Savings} \tag{9}$$

Summary

This chapter describes the methodology procedure used in this research. The parameters to be considered for site selection and power plant modeling are discussed in detail. A brief introduction to different blocks of CSP plant and components of PV system is presented. Furthermore, an economic model which covers all system costs and other financial parameter is discussed as well.

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Chapter 4

Results and Discussion

In this Chapter, the main findings of the research are presented and discussed in detail. This chapter covers the graphical interpretation and the simulation results after analyzing the data obtained from proposed model.

A study of 50 MW solar thermal power plant in four different climatic zones is performed in SAM. The performance of solar thermal power plants installed at selected sites is predicted by SAM's physical trough model. This model assumes that flow is unidirectional and heat transfer is in a radial direction for the receiver. For the collector, it accounts for the losses like geometry defects, tracking error, incidence angle modifier, shadowing, mirror reflectance, and soiling. TES is designed to store excessive thermal energy and run power cycle at its rated capacity. The plant is simulated for a period of one year for each potential zone and then the performance of the most feasible site for CSP is compared with the same capacity of PV for that location. In the end, emission analysis is performed on RETScreen.

4.1 Evaluation of CSP

4.1.1 Performance evaluation of CSP

The Figure 4-1 to 4-4 show monthly energy production along the capacity factor of four potential zones. It shows that monthly energy production is significantly higher during months of higher DNI and number of sunshine hours. All the sites have produced maximum energy from April to September due to relatively higher DNI in this span. Thus, the energy produced by the CSP plant is hugely dependent on the value of DNI. For Multan, the highest energy 14.13 GWh is produced in April with a capacity factor of 39.25% while the lowest energy 3.81 GWh was produced in January with a 10.24% capacity factor. For Islamabad, the highest energy 17.35 GWh is produced in May with a capacity factor of 46.65% while the lowest energy 2.69 GWh was produced in December with a 7.24% capacity factor. For Karachi, the highest energy 16.76 GWh is produced in April with a capacity factor of 46.54% while the lowest energy 6.76 GWh was produced in July with an 18.17% capacity factor. For Quetta, the highest energy 18.84 GWh is produced in September with a capacity factor of 52.34% while the lowest energy 7.52 GWh was produced in December with a 20.22% capacity factor. It is observed that months of higher average DNI and longer sunshine hours produce significantly higher energy. The performance is better in Quetta because of higher solar irradiance, lower ambient temperature, and lower humidity.

The annual energy production, capacity factor, and water usage of CSP based power plants at four potential sites are shown in Table 4.2. Simulation results indicate that CSP based power plant in Quetta can produce annual energy of 160.32 GWh with a capacity factor of 36.6%, followed by a power plant in Karachi which can produce annual energy of 129.26 GWh with a capacity factor of 29.5%. The power plant in Islamabad can produce annual energy of 113.42 GWh with a capacity factor of 25.9%, and 112.04 GWh with a capacity factor of 25.6% can be produced in Multan. The annual water consumption for these four sites ranges from 36,000 m^3 to 40,000 m^3.

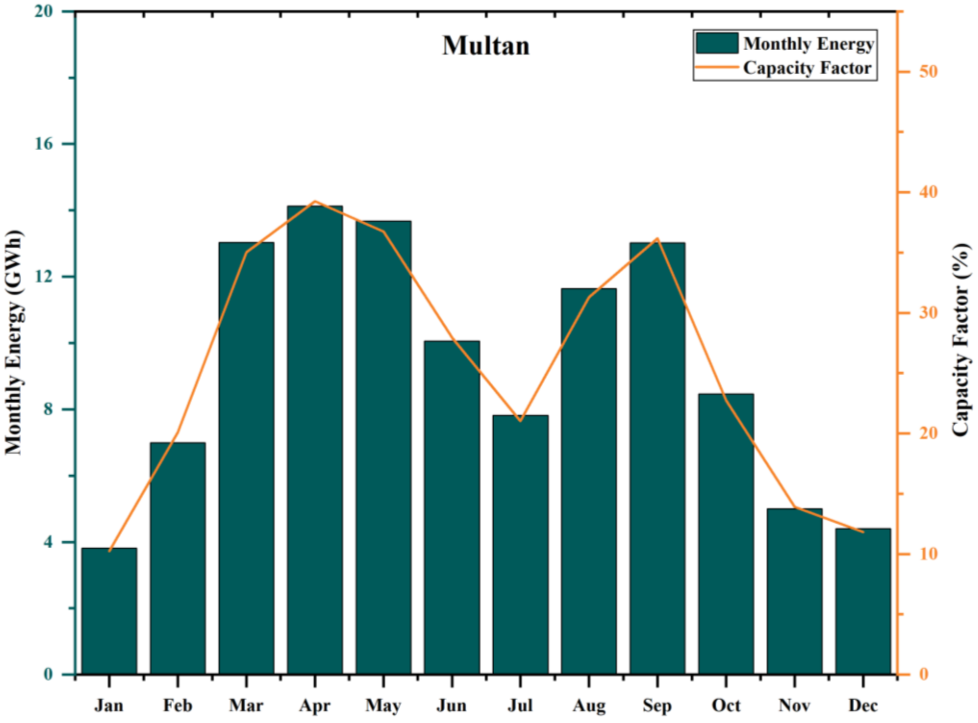

Figure 4-1: Monthly power generated and capacity factor from 50 MW CSP plant in Multan

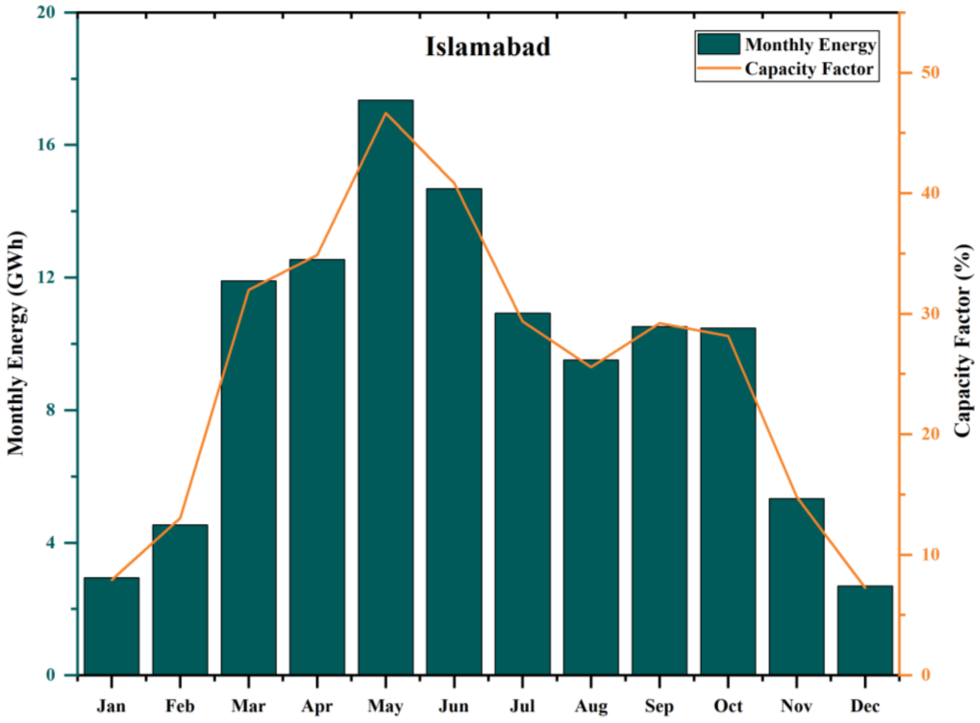

Figure 4-2: Monthly power generated and capacity factor from 50 MW CSP plant in Islamabad

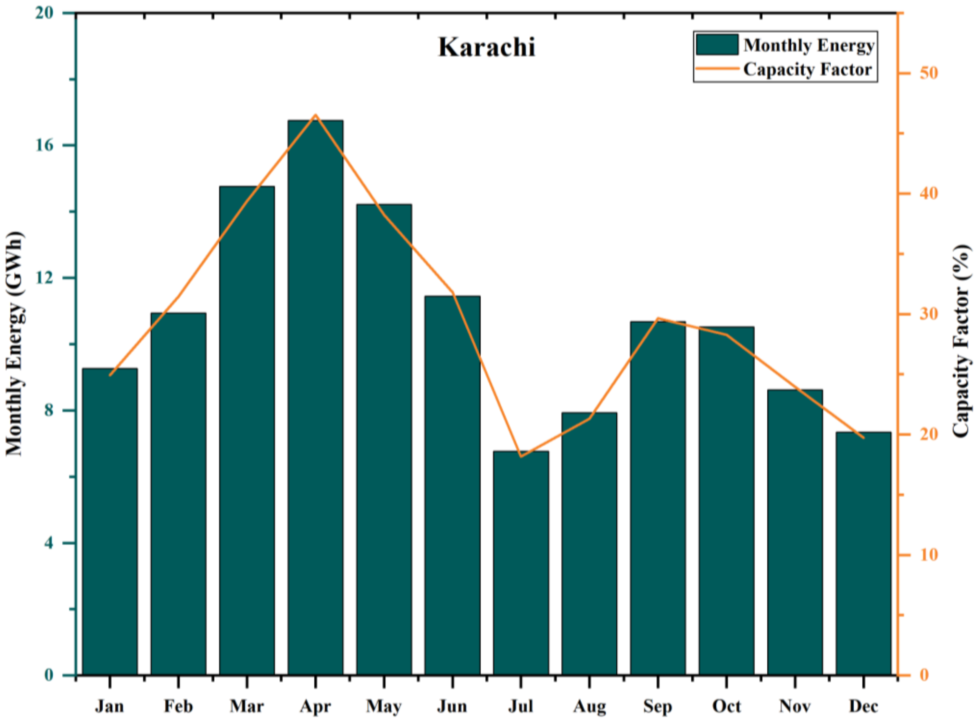

Figure 4-3: Monthly power generated and capacity factor from 50 MW CSP plant in Karachi

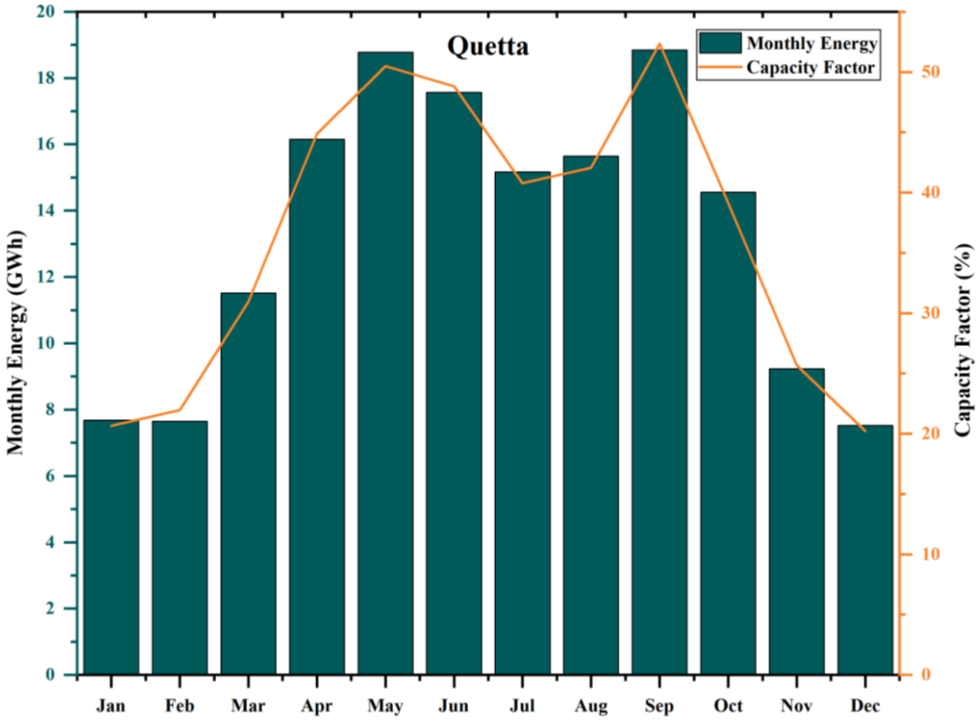

Figure 4-4: Monthly power generated and capacity factor from 50 MW CSP plant in Quetta

System power generation trend varies every day for each location according to TMY weather data. Figure 4-5 to 4-8 show the variation of system power generation in different seasons of Pakistan. Although DNI is available in the morning, yet system starts generating power a bit late because HTF needs to reach a specific temperature and fulfill the minimum turbine output fraction condition before the power plant starts producing power. Similarly, there is a notable dip in the late hours of the day because there is a temperature drop in HTF when TES starts functioning. The solar field thermal output increases due to higher intensity and longer duration of solar irradiance in June and September, consequently the duration of power plant operation hours is notably increased in these respective months. This highlights the significance of TES in seasons of higher average DNI, particularly in summer and fall for Quetta.

