# Optimization and Techno-Economic Assessment of 50 MWe Solar Tower Power Plant for Different Climatic Zones in Pakistan

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### Abstract

Optimal sizing of solar tower power (STP) plant with full load thermal energy storage (TES) hours and solar multiple (SM) is a challenge to reduce the overall cost of the system and increase system outputs. The growing trends of STP technology worldwide due to its higher efficiency make it an attractive option for several potential sites in Pakistan. The primary aim of this study is to check the effect of SM, solar field, TES hours and design point irradiance on the capacity factor (CF), annual energy generation (AEG) and levelized cost of electricity (LCOE) for STP plant with air-cooled and no backup system. The multi-objective optimization, comparison, and feasibility analysis of 50MW concentrated STP plant were performed at nine stations, receiving more than 1600 kWh/m$^2$ average annual direct normal irradiance (DNI), using the economic model of Pakistan. The solar radiation data of nine stations, used for performance analysis, was measured by ESMAP of the world bank. The techno-economic evaluation of the initial and optimized designs revealed that the optimized design has higher CF, AEG, and lower LCOE. It was found that LCOE depends on the SM, TES hours and DNI value of the location. The results indicate that the least LCOE under the optimized configuration of the proposed plant for Khuzdar is 6.67 ¢/kWh, followed by Quetta 7.25 ¢/kWh for Salt 1 (60% $NaNO_3$ and 40% $KNO_3$). It is, therefore, concluded that Khuzdar is the best-suited place for STP plant installation, followed by Quetta, and Lahore is the least suitable out of the nine stations.

*Keywords: Solar Tower power, Design-point DNI, Solar Multiple, System Advisory Model (SAM)*

## 1. Introduction

Energy demand is increasing rapidly all over the world with population and industrial growth. The environmental issues, high electricity prices and continuous depletion of fossil fuel-based resources have forced the world to harness the energy from renewable technologies (Bellos, Tzivanidis et al. 2017). The share of various energy sources in the total energy mix of Pakistan by the year 2021 for hydral, Regasified Liquefied Natural Gas (RLNG), Residual Fuel Oil (RFO), coal, gas, nuclear, wind, solar, and bagasse was 26, 19.66, 16.84, 12.8, 12.15, 6.68, 3.31, 1.07, and 0.98% respectively. Non-renewable energy contributes around 61.45% of total electricity generation in Pakistan which causes hazardous greenhouse gases (GHG) and exhaust emissions (Energy 2021). Pakistan aims to increase the share of electricity produced from renewable sources (solar, wind, and biomass) to 30% by 2030 (Uddin, Shaikh et al. 2021). Wind power plants have low-capacity factor (CF), intermittency issues, and noise pollution. Whereas high costs, food shortage, reduced efficiency, and a large land requirement are associated with biomass. Solar energy is among the most promising renewable energy options for Pakistan, owing to abundant solar radiation in the Sun Belt region, land and water availability, and high output efficiency. The leading solar technologies deployed for power production are Photovoltaic cells (PV) and concentrating solar power (CSP). The primary technology used to harness solar energy is photovoltaics (PV) cell, but it has shorter life span and storage drawbacks during non-solar hours of the day. Despite the more commercialization of PV systems, CSP technologies have several advantages over PV system because of their higher thermal efficiency, higher CF, better hybrid capability with other fuels and storage system to meet base, intermediate and peak load at night time (Hirbodi, Enjavi-Arsanjani et al. 2020). According to International Energy Agency (IEA) report, the total installed capacity of CSP plants will reach 982 GW as it becomes more competitive technology for power production in carbon-constrained regions of the world by 2050 (International Energy Agency 2014). However, due to the high initial cost, the actual growth


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of CSP is much slower than expected (Chen, Rao et al. 2018). CSP research and economic policies have been developed rapidly worldwide (Amadei, Allesina et al. 2013,page 5). The solar radiations received by major regions of Pakistan are between 4.45 and 5.83 kWh/m$^2$/day, and these values are much higher than the global average solar radiations of 3.61 kWh/m$^2$/day (Zeroual, Ankrim et al. 1995, Ullah, Rasul et al. 2013). CSP technologies use mirrors to concentrate sunlight from collectors (heliostats) to receiver tubes where this heat gets absorbed by heat transfer fluid (HTF) flowing inside the tube. As a result, the HTF temperature increases, and this heat is transferred to water via heat exchangers, where it is converted into steam. This steam then enters the turbine and generate electricity as a result of enthalpy drop of steam. CSP technologies consists of four main categories which include Parabolic Trough Collector (PTC), Linear Fresnel Reflector (LFR), Solar Tower Power (STP) and Dish Sterling technology.

STP technology continues to grow compared to other technologies as this is thermodynamically more efficient than LFR and PTC due to the higher outlet temperature of the system (Ogunmodimu and Okoroigwe 2018,page 5). STP system configuration uses many heliostats that track the sunlight by two-axis movement. These tracking mirrors reflect the sunlight to the stationary receiver located on top of the tower, capturing and storing thermal energy by HTF. HTF then returns to the heat exchangers, where stored heat energy is transferred to water, converting it into high-pressure superheated steam to produce electric power. STP technology often accompanies a thermal storage system that accumulates the excess solar energy collected by solar field and is used to run the plant; at times, solar radiations are not present (Srilakshmi, Suresh et al. 2017,page 1-2). Several studies have been reported to optimize the performance of STP plants throughout the world. A new method proposed by Casati et al. (Casati, Casella et al. 2015) was implemented to design a 100 MW STP plant with optimal storage hours in the USA, and the storage capacity was varied from 1 to 20 h for SM 1.5 to 3.5. Results of that study reported that optimal storage capacity corresponding to SM of 1.5 and 3.5 was 3 h and 20 h, respectively.
Solar multiple (SM) is the ratio of maximum thermal energy received by HTF to the input power required for power block to operate at the design point, and it has a significant role in the economic performance of plant because around 50% of the investment of STP plant is dedicated for heliostat field (Kolb, Jones et al. 2007). A hybrid solar-coal plant was optimized to get optimal SM by Zhao et al. (Zhao, Hong et al. 2017), and they concluded that LCOE and payback period were reduced with the optimization of SM. Design point DNI is a particular value of DNI, received by the solar field that produces the rated electric power output and is strongly dependent on solar radiations of a specific location (Chen, Rao et al. 2018). Low design DNI may result in an oversized solar field, and hence large investment for heliostats and more unutilized energy. Whereases high deign DNI may result in the undersized solar field, and thus smaller capacity factor with poor utilization of invested capital (Desai, Kedare et al. 2014). In the SAM software design point DNI is recommended to be computed at 12 noon on the summer solstice (between June 20-22 for Northern Hemisphere).