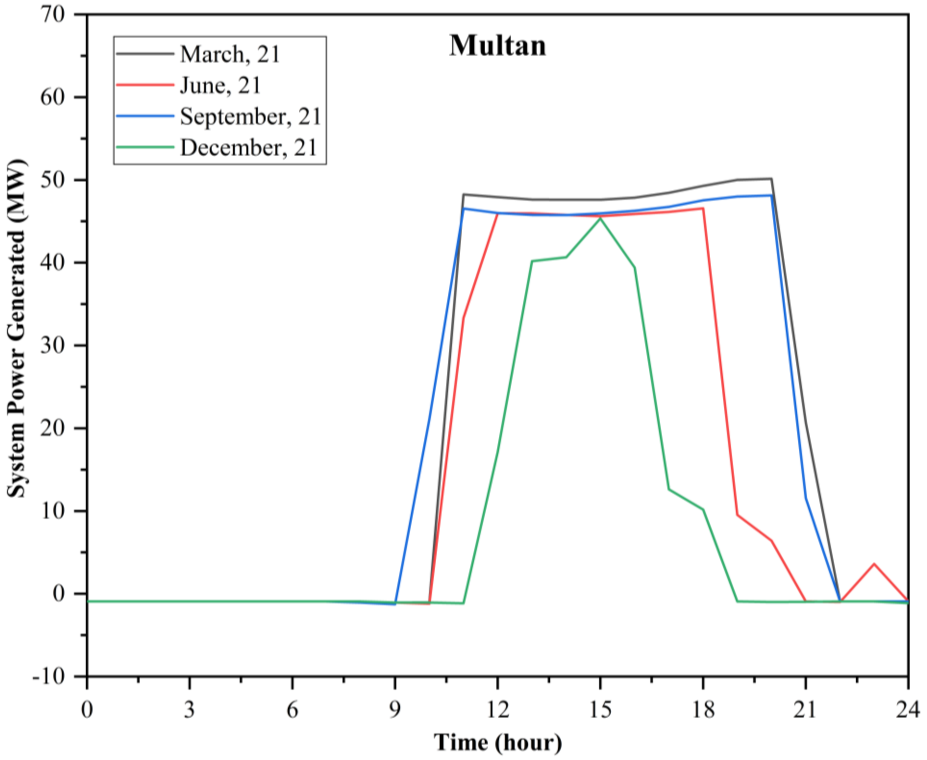

Figure 4-5: Seasonal variation in system power generation trend of CSP plant in Multan

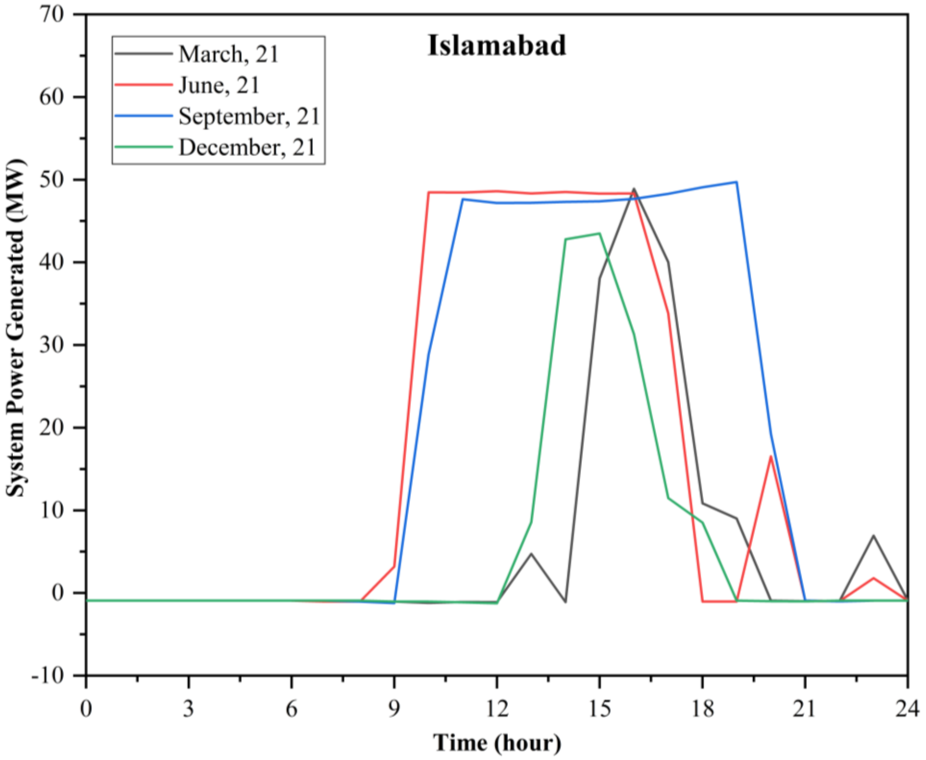

Figure 4-6: Seasonal variation in system power generation trend of CSP plant in Islamabad

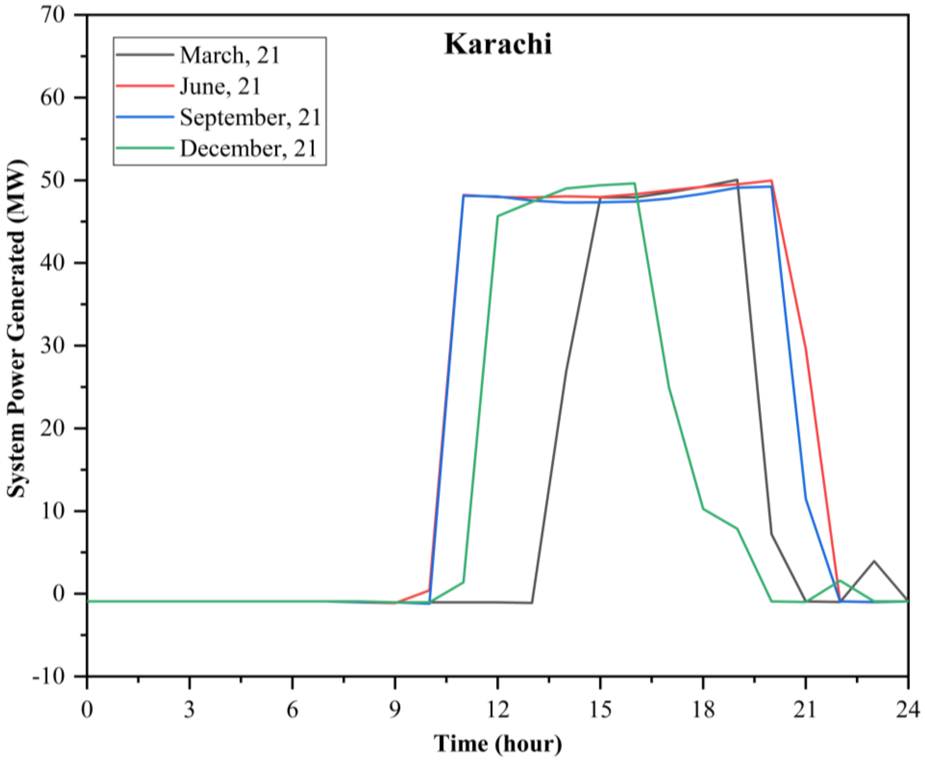

Figure 4-7: Seasonal variation in system power generation trend of CSP plant in Karachi

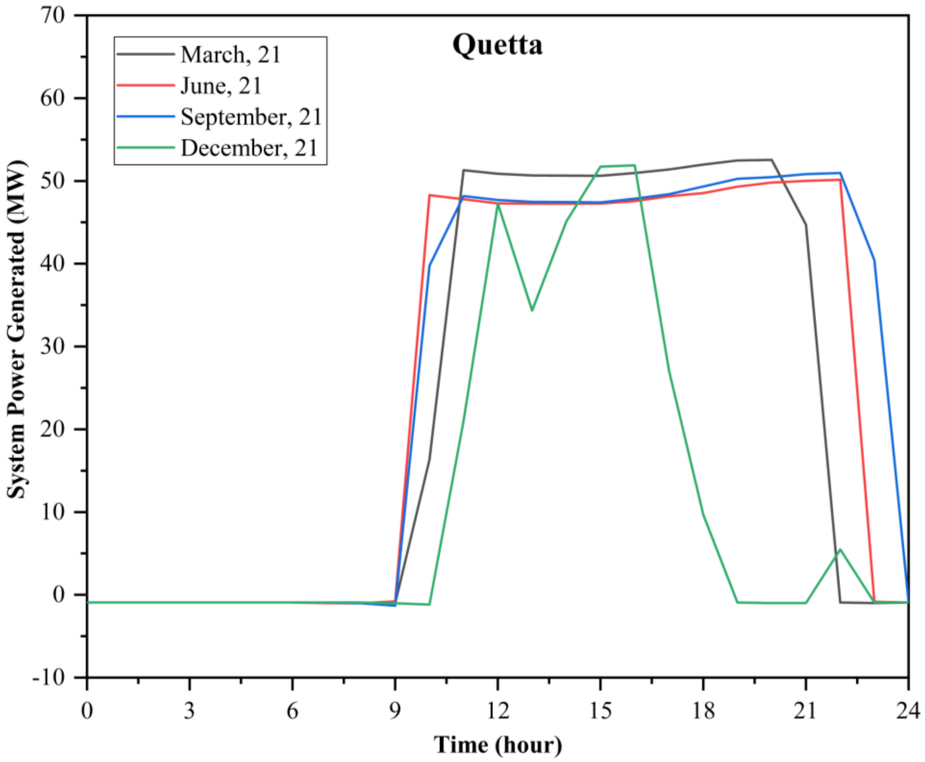

Figure 4-8: Seasonal variation in system power generation trend of CSP plant in Quetta

Figure 4-9 explains the monthly thermal energy flow at different stage of CSP plant in Multan. From this figure, we can observe that there is significant difference between thermal energy incident on the solar field and produced by the solar field. This difference occurs due to field-collector cosine losses factor. The figures shows that field cannot produce sufficient thermal energy in autumn and winter season, that is why thermal energy storage charge and discharge curve is almost flat from October to February.

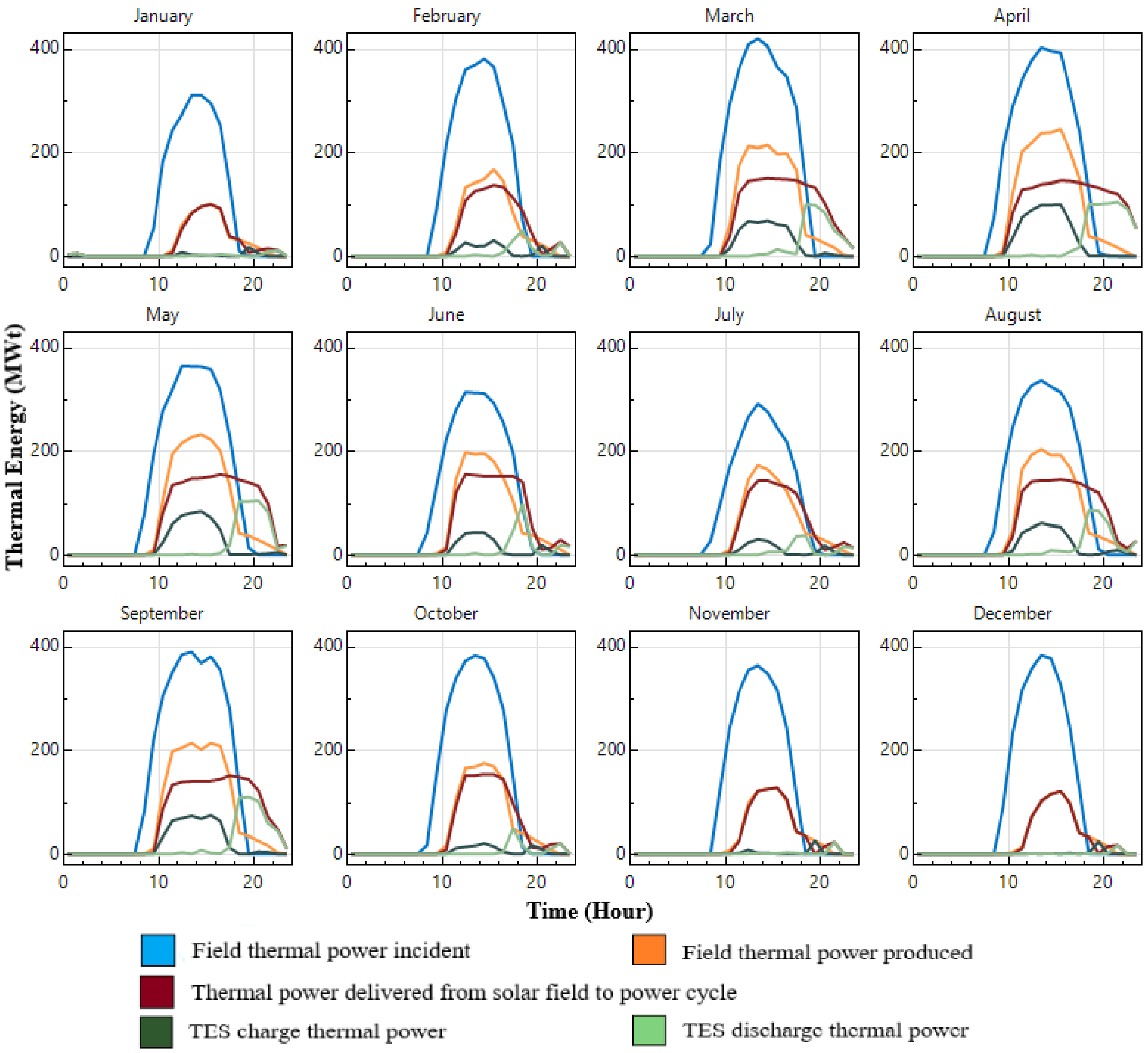

Figure 4-9: Monthly thermal energy flow at different stages of CSP plant in Multan

Figure 4-10 demonstrates the monthly thermal energy flow at different stages of CSP plant in Islamabad. CSP plant in Islamabad performs better in spring and autumn than fall and winter season. From the figure 4-10, there is no excessive thermal energy to store in thermal storage during the winter season. The excessive thermal energy produced by solar field is used to charge thermal energy storage to use it later during cloudy or night hours. For this location, May is best performing month for CSP generation over the year.

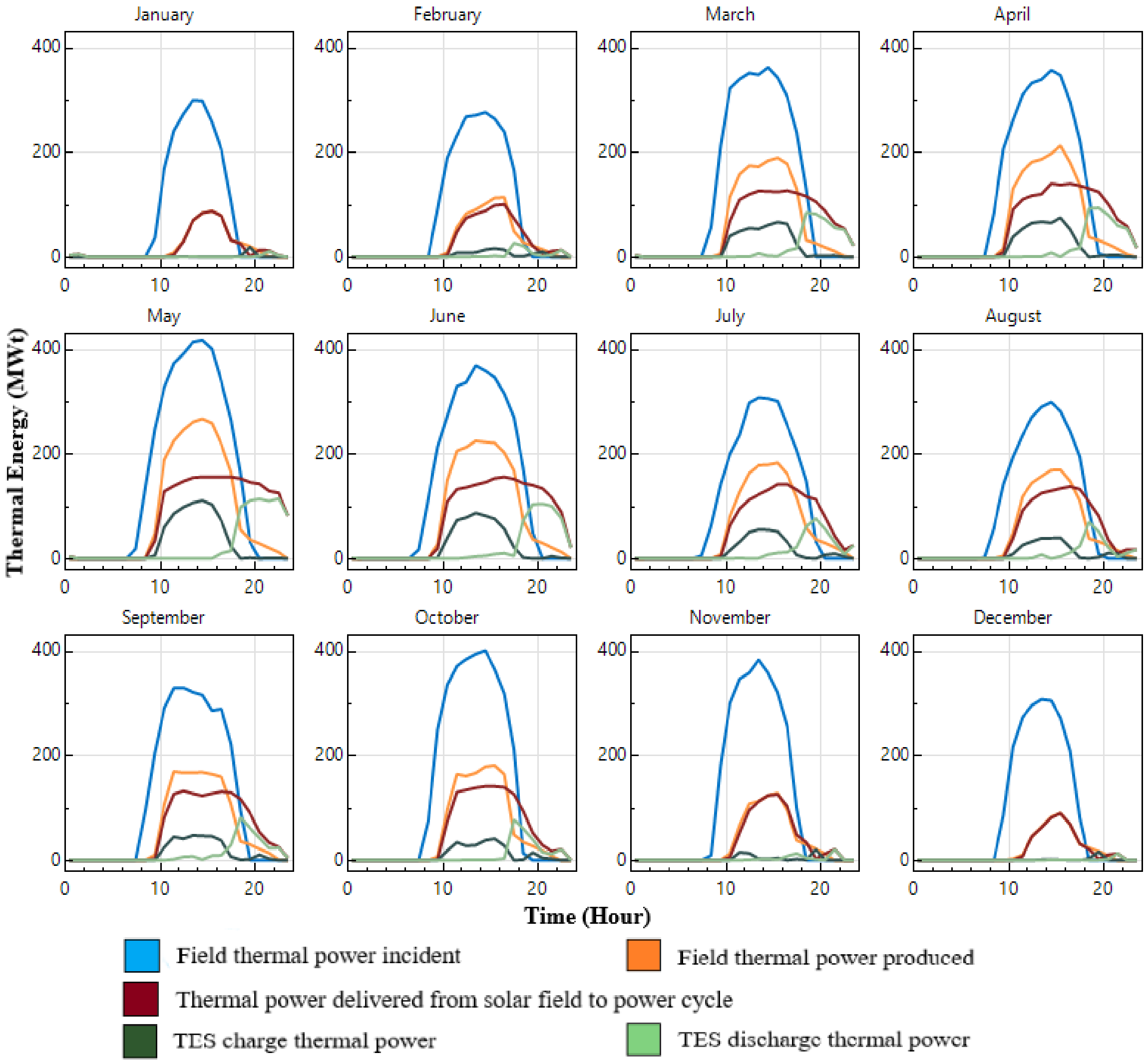

Figure 4-10: Monthly thermal energy flow at different stages of CSP plant in Islamabad

Karachi experiences lesser average sunshine hours in summer season among all the locations for CSP plant. From June to August, it receives average 150 to 170 monthly sunshine hours, resulting in relatively less field thermal power incident on solar filed and field thermal power produced, which can be clearly observed in Figure 4-11. This is the reason behind lowest energy generation of CSP plant in months of July and August for site of Karachi.

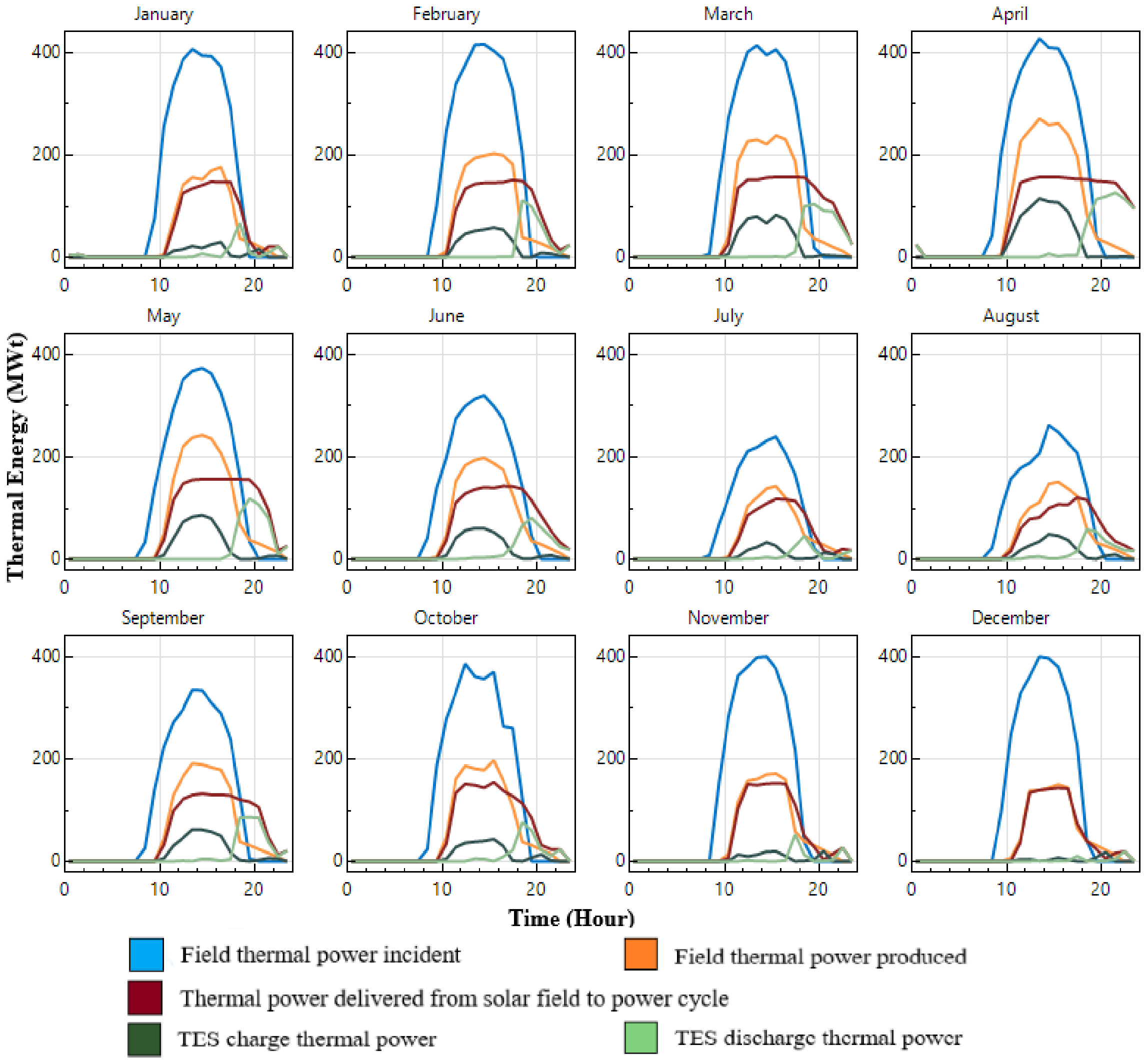

Figure 4-11: Monthly thermal energy flow at different stages of CSP plant in Karachi

Quetta receives highest average daily DNI of 6.13 kWh/m^2/day among all the selected sites for CSP plants and consequently performs extraordinary. Figure 4-12 indicates that it performs well in spring, summer, and autumn seasons due to less field-collector cosine losses. During these seasons, solar filed produces more than sufficient thermal energy required for power block to run it at its rated capacity. This excessive energy then goes to thermal storage which can be used later during cloudy or night hours. The plant produces highest energy in September since it receives average 305 sunshine hours during the month.