Capacity factor is the ratio of average energy generation to the maximum energy that could be generated if the plant operates at its full capacity during the whole period. Higher CF can be achieved with the integration of the TES system at high SM (Izquierdo, Montanes et al. 2010). There is no significant progress made by Pakistan for power production through CSP, apart from a Memorandum of Understanding (MoU) that has been signed between Pakistan and Korea to install a 300 MW CSP plant (Anwar, Mahar et al. 2018). Neighboring countries of Pakistan that have similar infrastructure and meteorological data are making steady progress in deploying the CSP technologies, including India and Bangladesh (Tahir 2021). The estimated potential of CSP without parametric optimization in 591 districts of India using SAM was evaluated to be 2700 GW (Purohit and Purohit 2017).

There are very few studies regarding the feasibility of CSP technologies in Pakistan. A comparative study was carried out for the techno-economic performance of four CSP technologies at four locations in Pakistan. It was reported that a 50 MW STP plant with air-cooling is a promising option for power production in Quetta. This study lacked in parametric optimization (Soomro, Mengal et al. 2019). A recent study presented by Tahir et al. (Tahir 2021), comprehensively analyzed a 100 MW PTC plant for six potential sites of Pakistan using SAM and performed parametric optimization. The minimum LCOE values reported under the optimized configuration of 100 MW PTC plant for Quetta and Pishin were 15.3 ¢/kWh and 14.7 ¢/kWh, respectively. The parametric optimization of the STP plant has not been considered in previous studies for potential sites of Pakistan.

The aim of this study is to compare the techno-economic feasibility of optimized design of 50 MW STP plant with perspective of maximum capacity factor and minimum LCOE. Optimal sizing of the solar field is obtained through number of heliostats and tower design parameters at nine stations of Pakistan receiving more than 1600 kWh/m$^2$ average annual DNI value. A multi-objective optimization technique was deployed to obtain optimal values of SM and TES hours for each station, and with optimal SM and TES hours, two types of molten salts; Salt 1 (60% $NaNO_3$ and 40% $KNO_3$) and Salt 2 (46.5% LiF, 11.5% NaF and 42% KF) were analyzed and best salt is selected. Finally, the most and least suitable stations for the installation of STP plant in Pakistan are proposed.

## 2. Solar Radiation Data

The solar radiation data used in the present work was measured by ESMAP of the world bank at nine stations which include Khuzdar (KZD), Hyderabad (HYD), Quetta (QUT), Lahore (LHR), Multan (MUL), Karachi (KHI), Bahawalpur (BHL), Islamabad (ISB) and Peshawar (PEW). The data was measured from 1$^{st}$ November 2014 to 30$^{th}$ April 2017 for Bahawalpur, Islamabad, Multan, and Lahore; for Peshawar, Karachi, and Hyderabad from 1$^{st}$ May 2015 to 30$^{th}$ April 2017; for Quetta and Khuzdar from 1$^{st}$ October 2015 to 30$^{th}$ April 2017 (Tahir, Hafeez et al. 2021). Two systems were used to measure this data, Tier 1 system was deployed at Islamabad and Bahawalpur, equipped with Kipp and Zonen CHP1 Pyrheliometer to obtain Direct normal irradiance (*DNI*), and Kipp & Zonen CMP21 Pyranometer having CVF4 ventilation system to measure Diffused horizontal irradiance (*DHI*) and Global horizontal irradiance (*GHI*). Tier 2 system was at rest of the stations to measure *DNI*, *DHI* and *GHI*, equipped with CSP Services Twin-Sensor Rotating Shadowband Irradiometer (RSI). To measure relative humidity ($R_H$) and ambient temperature ($T$), Campbell Scientific CS215 was used at Tier 1 and Tier 2 (Amjad, Asim et al. 2021). The details about sensors used in both systems, calibration of sensors, accuracy and uncertainty of sensors is presented in the Ref (Tahir, Hafeez et al. 2020).
The method proposed by the Baseline Surface Radiation Network (BSRN) (Long and Dutton 2010) was used for measured data quality check. First quality check of measured data is done by physical possible limits to recognize any large error present, maximum and minimum values given as eq. 1a and eq. 1b respectively. $G_e$ is distance between earth and sun in Astronomical units, and $G_{sc}$ is the solar constant (1367 W/m$^2$). The second quality check is carried out by extremely rare limits, maximum and minimum values are given as eq. 2b and eq. 2a respectively. Third quality check is applied taking the ratio of measured *DHI* and *GHI*; ratio is a function of solar zenith angle ($\theta_{sza}$), the limits are represented in eq. 3a and eq. 3b. Moreover, since cosine error is a function of $\theta_{sza}$ and it is maximum at lower solar altitude, so solar radiations data having $\theta_{sza} > 85^0$ were not considered (Hafeez, Asim et al. 2021).

$$GHI > -4 \text{ W/m}^2 \quad \text{(eq. 1a)}$$
$$GHI < 1.5\,(G_{sc}/G_e)\,(\cos\theta_{sza}^{1.2}) + 100 \quad \text{(eq. 1b)}$$
$$GHI > -2 \text{ W/m}^2 \quad \text{(eq. 2a)}$$
$$GHI < 1.2\,(G_{sc}/G_e)\,(\cos\theta_{sza}^{1.2}) + 50 \quad \text{(eq. 2b)}$$
$$DHI/GHI < 1.05 \qquad GHI > 50 \text{ W/m}^2,\ \theta_{sza} < 75^o \quad \text{(eq. 3a)}$$
$$DHI/GHI < 1.1 \qquad GHI > 50 \text{ W/m}^2,\ 75^o < \theta_{sza} < 93^o \quad \text{(eq. 3b)}$$