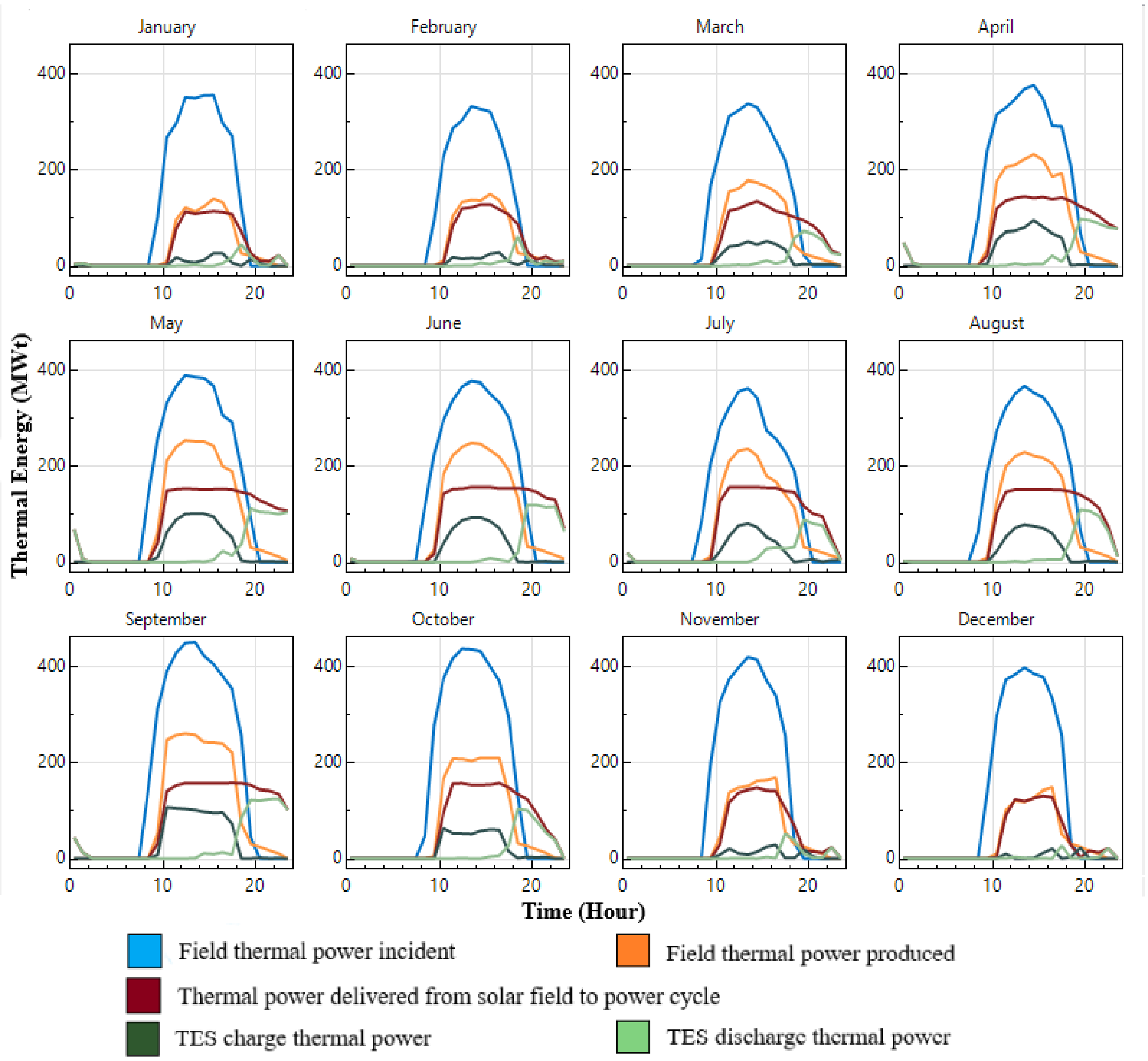

Figure 4-12: Monthly thermal energy flow at different stages of CSP plant in Quetta

The following Figure 4-13 demonstrates the energy flow in solar field. The total power incident on the solar field area is 1151.93 GWht, absorbed by trough collector is 572.17 GWh and thermal output by field is 550.9 GWht. The system power generated is 160.32 GWh with a capacity factor of 36.6% over a period of one year.

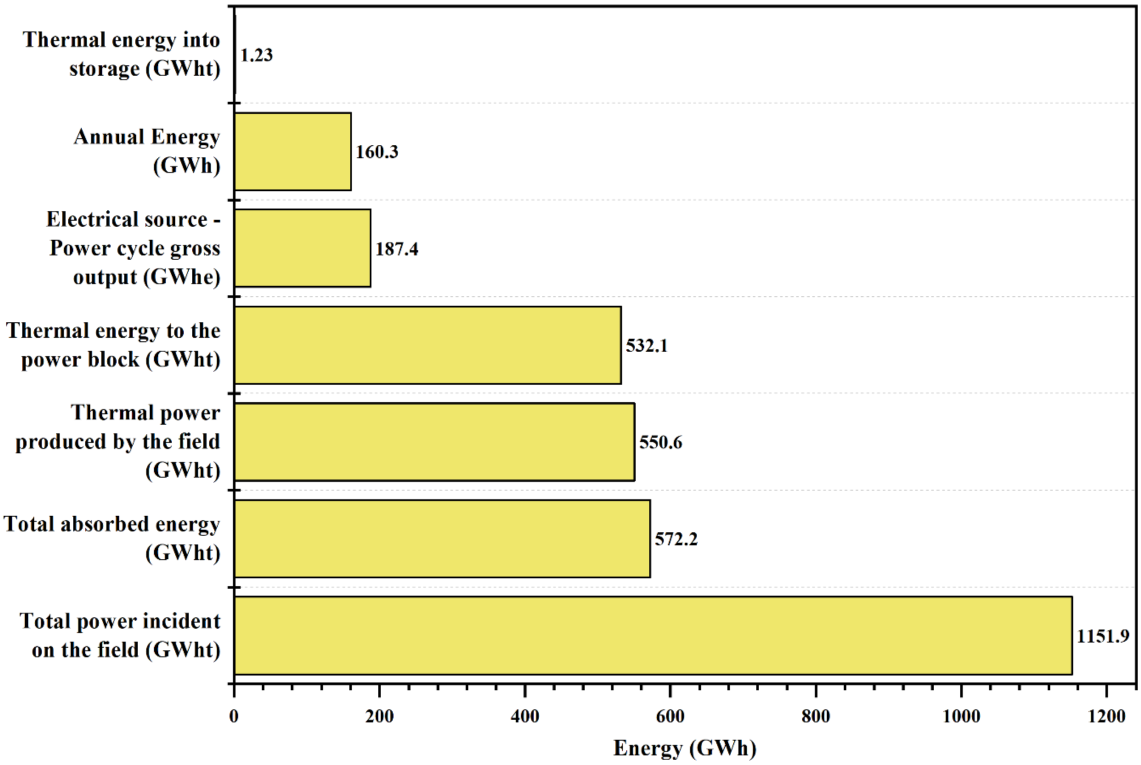

Fig. 4-13: Energy flow process in the solar field of CSP plant in Quetta

The Figure 4-14 shows the annual profile of average daily variation in loop inlet/outlet temperature, and mass flow rate with respect to DNI. When DNI reaches a specific value, HTF starts circulating in solar field and reaches to maximum value of 7.85 kg/s at some instance. Similarly, loop outlet temperature starts increasing with increase of DNI and reaches at maximum value of 524.7 °C when normal irradiance of 896 W/m^2 is available. So, solar field thermal output increases due to higher intensity and longer duration of solar irradiance.

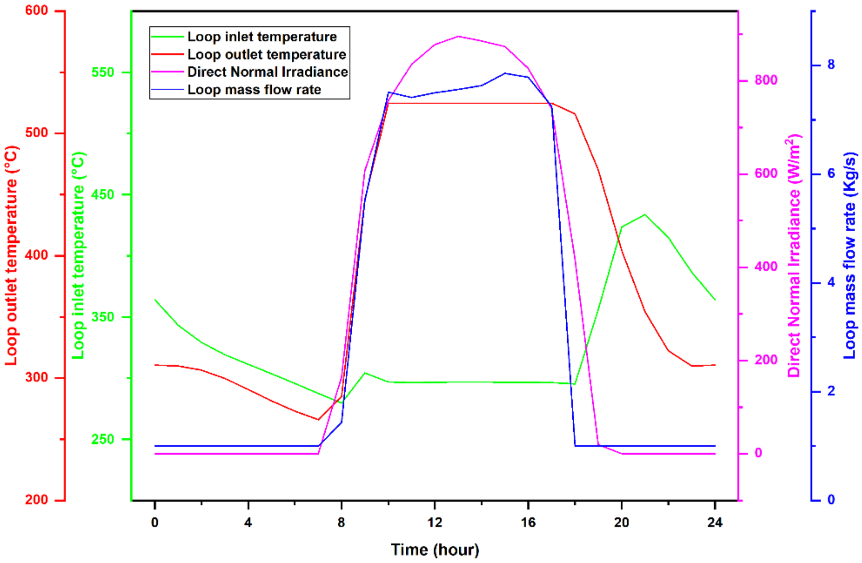

Fig. 4-14: Correlation of DNI with loop inlet/outlet temperature and mass flow rate on a typical summer day

4.1.2 Economic Evaluation of CSP

The aim of the economic assessment is to evaluate the feasibility of solar power plants. The economic feasibility of solar power plants is evaluated in terms of LCOE, NPV, and Payback Period. The values of financial parameters are mentioned in Table 3.7. The optimization of LCOE is performed by varying SM from 1 to 4, and TES from 0 to 15 h. Figure 4-15 to 4-18 show the Levelized Cost of Energy (LCOE) at different solar multiples (SM) and thermal energy storage (TES) hours. For Multan, the lowest value of LCOE of 15.88 cents/kWh can be achieved at SM of 4 and TES of 12 hours. For Islamabad, the lowest LCOE of 15.72 cents/kWh can be achieved at SM of 4 and TES of 12 hours. For Karachi, the lowest LCOE of 13.32 cents/kWh can be achieved at SM of 3.5 and TES of 12 hours. For Quetta, the lowest LCOE of 10.61 cents/kWh can be achieved at SM of 3.5 and TES of 12 hours.

These results show that LCOE with a fixed TES starts to decrease with increasing SM until it achieves a minimum value, and then it starts increasing gradually. Thus, there is an optimal SM for each TES size at which minimum LCOE occurs. The reason behind the LCOE increasing trend is, a bigger solar field attributes to enormous thermal losses. Generally, So, we can deduce that there is an optimal SM and TES capacity for minimized LCOE value. This minimum LCOE occurs at a higher SM for a CSP plant with a larger TES capacity. Since large-scale CSP plants are economically viable, LCOE will start decreasing with increasing power plant capacity. Similarly, solar-to-electricity efficiency (SEE) starts increasing with SM until it reaches a maximum value, and then it starts decreasing. Similarly, the Payback period starts to decrease with the increase of Solar Multiple to an extent. After that, it starts increasing gradually.

The results indicate that Quetta is the most suitable location for a concentrated solar thermal power plant among these four because of its highest AEP and lowest LCOE with 86.2% gross to net conversion factor and 7.7 years of payback period. Fig 4-19 demonstrates the after-tax cash flow of CSP plant in Quetta for its life cycle. The negative cash flow in initial years is due to its huge upfront capital cost as compared to solar PV.

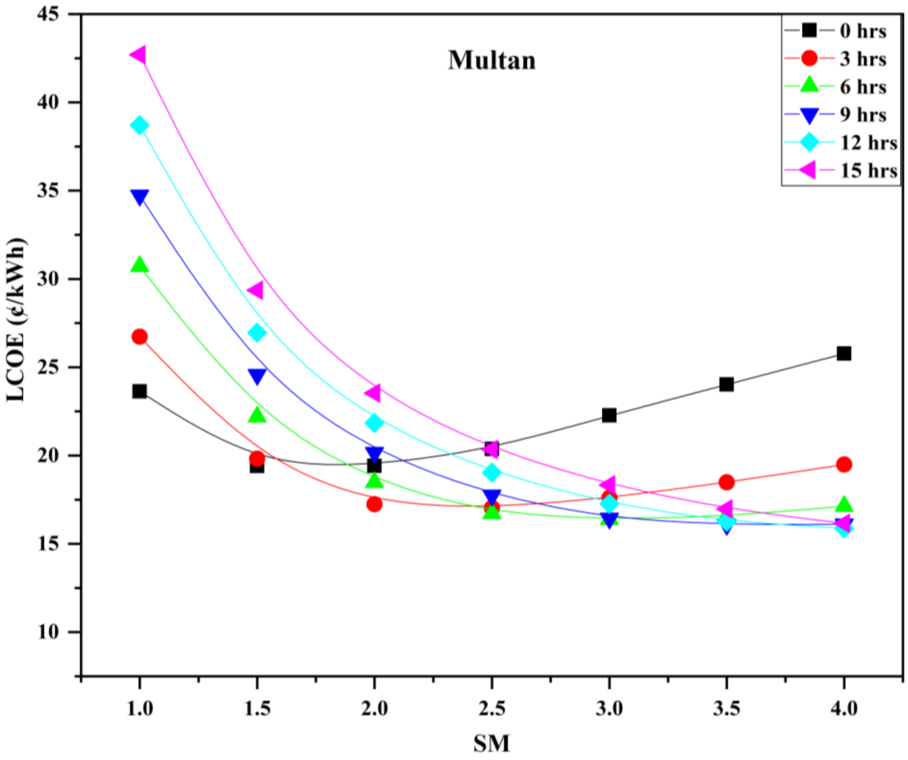

Figure 4-15: The impact of SM and TES on LCOE of CSP plant in Multan

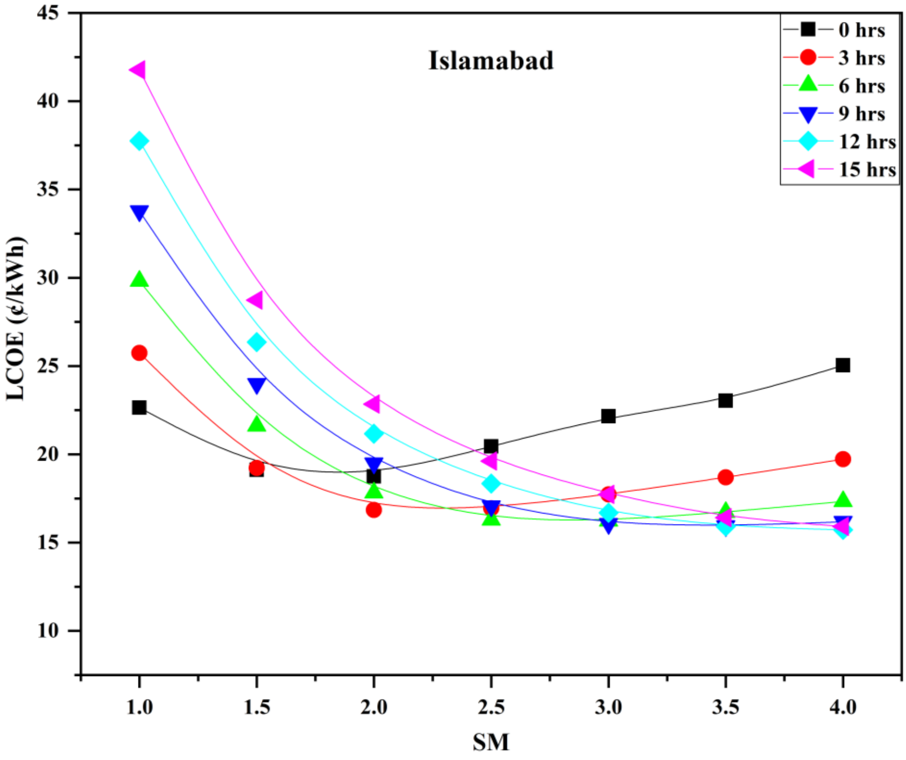

Figure 4-16: The impact of SM and TES on LCOE of CSP plant in Islamabad

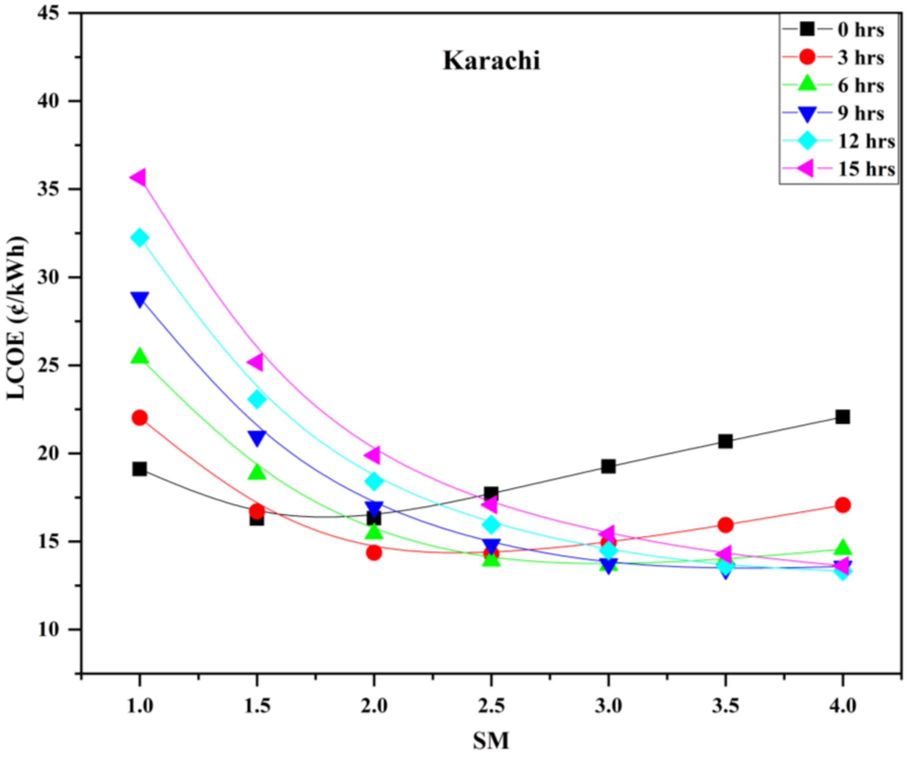

Figure 4-17: The impact of SM and TES on LCOE of CSP plant in Quetta

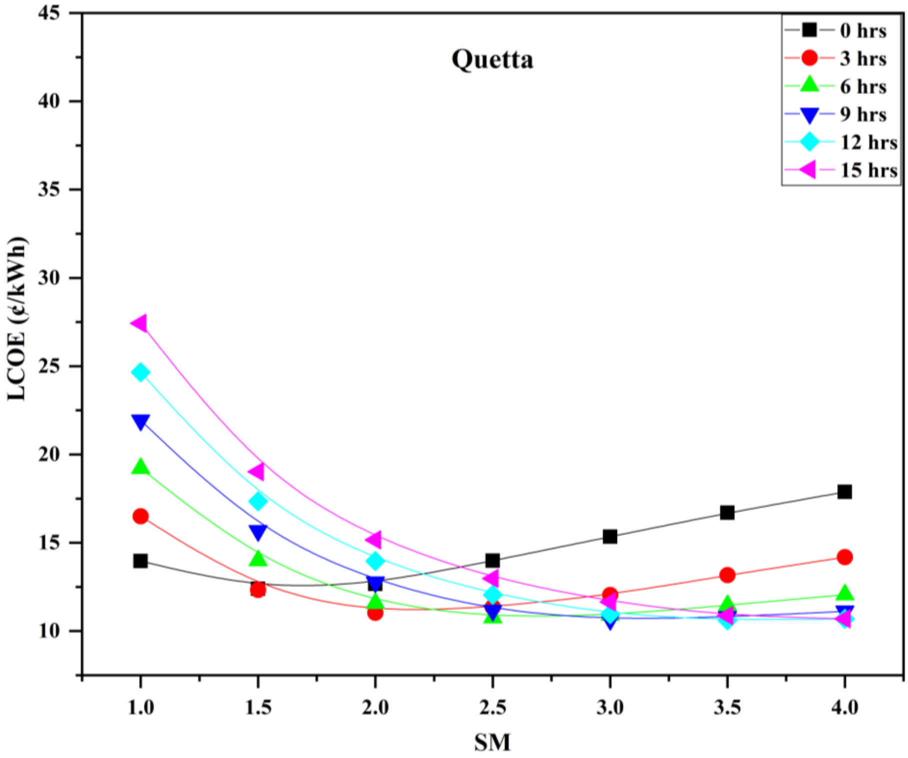

Figure 4-18: The impact of SM and TES on LCOE of CSP plant in Quetta

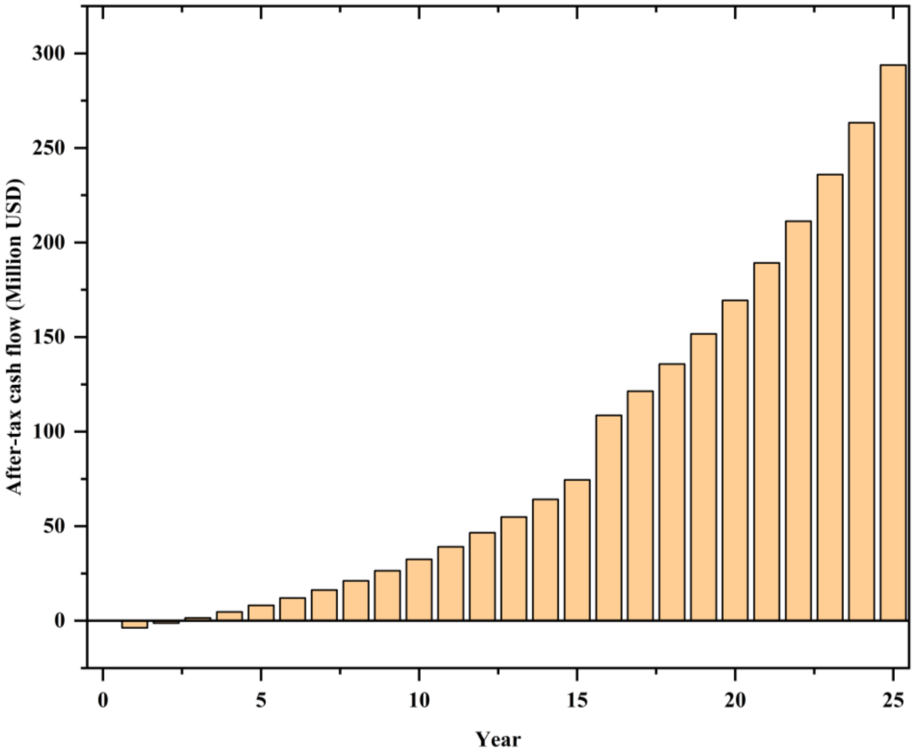

Figure 4-19: After-tax cash flow of CSP plant in Quetta

4.1.3 Sensitivity Analysis of CSP

Sensitivity analysis is used to depict the sensitivity of focused metrics to various inputs. The figures below show the effect of the inflation rate and discount rate on the economic viability of the project. Sensitivity analysis is performed by varying the inflation rate from 1.0 to 4.0% and the discount rate from 7.0 to 12.0%. Figure 4-20 indicates that an increase in the inflation rate from 1.0 to 4.0% results in a decrease in LCOE from 13.06 ¢/kWh to 10.21 ¢/kWh and an increase in NPV from 477 to 833 million US$. On the other hand, an increase in the discount rate from 7.0 to 12.0% results in an increase in LCOE from 10.84 ¢/kWh to 12.45 ¢/kWh and a decrease in NPV from 941 to 372 million US$ as shown in Figure 4-21.

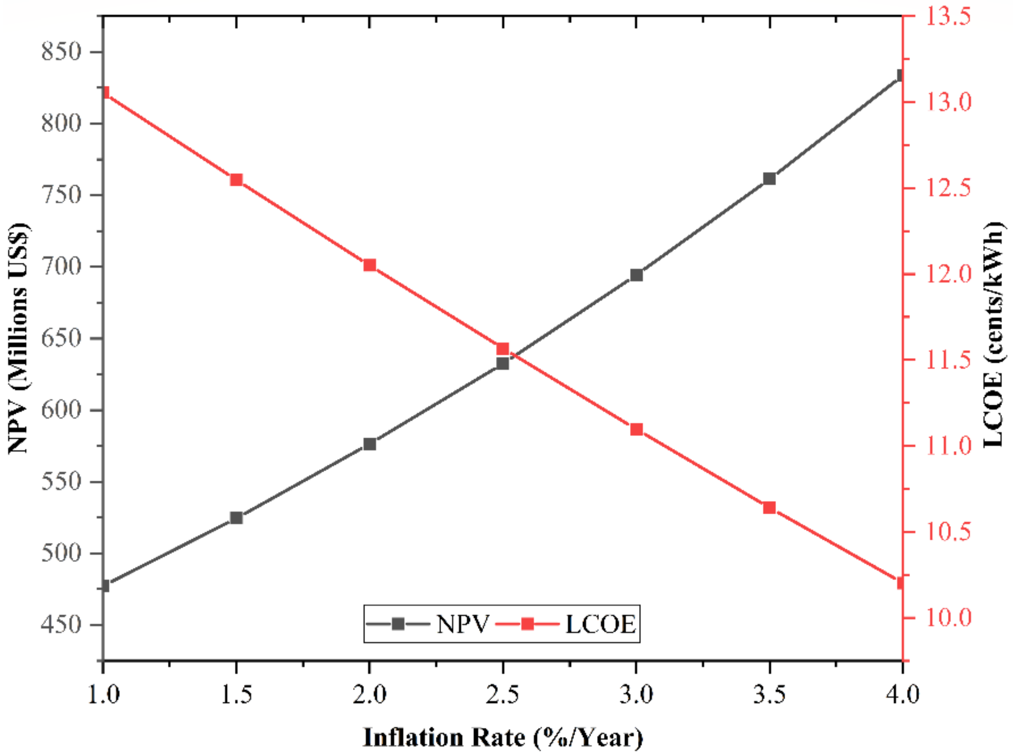

Fig. 4-20: Sensitivity analysis carried out on inflation rate for CSP plant in Quetta