## 3. Methodology

Techno-economic analysis was carried out for the performance evaluation of the solar tower power plant at nine stations in Pakistan under different weather conditions. A 50 MW capacity concentrated solar power plant (CSP) is very common in the world (Trabelsi, Chargui et al. 2016). Since Pakistan has no CSP plants, it would be necessary to install a 50 MW PTC plant to cover the country's base, intermediate and peak loads. An Excel spreadsheet containing user-entered costs was used to provide plant costing information. The analysis of the plant was done with a multi-objective optimization technique using System Advisory Model (SAM). SAM software is developed and provided by the National Renewable Energy Laboratory (NREL), operated by the Alliance for Sustainable Energy for the United States Department of Energy (DOE), and can predict hourly energy production for renewable energy projects (Blair, Dobos et al. 2014, Hernández, Barraza et al. 2020). Several scholars have used this simulation tool to assess the performance and financial feasibility of a variety of standalone and hybrid renewable energy technologies (Bai, Liu et al. 2017, Awan, Mouli et al. 2020, Nassar, Abdunnabi et al. 2021).

## 3.1. Economic and technical modelling

A comprehensive analysis of economic and technical parameters was conducted before the simulations. The main sources of economic parameters were accordingly taxing system of Pakistan and tariffs approved by the National Electric Power Regulatory Authority (NEPRA) for various PV power plants, including Quaid-e-Azam Solar Power, Zorlu Solar Pakistan and Javed Solar Park (Pvt.) Ltd. due to similarity in the taxing policies of PV and CSP for the same country (Authority 2021). Solar power tower technology with a single owner was considered. The exchange rate of 155.007 Rs per US $ ( as on March 19, 2021) was used for the analysis (Pound Sterling Live 2021). The costs of some technical components of the STP plant were used as recommended by SAM (National Renewable Energy Laboratory and Department of Energy 2020). These values are updated in each new version of SAM according to market trends. Project life period was taken as 25 years for all stations, comprising of 2 years for construction and 23 years for operational life. All the economic parameters were assumed the same for nine stations, as these stations are in the same country, ignoring small variations in financial factors for each station. All the main input cost parameters for the proposed plant with thermal storage and no backup system are summarized in Tab. 1.

**Tab. 1: Summary of economic parameters**

| Component | Cost | Component | Cost |
|---|---|---|---|
| Site improvement cost | 16 US$/m2 | Total Land cost | 2000 US$/acre |
| Solar field | 140 US$/m2 | EPC and owner cost | 11% of direct cost |
| Thermal storage (Two tank) | 22 US$/kWh | Contingency | 8 % of subtotal |
| Moratorium | 5 years | Inflation rate | 8 % /year |
| Insurance rate | 0.5% of installed cost | Real discount rate | 6.25 % /year |
| Net salvage value | 10 % of installed cost | Total Land cost | 2000 US$/acre |

Design-point DNI values for each station were taken on the summer solstice at solar noon between June 20 to 22 for Northern Hemisphere to minimize energy losses for each station as recommended by SAM. The design point DNI values were evaluated to be 777, 858, 599, 633, 544, 450, 457, 503 and 640 W/m$^2$ for measured data of KZD, QUT, HYD, ISB, KHI, LHR, MUL, BHP and PEW stations respectively. The built-in capability of SAM, due to integration with NREL's SolarPILOT™ software, was used to optimize the geometrical parameters of the heliostat field, which include receiver height, receiver diameter, tower height, heliostat count and field layout based on measured data of respective location, SM, and design point DNI. These parameters were optimized each time as the SM and design point DNI were changed. This standard optimized modelling of the solar field with two tank energy storage, air-cooled system, and steam Rankine cycle, as defined by NREL, were used for STP configuration. Two types of molten salts were used, designated as Salt 1 (60% $NaNO_3$ and 40% $KNO_3$) and Salt 2 (46.5% LiF, 11.5% NaF and 42% KF).

**Tab. 2: Summary of technical parameters**

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Material type | Stainless AISI 316 | HTF hot temperature | 574 ºC |
| Boiler operating pressure | 100 Bar | HTF cold temperature | 290 ºC |
| Storage type | 2 Tank | Condenser type | Air-cooled |
| Tank height | 12 m | Thermal power cycle | Rankine cycle |
| Cycle thermal efficiency | 41.2 % | Annual degradation | 0.4 % /year |
| Estimated gross to net conversion factor | 0.9 | HTF type | Molten salt |

## 3.2. Optimization procedure

The present study estimates maximum CF and minimum LCOE for plant having thermal storage and no backup system with different combinations of SM and TES hours for each station. To optimize output parameters (CF and LCOE) simultaneously, a multi-objective optimization approach was adopted to obtain optimal values of SM, TES hours, and heliostat field for each station (Awan, Mouli et al. 2020, page 8). After defining all technical and economic parameters, TES hours were varied from 4 to 16 h for SM from 2 to 3. The solar field was optimized for each new value of SM by running an optimization wizard tool. The optimized values of SM, TES, and heliostat field through plots for each station were listed in Tab.3 and Tab.4, respectively. A comparison was made, based on minimum LCOE and maximum CF, among nine stations by taking into account the optimized results. Further, two molten salts were also compared, and the best molten salt is proposed. The structure adopted for the simulation study is presented in Fig. 1.

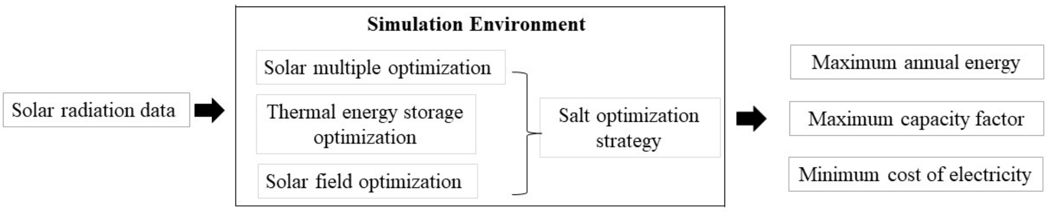


**Fig. 1: Simulation procedure of 50 MWe STP plant**

# 4. Results and Discussion

## 4.1. Optimal SM and TES hours for each station

The determination of optimal SM and TES hours are the key technical parameters for the techno-economic analysis of the STP plant to get a high value of CF and a low value of LCOE. Based on that, an optimized combination of SM and TES hours is chosen for every station based on two output parameters i.e., CF and LCOE. Optimized combinations are so obtained to give the highest CF and least LCOE for each station. It is observed that CF has a direct relationship with both SM and TES hours, as represented in Fig. 2(a), Fig. 3(a) & Fig. 4(a). This is because smaller solar field can use a little part of the solar resource available and hence plant can operate for small duration at its rated capacity during off-peak times, while the large solar field can absorb much of solar energy and the plant can operate for longer duration at its rated capacity during off-peak times. For a specific SM, CF increases linearly with an increase in TES hours at the start, and it becomes almost stable after a certain value of TES hours. This is because, with TES hours increasing, the capacity of the system to store thermal energy also increases. However, the large storage capacity of a system will result in higher thermal losses due to the large volume of the tank. Fig. 2(b), Fig. 3(b) & Fig. 4(b) reveals that LCOE decreases with an increase in TES hours for specific SM. Beyond a certain value of TES hours, LCOE breaks downtrend and tends to increase due to higher incremental cost for thermal storage compared to increment in annual energy generation (AEG). Furthermore, TES hours heavily depend on SM and design point DNI of a location. For a higher value of SM, TES hours and design DNI, the CF is high and LCOE are low. The two stations with the highest DNI are KZD and QUT, whereas the station with the lowest DNI is LHR among nine stations and is represented in Fig. 2, Fig. 3, and Fig. 4, respectively. From the plots of CF and LCOE, it is cleared that large TES capacity and SM are not always beneficial and need to be optimized for each station corresponding to maximum CF and minimum LCOE. For the KZD station, optimized results are obtained at SM 3 and TES 15 h and followed by QUT with profitable size of SM 2.9 and TES 14 h. From Fig. 4, it is observed that the maximum CF and minimum LCOE converges to SM 2.8 and TES 14h for LHR. Thus, there is a tradeoff between minimum LCOE and maximum CF to get the optimal values of SM and TES capacity. The same procedure is adopted for all stations, and final optimized results are listed in Tab. 3.

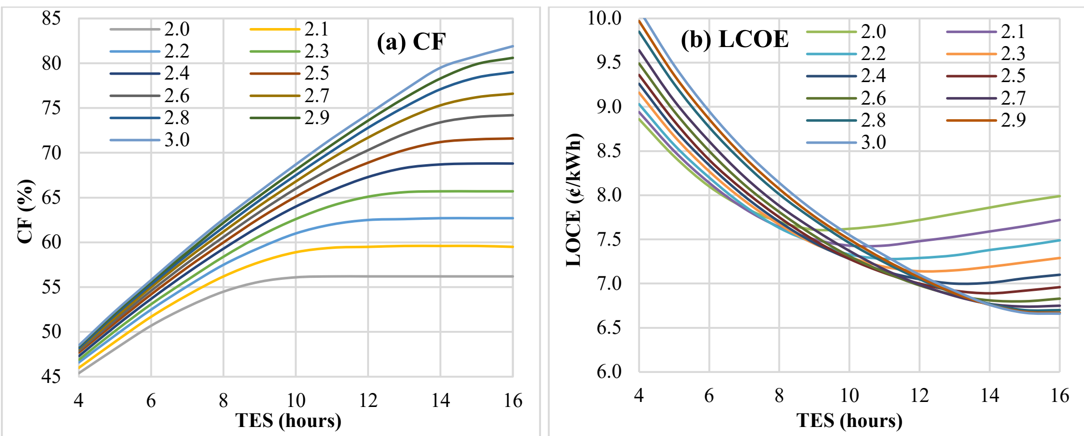


**Fig. 2: Optimized output parameters of Khuzdar for different values of solar multiple against thermal energy storage hours (a) Capacity factor, (b) Levelized cost of electricity**

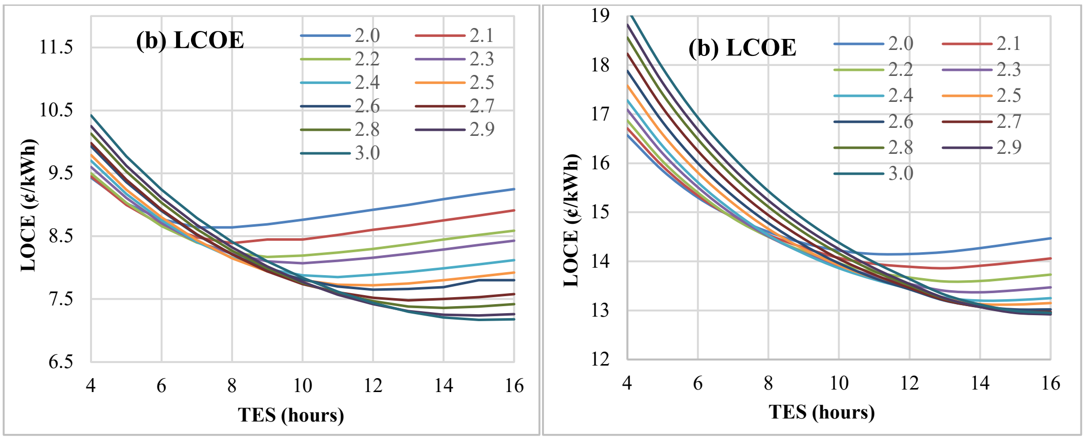


**Fig. 3: Optimized output parameters of Quetta for different values of solar multiple against thermal energy storage hours (a) Capacity factor, (b) Levelized cost of electricity**