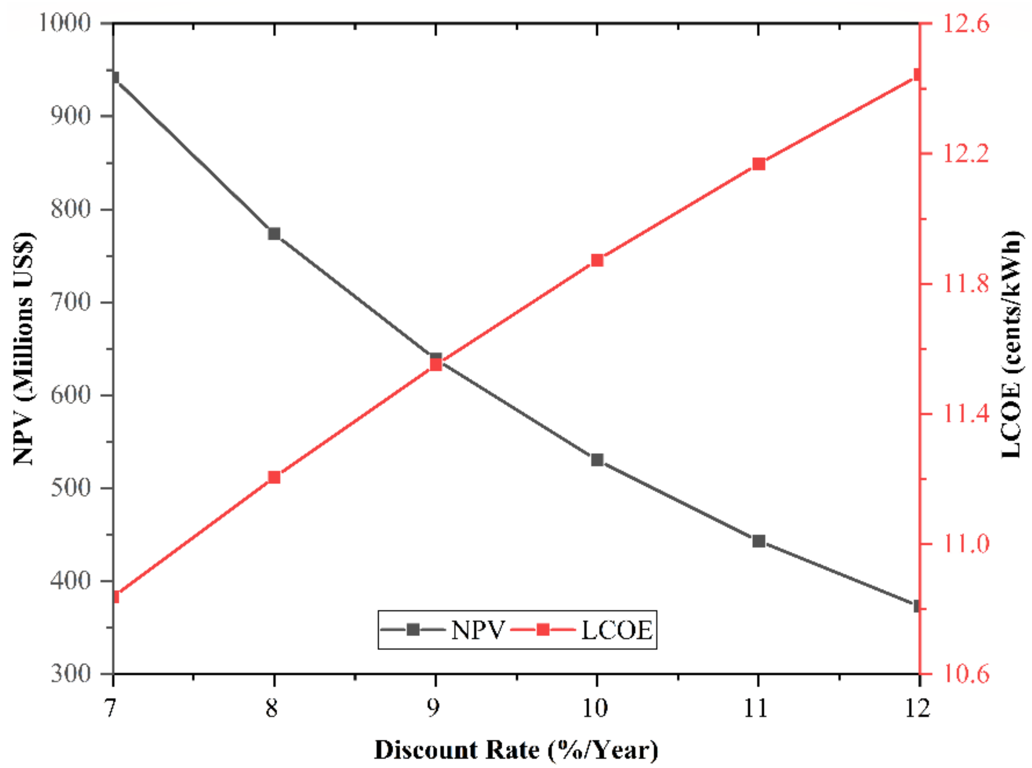

Fig. 4-21: Sensitivity analysis carried out on discount rate for CSP plant in Quetta

4.1.3.1 Impact of Solar Multiple (SM)

Generally, higher SM increases solar field area thus resulting in higher field thermal output. With increasing SM, a sharp increase in AEP can be observed. This trend continues until field thermal output is sufficient to operate power plants at their rated capacities. The excessive field thermal output is then stored in TES to use later when needed. After that, the hike in AEP is relatively less intense.

To find the impact of SM on the techno-economic viability of the project, the value of SM is varied from 1.0 to 4.0 with an interval of 0.25. Figure 4-22 shows the variation in annual energy production based on SM and hours of TES. For a specified TES, the value of AEP increases rapidly with increasing SM at an initial stage. This trend continues until field thermal output is sufficient to run the plant with or without TES at its design capacity. After that, the increase in AEP becomes less intense with a further increase in SM. Thus, initially increasing SM contributes to larger field thermal power output which results in a sharp increase in the value of AEP at the initial stage but a further increase in SM attributes more to field thermal losses than AEP.

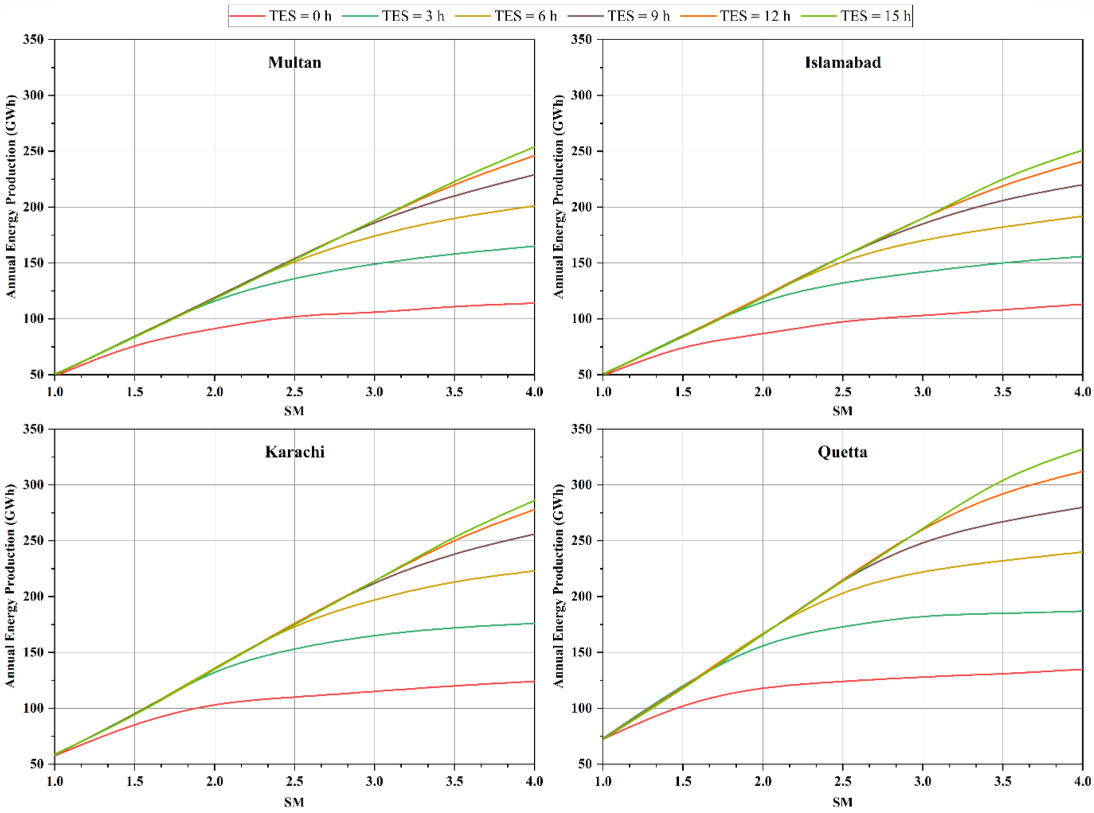

Fig. 4-22: The impact of SM on AEP of four selected sites for CSP

4.1.3.2 Impact of Thermal Energy Storage (TES)

Having a larger TES is not always beneficial against each solar field size. Thus, it is essential to determine the optimal TES capacity for each SM concerning the viability of CSP plants from an economic perspective. The capacity of thermal energy storage (TES) is varied from 0 to 15 h with an interval of1 h. To assess the impact of TES capacity on techno-economic viability, the variation of AEP is shown in Figure 4-23. Based on the following figure, an increase in the capacity of TES has no significant impact on AEP for the plants with SM of 1.0 because field aperture area can only provide sufficient field thermal output to run power block at its rated capacity under the design conditions. Therefore, there is no excessive field thermal output for storing in TES to generate electricity during no sunshine hours. Consequently, an increase in TES shows no impact on AEP for power plants with SM of unity.

When SM starts increasing from 1.0, the impact of TES can be seen on the values of AEP and LCOE. For such cases, the excessive field thermal output is used to charge TES for producing power during cloudy or nighttime. Accordingly, the amount of AEP increases, and consequently, the value of LCOE decreases. This trend continues until all the excessive field thermal output is stored in a storage system. After that, a further increase in TES capacity shows no significant impact on AEP, and it only increases the storage cost, and as a result, the value of LCOE starts increasing as discussed earlier in Figure 4-15 to 4-18. Thus, an optimal TES size can be determined against each SM according to the objective of minimized LCOE. The optimal TES size increases with an increase in SM, so the power plants with higher SM should have larger TES capacity for the sake of economic viability. Table 4-1 shows the optimized TES capacity against each SM value. This optimal TES size against each step of SM is based on the objective function of minimized LCOE.

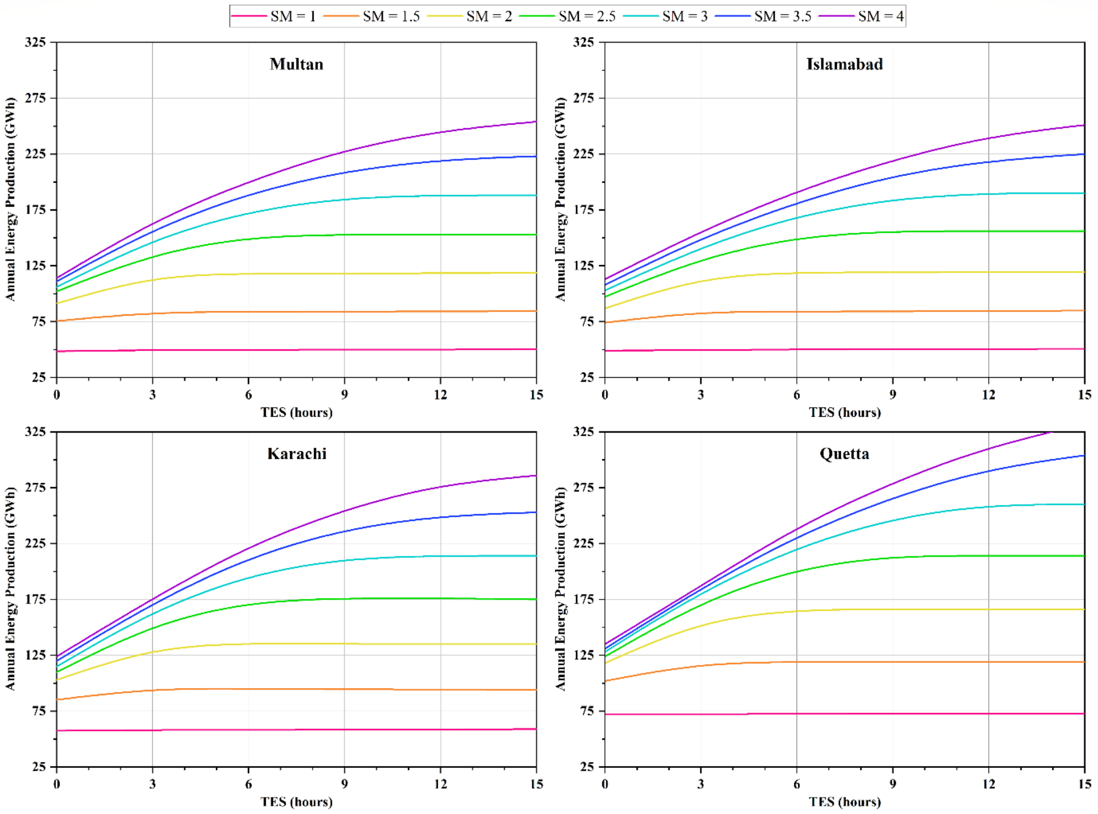

Fig. 4-23: The impact of TES on AEP of four selected sites for CSP

Table 4-1
AEP, CF, LCOE, PBP, and water usage with optimal TES based on the minimum LCOE