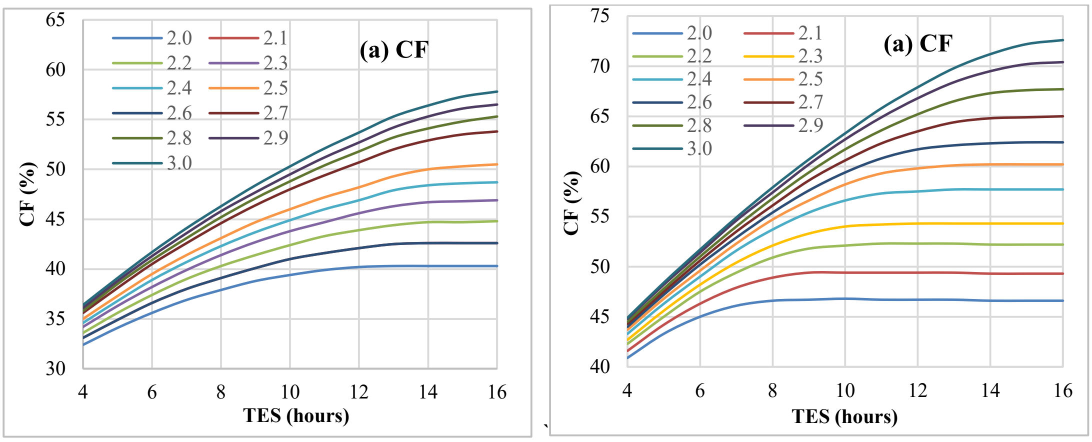


**Fig. 4: Optimized output parameters of Lahore for different values of solar multiple against thermal energy storage hours (a) Capacity factor, (b) Levelized cost of electricity**

**Tab. 3: Optimal SM and TES hours for each station**

| Station | QUT | HYD | PEW | MUL | LHR | ISB | KHI | KZD | BHL |
|---|---|---|---|---|---|---|---|---|---|
| Solar Multiple | 2.9 | 2.9 | 3 | 2.8 | 2.8 | 2.8 | 2.8 | 3 | 2.7 |
| TES (hours) | 14 | 15 | 14 | 13 | 14 | 13 | 14 | 15 | 13 |

## 4.2. Initial and optimized design model

The proposed plant was initially designed with the common values of SM 2 and TES 6 h taken from Tahir et al. study (Tahir 2021), while other cost and technical parameters are given in Tab. 1 & Tab. 2 respectively. The optimization of heliostat field can significantly enhance the performance of STP plant for a location. Small SM in STP plant is not capable of taking advantage of the available solar resource, while large SM requires extra land area, and their optical efficiency is low in the outer heliostat circles. There are some heliostats that do not contribute much during peak solar irradiance hours due to their defocused design to prevent exceeding the maximum thermal flux rating of the receiver. This signifies the need to determine the optimal value of a solar field that gives the plant optimal performance. Tower and receiver design are also important factors and are affected by blocking shading and attenuation losses. A large solar tower has a high construction cost and relatively high attenuation losses without any additional reduction in shading or blocking losses. It is evident that SM, tower height, and TES are interconnected (Carrizosa, Domínguez-Bravo et al. 2015). The performance of heliostat field and tower height is obtained through SAM. Fig. 5(a) and (b) shows the arrangement of heliostat field for KZD with initial and optimized design, respectively. The optimization process involves several iterations due to the interdependency of these parameters. Multi-objective optimization is used to optimize the sizing of these design parameters, and the comparison of the initial and optimized design model is represented in Tab. 4. The resulting receiver height, receiver diameter, tower height and heliostat count of optimized design are larger than that of the initial design for each station, due to higher SM and TES hours. A maximum and minimum value of design parameters are seen for LHR and QUT, respectively. It is found that sites with higher solar energy resources require low value design parameters, whereas sites with lower solar insolation need high-performance parameters.