Location	SM	Optimal TES (h)	LCOE (¢/kWh)	AEP (GWh)	CF (%)	PBP (Years)	Water used x10^3 (m^3)
Multan	1.0	0	23.6	48.5	11.1	12.36	20.0
	1.5	1	18.5	83.1	19.2	10.4	30.5
	2.0	3	17.2	116.0	26.5	9.9	40.7
	2.5	5	16.6	148.7	33.8	9.6	50.6
	3.0	8	16.3	183.8	41.9	9.5	61.2
	3.5	10	16.1	214.4	49.1	9.4	71.1
	4.0	12	15.9	246.6	56.2	9.3	81.2
Islamabad	1.0	0	22.7	49.1	11.2	12.0	19.1
	1.5	1	18.1	83.4	19.0	10.3	29.2
	2.0	3	17.0	115.4	26.3	9.8	39.2
	2.5	5	16.3	146.9	33.7	9.5	48.4
	3.0	8	16.0	181.6	41.5	9.4	58.3
	3.5	10	15.9	211.4	48.2	9.3	68.1
	4.0	12	15.7	241.7	55.1	9.2	77.3
Karachi	1.0	0	19.1	57.5	13.1	10.8	19.6
	1.5	1	15.5	94.2	21.5	9.2	29.4
	2.0	3	14.4	132.3	30.3	8.7	39.6
	2.5	5	13.8	169.5	38.6	8.5	49.6
	3.0	8	13.6	209.6	47.8	8.4	59.6
	3.5	10	13.4	244.8	55.8	8.3	69.5
	4.0	13	13.3	282.1	64.6	8.3	79.5
Quetta	1.0	0	14.0	72.4	16.5	8.6	18.7
	1.5	1	11.7	115.8	26.3	7.5	28.3
	2.0	4	11.0	163.2	37.2	7.2	38.1
	2.5	7	10.8	209.3	47.8	7.1	48.0
	3.0	10	10.7	254.7	58.0	7.1	57.2
	3.5	12	10.6	292.5	66.8	7.0	66.5
	4.0	14	10.6	330.4	75.4	7.0	75.3

4.1.3.3 Impact of Cooling System

CSP plants require water for mirror washing, as well as for cooling purposes. About 6% of the total water is used for mirror washing purposes, while the rest is consumed by cooling CSP plants. In this study, two types of cooling systems, air-cooled and water-cooled condensers have been investigated. Since the air-cooled condenser works on dry bulb temperature and the water-cooled works on wet bulb temperature. The performance of a CSP plant improves by replacing an air-cooled condenser with an evaporative condenser, but water usage increases exponentially. The wet cooling system increases the AEP by almost 5% and decreases the LCOE by 4.5%. However, wet cooling systems consume water much more than dry cooling systems. Table 4.2 indicates that water usage for a power plant with a dry cooling system is 94% less than that for a plant with a wet cooling system. The average water requirement for dry cooling is 0.3 m^3/MWh, while it exceeds up to 3 m^3/MWh in case of wet cooling [1]. So, CSP plants with evaporative condensers have slightly better efficiency and can be built in regions where water is excessively available. But there is no justification for using wet cooling systems for those regions which suffer from the water shortage. CSP plants' performance and water usage for both types of cooling systems are shown in Table 4-2. It is to be noted that water costs are not considered in the evaluation of condenser type.

Table 4-2
Impact of condenser type on the performance of solar thermal power generation

Location	Condenser Type	Annual Energy (GWh)	Capacity Factor (%)	LCOE (¢/kWh)	Water Usage (m^3)
Multan	Air-cooled	112.77	25.7	18.46	40463
	Evaporative	119.06	27.2	17.53	558523
Islamabad	Air-cooled	113.35	25.9	17.82	38682
	Evaporative	119.26	27.3	16.96	541480
Karachi	Air-cooled	129.21	29.5	15.47	39448
	Evaporative	135.33	30.9	14.78	602343
Quetta	Air-cooled	160.27	36.6	11.57	38058
	Evaporative	168.01	38.4	11.05	635411

4.2 Evaluation of PV system

4.2.1 Performance evaluation of PV

In this section, performance evaluation of Photovoltaic (PV) is presented and discussed. The monthly average ambient temperature and wind speed are shown in Figure 3-7 and 3-8, respectively**.** The daily average ambient temperature is 18.7 °C, with average minimum and maximum temperatures varying from -2 °C in January to 35 °C in July. The monthly average ambient temperature changes from 4.7 °C in January to 29.5 °C in July. The daily sunshine hours vary from 7 to 11 for winter and summer, respectively.

Figure 4-24 shows the month-wise performance of a solar photovoltaic power plant of the same capacity. The highest monthly energy of 7.71 GWh is produced in May with a capacity factor of 20.72% while the lowest 5.68 GWh is produced in February with a 16.34% plant capacity factor. PV system specific yield recorded as 1,730 kWh/kW and annual performance ratio (PR) was 73%.

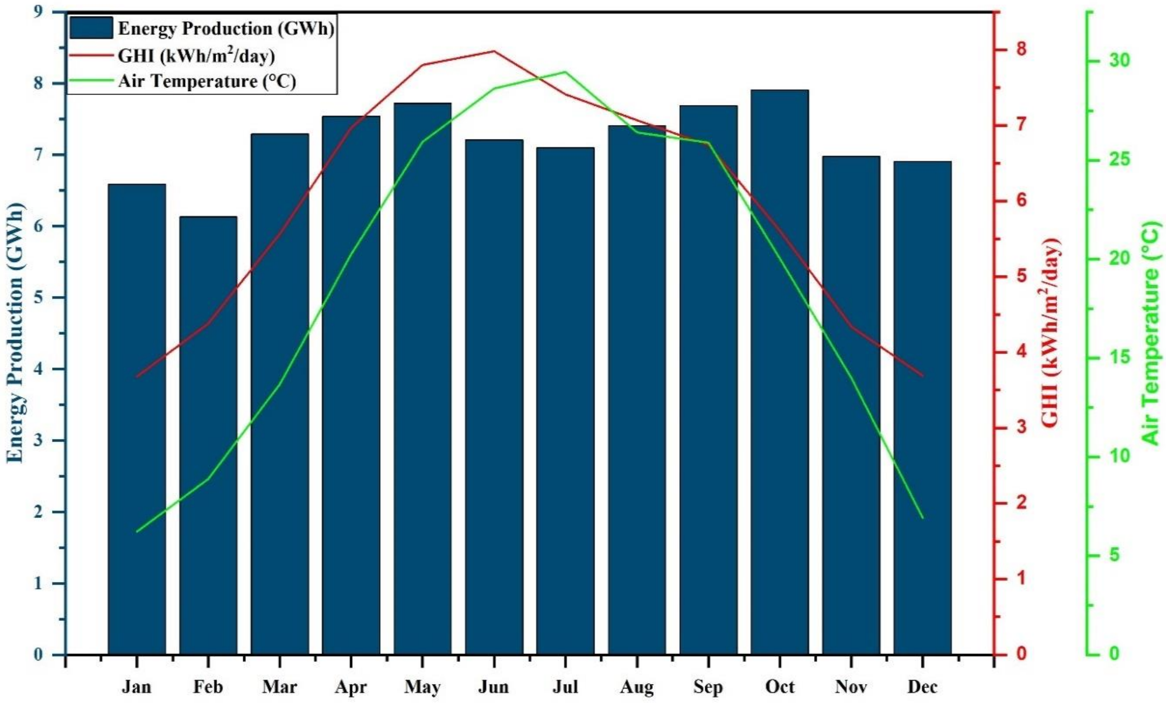

Fig. 4-24: Monthly energy generation and capacity factor of the solar PV plant in Quetta

A tracking system improves energy yield, but it costs additional capital cost to deploy trackers. The parametric simulation showed that 31° is the optimum tilt angle for a solar PV system in Quetta. Table 4-3 shows the difference in energy yield with fixed, one axis, and two axis tracking systems.

Table 4-3
PV system performance variation by tracking mode

Tracking Mode	Fixed tilt	One axis	Two axis
Energy (GWh)	86.51	100.89	112.92
Capacity Factor (%)	19.8	23	25.8
Energy yield (kWh/kW)	1730	2018	2259

Studies show that thin-film modules perform better from performance perspective while crystalline silicon modules perform better from economic perspective. Thus, Thin film modules perform extraordinary at high ambient temperature because of the lower temperature coefficient of modules which makes them a suitable choice for tropical climate regions.

4.2.2 Economic evaluation of PV

In order to determine the feasibility of any energy project, it is very crucial to perform the economic evaluation of that project. System cost and other economic parameters of PV plant are presented in Table 3.9 and Table 3.10, respectively. Results indicate that the installed PV plant in Quetta performs better from an economic perspective. This is due to the reason that PV systems have much lower upfront capital cost as compared to CSP technology. The sizeable negative cash flow at the initial stage of the project indicates the investment cost of the project. The positive cash flow in the next stage indicates the revenue generated through the PV plant by selling electricity to the grid. The levelized tariff of the PV plant is 4.69 cents/kWh with a payback period of 4.1 years. The NPV value of 475.32 million US$ shows that this project is economically feasible. Figure 4-25 demonstrates the after-tax cash flow of solar PV project in Quetta.

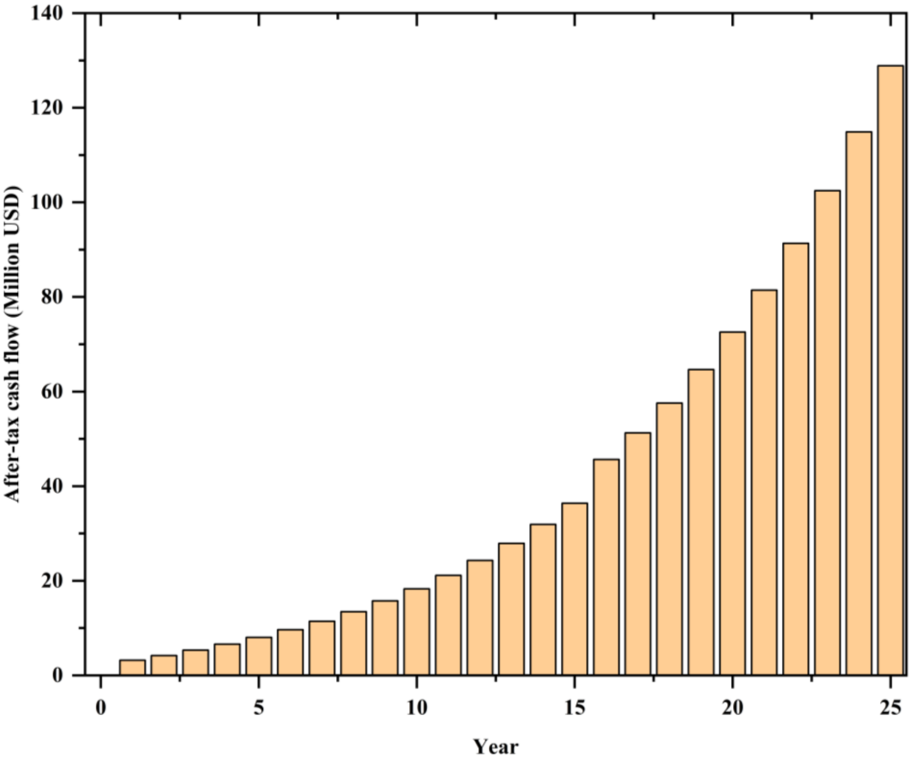

Fig. 4-25: After-tax cash flow of PV plant in Quetta

4.2.3 Sensitivity Analysis of PV

The sensitivity analysis of PV is also carried out on inflation rate and discount rate and a similar to CSP is observed. The inflation rate from 1.0 to 4.0% and the discount rate from 7.0 to 12.0% are varied to find the economic viability of the project. The change in the inflation rate from 1.0 to 4.0% results in a change in LCOE from 5.22 ¢/kWh to 4.21 ¢/kWh and NPV from 242 to 396 million US$ as shown in Figure 4-26. By varying discount rate from 7.0 to 12.0% results in a change in LCOE from 4.43 ¢/kWh to 5.02 ¢/kWh and NPV from 449 to 190 million US$ as shown in Figure 4-27.

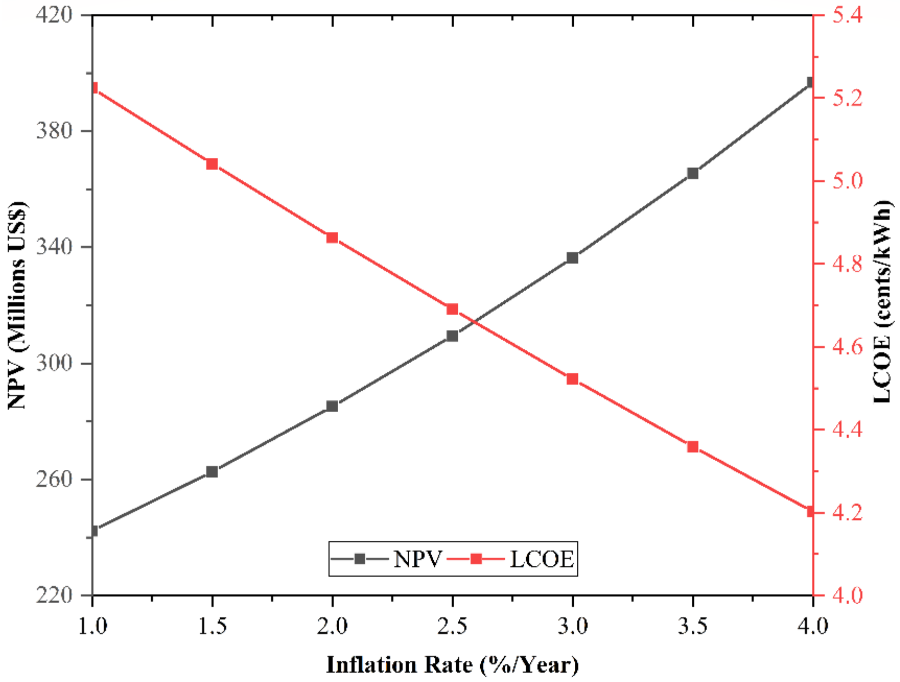

Fig. 4-26: Sensitivity analysis performed on inflation rate for PV system

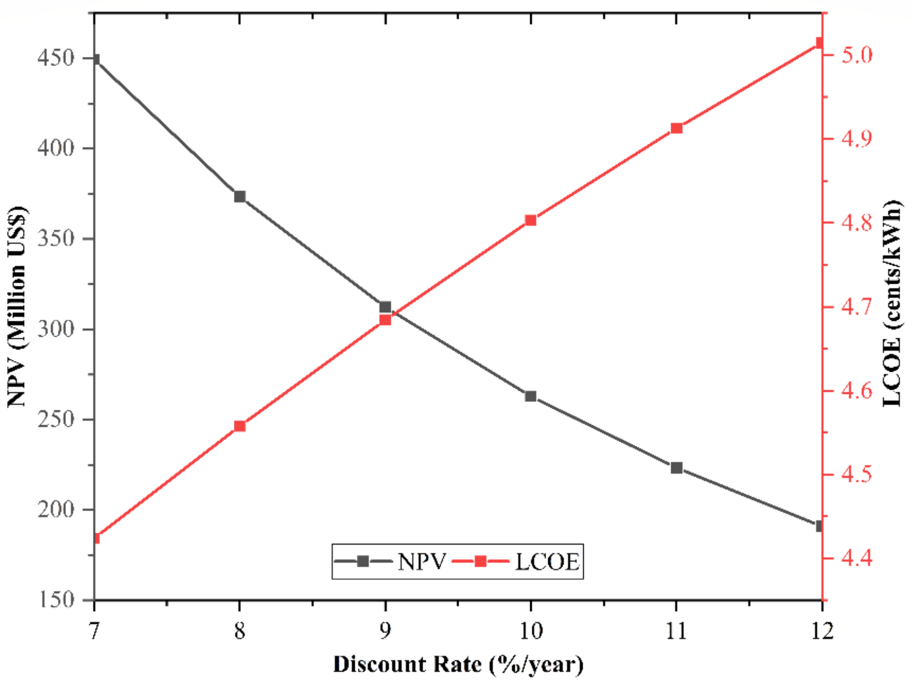

Fig. 4-27. Sensitivity analysis performed on discount rate for PV system

4.3 Environmental Analysis

This section identifies the environmental impacts of installing CSP and PV plants to generate electricity in selected sites. The power sector is considered one of the main reasons for GHG emissions in most parts of the world because of its huge dependence on fossil fuel based thermal power generation. The global energy mix is dominated by fossil fuels which account for more than 80% of energy consumption. GHG emissions can possibly be reduced by deploying cleaner energy technology such as alternative and renewable (ARE). In order to formulate an energy policy with an aim to mitigate GHG emissions and devise an environmental strategy to deter climate change impact, it is provident to accurately estimate GHG emissions from fossil fuel-based plants. Thus, a weighted average baseline scenario is determined to forecast GHGs emissions from the power sector and mitigate those emissions. This baseline emission factor is determined by analyzing the data of power generation plants, their efficiencies, and fuel consumption proportion [2]. In this study, a base case of weighted average GHG emission electricity system is compared with a proposed case of solar photovoltaic and thermal power plants. The baseline weighted average GHG emission factor of the current energy mix scenario stands at 518 gCO_2/kWh for Pakistan, while the GHG emission factor of the life cycle of solar power stands at 16–40 gCO_2/kWh in most cases [3] [4]. GHG emission analysis shown in Table 4-4, is performed on RETScreen. These are calculated as tons of CO_2 avoided or barrels of crude oils not consumed annually because of the use of renewable energy technology instead of fossil fuel based thermal plants. The GHG emissions and fossils fuel saved (FFS) are approximated from Equ. (10) and Equ. (11), respectively.

$$E_{GHG} = A_{rate} \times F_e \times \left(\frac{1 - \eta_{er}}{100}\right) \tag{10}$$

$$FFS = \frac{EG}{\eta_{th} \times NCV} \tag{11}$$

Where,

A_{rate} = Activity rate

F_e = Emission factor

η_{er} = Emission reduction efficiency

EG = Electricity generated

η_{th} = Thermal efficiency

NCV = Net calorific value of fossil fuel

Results indicate that a 50 MW CSP based solar thermal plant in Quetta will reduce 81,423 tCO_2 annual emissions that are equivalent to 189,355 barrels of crude oil consumed. Therefore, these renewable energy projects are a viable source of energy security because country had to import a huge chunk of petroleum products. The complete life cycle water consumption (WC) coefficient for dry-cooled and wet-cooled PT solar thermal plants is 0.9 and 3.98 L/kWh, respectively; while it stands at 0.33 for PV crystalline silicon [5].

Table 4-4
Annual GHG emission reduction figures

Solar Technology	**PV**	**CSP**			
Location	Quetta	Quetta	Karachi	Islamabad	Multan
Annual Energy (GWh)	86.51	160.31	129.26	113.42	112.04
Capacity Factor (%)	19.8	36.6	29.5	25.9	25.6
GHG emissions reduced (tCO_2)	45,606	81,423	65,627	57,619	56,951
Crude oil saved (Barrels)	106,059	189,355	152,622	133,997	132,445

4.4 Comparison of CSP and PV

Quetta is the most feasible site for both solar technologies in terms of NPV. Plant simulation for one year shows that the same capacity of CSP and PV plants for Quetta produce 160.31 GWh and 86.59 GWh energy, respectively. The capacity factor for solar PV is 19% while it reaches up to 36.6% in case of the CSP plant. In terms of economic performance, LCOE of CSP power plant is relatively higher due to its almost 5 times higher capital cost. The land area required to build a CSP plant is larger as compared to PV plant of an equivalent capacity. The simple payback period of most feasible site for CSP plant is 7.7 years as compared to 4.1 years for PV plant.

Through the application of TES technology, CSP systems are capable of storing thermal energy. As a result, they can produce power during periods of little to no sunlight, such as weather transients, peak demand hours, or at night. Due to this ability, penetration of CSP in the power generation industry can be increased because it helps overcome intermittency problems. Meanwhile, PV systems aren’t capable of storing thermal energy since they directly convert sunlight into electricity. So, in terms of energy storage and efficiency, CSP technology is better. On the other hand, PV systems are favored due to their much lower capital cost and being easier to build. A comparison of CSP and PV plants from performance and economic perspectives is shown in Table 4-5.

Table 4-5
Comparison of CSP and PV plant from performance and economic perspective

	CSP	**PV**
Annual Energy (GWh)	160.31	86.51
Capacity Factor (%)	36.6	19.8
LCOE (cents/kWh)	11.57	4.69
Payback Period (Years)	7.7	4.1
Generation (Acres/GWh/year)	2.77	2.33
Capacity (Acres/MW)	8.8	4.06
Solar to electrical efficiency (%)	14.2	20.8
GHG emissions reduction (tCO_2)	93,924	50,812
Net Present Value (USD)	632,200,256	309,513,312

Summary

This section shows results of the performance of CSP plants at four selected sites and a PV plant at most feasible site. The performance of CSP and PV is discussed from technical, economic, and environmental perspective. In the end, a comparative analysis of CSP and PV technologies is drawn on the basis of various decision-making parameters.

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Chapter 5

Conclusions and Recommendations

5.1 Conclusions

The prospects of deploying solar power technology in terms of metrological, technical, economic, and environmental perspectives are analyzed for four selected locations in different climate zones. The availability of high solar irradiance, land, water, infrastructure and grid connectivity makes a location feasible for solar thermal power plants, while ambient temperature and wind speed play a critical role in the performance of solar photovoltaic plant. Solar thermal power generation is found to be technically and economically viable for locations with an average daily DNI greater than 5 kWh/m^2 and a slope angle of no more than 3%.

A study of 50 MW CSP and PV based power plant is simulated for a period of one year. Simulation results show that the northwestern part of Baluchistan is very promising for CSP deployment due to the availability of high solar irradiance. Out of selected sites, Quetta performed better in terms of both technical and financial aspects due to its high solar irradiance availability for CSP and low average ambient temperature for PV based power plant. For Quetta, the annual energy production of CSP is 160.27 GWh with capacity factor of 36.6% while it is 86.59 GWh with capacity factor of 19% for solar PV. The LCOE for CSP power plant is 11.57 cents/kWh with a payback period of 7.7 years while it is 4.69 cents/kWh with a payback period of 4.1 years for solar PV. CSP plant has superior annual energy production and capacity factor in comparison to PV plant, while PV plant is superior in terms of project capital cost and levelized cost of energy. Thus, it indicates that CSP technology performs better from technical perspective, while PV technology performs better from economic perspective. Lack of awareness about the impact of fossil fuel-based power plants on the environment and no interest in shifting towards renewable energy sources is a primary hurdle in adopting clean and green energy. Furthermore, Infrastructure upgradation and modernization is needed to boost resilience and improve the flexibility of diversified system capable of accommodating substantial proportions of renewable energy.

5.2 Recommendations

- This work can be used as reference to carry out the techno-economic and environmental assessment of other CSP technologies such as solar power tower, parabolic dish, and linear fresnel reflectors.
- The proposed model showed reasonably good thermal performance and can be used for forecasting solar thermal power plant potential at any given location.
- This model can be used as baseline for comparative analysis of two different solar technologies CSP and PV for any given location

Appendix A

Publications

Title: Techno-Economic and Environmental Impact Assessment of Concentrated Solar Thermal and PV Systems for Different Climate Zones

Authors: Asad Ullah; Mariam Mahmood; Sheeraz Iqbal; Muhammad Bilal Sajid; Zohaib Hassan; Kareem M. AboRasc; Hossam Kotb; Mokhtar Shouran; Bdereddin Abdul Samad

Abstract: In this study, energy production through two solar technologies concentrated solar power (CSP) and PV is compared from technical, economical, and environmental perspectives. Initially, a 50 MW CSP plant is modeled and simulated at four selected locations in Pakistan, then the most feasible location for CSP plant is compared with a solar PV plant of the same capacity. The impact of solar multiple, thermal storage size, and cooling system for CSP, while tracking system for PV are investigated to evaluate the techno-economic performance of power plants. Technical performance is evaluated on energy generation and capacity factors metrics, while economic performance is evaluated with respect to levelized cost, payback period, and net present value. In addition, environmental parameters such as GHG emissions reduction, fossil fuel savings, and life cycle water consumption are evaluated. From the results, it is concluded that CSP plant located at Quetta is technically and economically viable. The capacity factor of this CSP plant is 36.6% as compared to 19.8% for the PV plant, while the solar to electrical efficiency of CSP plant is 14.2% as compared to 20.8% for the PV plant. The land area required is 2.77 acres/GWh for CSP and 2.33 acres/GWh for PV plant, while the net capital cost for CSP is 5 times higher than that of PV plant. The optimization of different design parameters is performed to obtain the minimized levelized cost of energy (LCOE) for both CSP and PV plants. Results for CSP and PV plants indicate that LCOE can be minimized to 11.57 cents/kWh and 4.69 cents/kWh, respectively. Thus, the CSP plant performs better from technical perspective while the PV plant performs better from economic perspective.

Keywords: Solar PV; Concentrated Solar Power; Techno-economic Assessment; Sensitivity Analysis; Environmental Sustainability

Journal: Energy Reports [ELSEVIER]
Status: Under Review