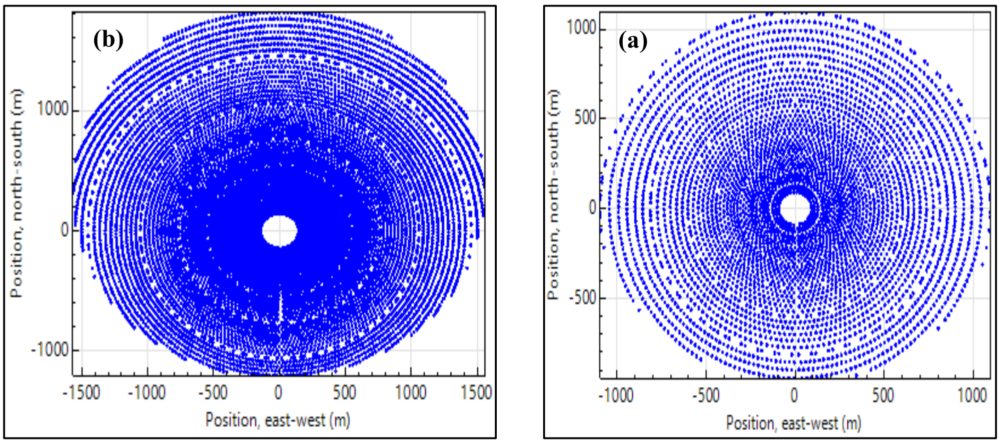


**Fig.5: Solar field layout for Khuzdar at (a) Initial design, (b) Optimized design**

**Table 4: Comparison of initial and optimized design**

| Station Code | Initial Design | | | | Optimized design | | | |
|---|---|---|---|---|---|---|---|---|
| **Design parameters** | **Receiver height (m)** | **Receiver diameter (m)** | **Tower Height (m)** | **Heliostat Count** | **Receiver height (m)** | **Receiver diameter (m)** | **Tower Height (m)** | **Heliostat Count** |
| BHP | 15.64 | 14.78 | 161.59 | 6343 | 17.95 | 16.66 | 178.95 | 8703 |
| KZD | 12.93 | 10.98 | 123.15 | 3974 | 15.87 | 12.82 | 145.38 | 5592 |
| KHI | 14.59 | 14.12 | 149.23 | 5897 | 17.54 | 16.86 | 180.95 | 8230 |
| ISB | 13.97 | 12.75 | 137.9 | 4966 | 16.50 | 12.22 | 168.92 | 6899 |
| LHR | 16.11 | 16.72 | 166.96 | 7249 | 18.49 | 19.11 | 192.40 | 10325 |
| QUT | 12.35 | 10.49 | 117.96 | 3631 | 14.99 | 13.34 | 145.38 | 5210 |
| MUL | 15.39 | 16.21 | 165.89 | 7138 | 18.24 | 19.03 | 191.20 | 10110 |
| PEW | 13.47 | 13.66 | 143.26 | 4830 | 16.09 | 17.27 | 169.57 | 7392 |
| HYD | 13.37 | 13.70 | 142.90 | 5270 | 16.92 | 17.20 | 178.08 | 7897 |

Fig. 6 depicts that AEG is more in the case of optimized design due to the larger solar field. It is observed that the maximum AEG of 318.40 GWh is for KZD, followed by 297.02 GWh for HYD and a minimum 208.9 GWh for PEW. For the KZD station, there are 5592 heliostats in the optimized STP plant, compared with 3974 in the initial design, resulted in 318.40 GWh of energy in the first year of operation. Although the optimized design has approximately 40% more heliostats than the initial design, but it also has approximately 70% more energy output. The same percentage increasing trend of heliostats and AEG can be seen for all the stations in Tab. 4 and Fig. 6 respectively. It is therefore required to optimize the design parameters for STP plant viability.

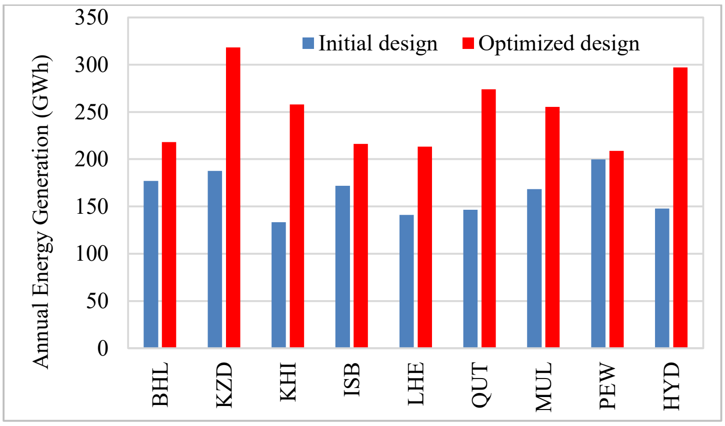


**Fig. 6: Comparison of annual energy generation for initial and optimized design**

## 4.3. Feasibility of STP plant

The optimized results are considered to the feasibility of the STP plant at nine stations. The CF, AEG, LCOE and NCC for each station at optimal design values of SM, full load TES hours, heliostat field and design-point DNI using Pakistan economic model with two salts are shown in Fig. 7 and Fig. 8. A comparison is made between two salts for nine stations based on CF is shown in Fig. 6(a), and it should be noted that all the stations with Salt 1 have higher CF as compared to the corresponding station with Salt 2. Considering the optimized results with Salt 1, the maximum CF of 80.8% is for KZD followed by HYD having CF of 77.2%, and the minimum CF is 53% for PEW. The highest AEG of 318.40 GWh is for KZD and the lowest AEG of 208.90 GWh for PEW with Salt 1 as shown in Fig. 7(b). It reflects that CF and AEG have the same trend for the respective station.

Fig. 8(a) represents a comparison between two salts for nine stations with the perspective of minimum LCOE, and it can be noted that all the stations with Salt 1 have lower LCOE as compared to corresponding stations with salt 2. With consideration of optimized results and salt 1, the minimum LCOE of 6.67 ¢/kWh is for KZD, followed by QUT having LCOE of 7.25 ¢/kWh, and from all stations, LCOE of 13.07 ¢/kWh is the maximum for LHR. Fig. 8(b) represents the NCC is almost same for salt 1 and 2. QUT has the smallest NCC of 441.31 M$ due to good infrastructure, land, abundant solar radiations and water availability. KZD exhibits nearly 16% greater CF and AEG, and a reduction of 8.6% in the LCOE with Salt 1 compared to QUT.

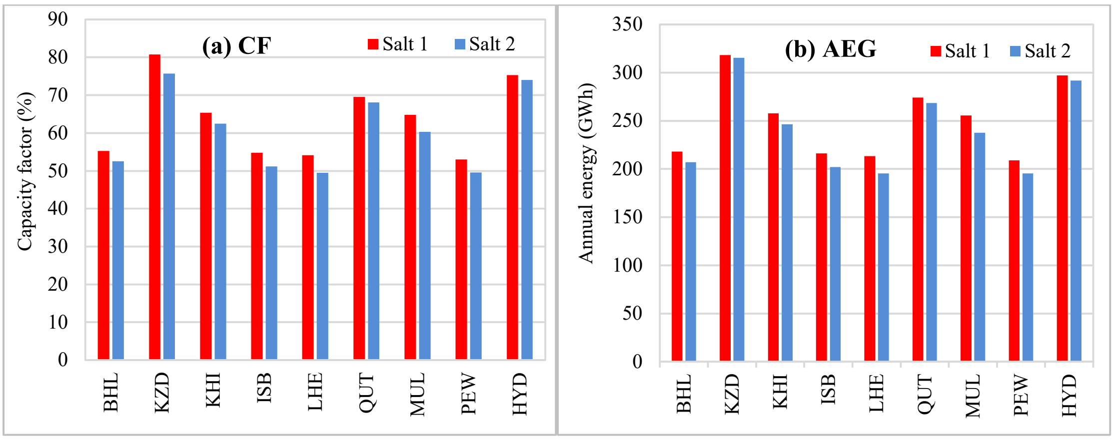


**Fig. 7: Comparison of output parameters for nine stations using two salts (a) Capacity factor, (b) Annual energy generation**

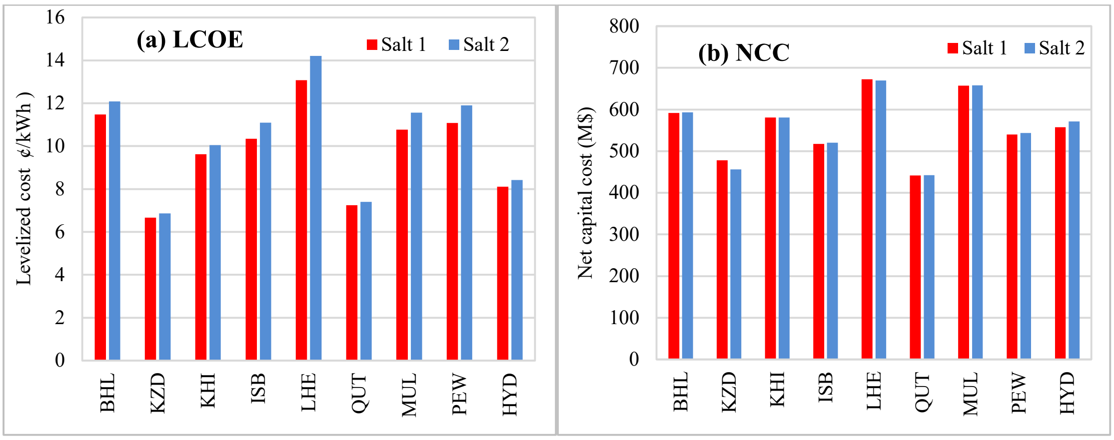


**Fig. 8: Comparison of output parameters for nine stations using two salts (a) Levelized cost of electricity, (b) Net capital cost**

## 5. Conclusion

In this study, detailed analysis and optimization of SM, TES hours and solar field of a 50 MW STP plant with molten salt storage system, financial parameters in accordance with the taxing system of Pakistan, air-cooled and no backup, is carried out with the perspective of minimum LCOE, and maximum CF and AEG. For this purpose, initial design of STP plant for different climatic zones in Pakistan is proposed for SM 2 and TES 6h. Output performance parameters resulted in lower CF and higher LCOE value for each station despite of lower total installed cost of plant. The main reason for limiting value of output parameters is under-sizing of the plant and lower TES hours. The effect of SM and TES hours is analyzed to enhance the performance of output parameters of the designed plant. The comparison of initial and optimized design has shown that the performance of the STP plant was enhanced after parametric optimization. Furthermore, in the case of optimized design, the CF has increased by about 26.2, 24.5 and 18.2% for KZD, QUT and LHR, respectively as compared to the initial design. Also, LCOE has been lowered by an amount of 1.35, 1.50 and 2.21 ¢/kWh for KZD, QUT and LHR stations, respectively. Salt 1 is proposed as a best HTF for this STP configuration because of its better techno-economic performance. The most feasible location among nine stations for the STP plant with optimized SM, TES hours and solar field is KZD with the lowest LCOE of 6.67 ¢/kWh and highest CF of 80.8%, followed by QUT having LCOE of 7.25 ¢/kWh and CF of 69.5%. It is, therefore, concluded that KZD is most feasible, and LHR is not a suitable place for STP plant installation among nine stations due to its high LCOE of 13.07 ¢/kWh and low CF of 54% for Salt 1. The results of this study have revealed that optimization of solar field, SM and TES hours has a significant effect on the techno-economic performance of the STP plant.

## 6. References

Amadei, C., G. Allesina, P. Tartarini and W. Yuting (2013). "Simulation of GEMASOLAR-based solar tower plants for the Chinese energy market: influence of plant downsizing and location change." Renewable energy **55**: 366-373.

Amjad, M., M. Asim, M. Azhar, M. Farooq, M. J. Ali, S. U. Ahmad, G. M. Amjad and A. Hussain (2021). "Improving the accuracy of solar radiation estimation from reanalysis datasets using surface measurements." Sustainable Energy Technologies and Assessments **47**: 101485.

Anwar, N. U. R., W. A. Mahar and J. F. Khan (2018). Renewable energy technologies in Balochistan: Practice, prospects and challenges. Proceedings of the 5th International Conference on Energy, Environment and Sustainable Development (EESD) 2018, Mehran University of Engineering and Technology (MUET).

Authority, N. E. P. R. (2021). "Financing system of Pakistan." Retrieved 9/3, 2021, from https://nepra.org.pk/tariff/Petitions.php.

Awan, A. B., K. V. C. Mouli and M. Zubair (2020). "Performance enhancement of solar tower power plant: a multi-objective optimization approach." Energy Conversion and Management **225**: 113378.

Awan, A. B., K. V. C. Mouli, M. J. E. C. Zubair and Management (2020). "Performance enhancement of solar tower power plant: a multi-objective optimization approach." **225**: 113378.

Bai, Z., Q. Liu, J. Lei, H. Hong and H. J. A. E. Jin (2017). "New solar-biomass power generation system integrated a two-stage gasifier." **194**: 310-319.

Bellos, E., C. Tzivanidis and D. Tsimpoukis (2017). "Multi-criteria evaluation of parabolic trough collector with internally finned absorbers." Applied Energy **205**: 540-561.
Blair, N., A. P. Dobos, J. Freeman, T. Neises, M. Wagner, T. Ferguson, P. Gilman and S. Janzou (2014). System advisor model, sam 2014.1. 14: General description, National Renewable Energy Lab.(NREL), Golden, CO (United States).
Carrizosa, E., C. Domínguez-Bravo, E. Fernández-Cara and M. Quero (2015). "Optimization of multiple receivers solar power tower systems." Energy **90**: 2085-2093.
Casati, E., F. Casella and P. Colonna (2015). "Design of CSP plants with optimally operated thermal storage." Solar Energy **116**: 371-387.
Chen, R., Z. Rao and S. Liao (2018). "Determination of key parameters for sizing the heliostat field and thermal energy storage in solar tower power plants." Energy conversion and management **177**: 385-394.
Chen, R., Z. Rao, S. J. E. c. Liao and management (2018). "Determination of key parameters for sizing the heliostat field and thermal energy storage in solar tower power plants." **177**: 385-394.
Desai, N. B., S. B. Kedare and S. Bandyopadhyay (2014). "Optimization of design radiation for concentrating solar thermal power plants without storage." Solar Energy **107**: 98-112.
Energy. (2021). "Pakistan Economic Survey " Retrieved 9/19, 2021, from http://www.finance.gov.pk/survey/chapters_21/14-Energy.pdf.
Hafeez, S., M. Asim, M. Amjad, M. Farooq, M. Azhar and G. M. Amjad (2021). "Estimation of daily diffuse solar radiation from clearness index, sunshine duration and meteorological parameters for different climatic conditions." Sustainable Energy Technologies and Assessments **47**: 101544.
Hernández, C., R. Barraza, A. Saez, M. Ibarra and D. J. E. Estay (2020). "Potential map for the installation of concentrated solar power towers in Chile." **13**(9): 2131.
Hirbodi, K., M. Enjavi-Arsanjani and M. Yaghoubi (2020). "Techno-economic assessment and environmental impact of concentrating solar power plants in Iran." Renewable and Sustainable Energy Reviews **120**: 109642.
International Energy Agency (2014). Technology Roadmap Solar Thermal Electricity.
Izquierdo, S., C. Montanes, C. Dopazo and N. Fueyo (2010). "Analysis of CSP plants for the definition of energy policies: the influence on electricity cost of solar multiples, capacity factors and energy storage." Energy policy **38**(10): 6215-6221.
Kolb, G. J., S. A. Jones, M. W. Donnelly, D. Gorman, R. Thomas, R. Davenport and R. Lumia (2007). "Heliostat cost reduction study." Sandia National Laboratories, Albuquerque, NM, Report No. SAND2007-3293 **103**.
Long, C. N. and E. G. Dutton (2010). "BSRN Global Network recommended QC tests, V2. x."
Nassar, Y. F., M. J. Abdunnabi, M. N. Sbeta, A. A. Hafez, K. A. Amer, A. Y. Ahmed, B. J. E. C. Belgasim and Management (2021). "Dynamic analysis and sizing optimization of a pumped hydroelectric storage-integrated hybrid PV/Wind system: A case study." **229**: 113744.
National Renewable Energy Laboratory, A. f. S. E., LLC for and U. Department of Energy. (2020). "SAM, System Advisor Model." 9/5/2021, from https://sam.nrel.gov/.
Ogunmodimu, O. and E. C. Okoroigwe (2018). "Concentrating solar power technologies for solar thermal grid electricity in Nigeria: A review." Renewable and Sustainable Energy Reviews **90**: 104-119.
Pound Sterling Live (2021). "Historical Rates for the USD/PKR currency conversion on 19 March 2021." Retrieved March 19, 2021, 2021, from https://www.poundsterlinglive.com/best-exchange-rates/us-dollar-to-pakistani-rupee-exchange-rate-on-2021-03-19.
Purohit, I. and P. Purohit (2017). "Technical and economic potential of concentrating solar thermal power generation in India." Renewable and Sustainable Energy Reviews **78**: 648-667.
Soomro, M. I., A. Mengal, Y. A. Memon, M. W. A. Khan, Q. N. Shafiq and N. H. Mirjat (2019). "Performance and economic analysis of concentrated solar power generation for Pakistan." Processes **7**(9): 575.
Srilakshmi, G., N. Suresh, N. Thirumalai and M. Ramaswamy (2017). "Preliminary design of heliostat field and performance analysis of solar tower plants with thermal storage and hybridisation." Sustainable Energy Technologies and Assessments **19**: 102-113.
Tahir, Z. J. R. S. E. R. (2021). "Validating global horizontal irradiance estimated by McClear model under clear-sky and all-sky conditions in Pakistan."
Tahir, Z. J. R. S. E. R., S. Hafeez, M. Asim, M. Amjad, M. Farooq, M. Azhar, G. M. J. S. E. T. Amjad and Assessments (2021). "Estimation of daily diffuse solar radiation from clearness index, sunshine duration and meteorological parameters for different climatic conditions." **47**: 101544.
Tahir, Z. R., S. Hafeez, M. Asim, S. Imran, A. Hussain and P. Blanc (2020). "Estimation of daily diffused solar radiation from clearness index, sunshine duration and meteorological parameters for different climatic conditions of Pakistan " Renewable Energy.
Trabelsi, S. E., R. Chargui, L. Qoaider, A. Liqreina, A. J. E. C. Guizani and Management (2016). "Techno-economic performance of concentrating solar power plants under the climatic conditions of the southern region of Tunisia." **119**: 203-214.

Uddin, R., A. J. Shaikh, H. R. Khan, M. A. Shirazi, A. Rashid and S. A. Qazi (2021). "Renewable Energy Perspectives of Pakistan and Turkey: Current Analysis and Policy Recommendations." Sustainability **13**(6): 3349.

Ullah, I., M. G. Rasul, A. Sohail, M. Islam and M. Ibrar (2013). "Feasibility of a solar thermal power plant in Pakistan." Thermal Power Plants-Advanced Applications.

Zeroual, A., M. Ankrim and A. Wilkinson (1995). "Stochastic modelling of daily global solar radiation measured in Marrakesh, Morocco." Renewable Energy **6**(7): 787-793.

Zhao, Y., H. Hong and H. Jin (2017). "Optimization of the solar field size for the solar–coal hybrid system." Applied Energy **185**: 1162-1172.