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Research Article

Potential Assessment and Economic Analysis of Concentrated Solar Power against Solar Photovoltaic Technology

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Competition between concentrated solar power and solar photovoltaic has been the subject of frequent debate in recent years based on their cost of fabrication, efficiency, storage, levelized cost of energy, reliability, and complexity of respective technologies. Taking Pakistan as a testbed, a study was conducted to determine which technology is economical in a particular location and climate. The study assesses the meteorological, orographic, and spatial factors that impact the performance and cost of both renewable energy systems. A SWOT analysis, followed by technoeconomic analyses, was conducted to determine suitable sites for setting up solar power plants in Pakistan. A detailed assessment of siting factors for solar power plants was conducted to shortlist the most suitable sites. Based on the results, economic analysis was performed to install 100 MW photovoltaic and parabolic trough power plants at selected locations. The levelized cost of energy for the 100 MW parabolic trough is 10.8 cents/kWh and 12 cents/kWh in best-case scenarios, i.e., for locations of Toba and Quetta, respectively, whereas the LCOEs of 100 MW photovoltaic systems stand comparatively low at 7.36 cents/kWh, 7.21 cents/kWh, 7.01 cents/kWh, 6.82 cents/kWh, 6.02 cents/kWh, and 5.95 cents/kWh in Multan, Bahawalpur, Rahim Yar Khan, Hyderabad, Quetta, and Toba, respectively. The results favor choosing solar PV plants over solar CSP plants in terms of finances in the selected regions. The findings will assist financiers and policymakers in creating better policies in terms of long-term goals.

1. Introduction

The conventional ways of electricity production are facing a huge crisis due to the depletion of natural resources and environmental hazards. According to IEA reports, fossil fuels (coal, gas, and oil) [1] account for over 80% of the global energy mix. Furthermore, reliance on nonsustainable resources exacerbates fuel crisis, inflation, and dependence on finite resources. As a result, glaciers are melting rapidly, posing a serious concern to the earth's future. In 2019, the global CO_2 emissions were 33.4 $GtCO_2$. Then in 2020, global CO_2 emissions declined by 5.8%, the largest of all time, and reached 31.5 $GtCO_2$ (primarily due to the pandemic-induced shutdown of industries. Despite a decrease of 5.8% in 2020, global CO_2 emissions in 2021 increased and reached 33.0 $GtCO_2$ [2]. Greenhouse gases leads to global warming, acid rain, toxic air, and severe climate changes. These climates disrupt and degrade the ecosystem.

The other concern is that the need for electricity is rising every coming day, and transformation to renewable resources to save the environment is inevitable. Solar, wind, hydro, and biomass power plants are the trending technologies for energy production in developed countries. In 2020, the renewable energy share remained at 12.13%, excluding hydropower (16.85%).

Pakistan has been facing a severe energy crisis for a long time. According to the Ministry of Energy, the thermal system (oil, coal, and gas) is still the major source of electricity production in Pakistan, up to 59.42%, followed by hydropower, nuclear, and renewable energy, having a share of 30.52%, 7.82%, and 2.23%, respectively [3]. Renewable energy in Pakistan is at a nascent stage. Although, recent data collections and literature suggest that Pakistan is blessed with a huge solar energy potential for both CSP and PV systems. Pakistan's average solar direct horizontal irradiation (DHI) is 2071 kWh/m^2. With such high solar irradiation, photovoltaic systems are highly appreciated. The average values of solar DHI in Balochistan, Punjab, and Sindh are 2319, 2156, and 2333 kWh/m^2 [4], respectively, while KPK, Northern, and Azad Kashmir possess comparatively low solar irradiation. Overall solar DNI map of the country is shown in Figure 1 [5]. Unlike solar PV, the CSP counts on DNI received.

The location selection for solar technology installation majorly depends upon the availability of solar resources. However, other factors can significantly affect the performance and levelized cost of energy (LCOE). Availability of water resources, wind velocity, land resources, population, and meteorological assessment also affect the CSP finances and PV technologies. A power plant's feasibility requires assessing required siting factors and choosing the most suitable site. Siting factors fall under four categories, i.e., environmental, orographic, spatial, and climatic. The environmental factors include land use, sand/dust risk, water resources, and proximity to a power grid. Orographic factors refer to assessing terrain slope, land cover, population density, and water resources. Spatial factors encompass the assessment of gas pipelines, highways, and transportation, distance to urban areas, and distance from the grid. Climatic factors assess wind speed, rainfall, temperature, solar irradiation, and sun hours.

No comparative studies have been carried out between solar CSP and solar PV technologies in Pakistan hitherto. The present work comprehensively compares performance and economic between parabolic trough (PT) and photovoltaic (PV). The parabolic trough, the most mature and widely adopted CSP type, was selected for comparison [6, 7].

Pakistan has recently updated its renewable energy policies, aiming to produce 20% of its electricity from renewable energy sources by 2025 and 30% by 2030 [8]. The objective is to reduce CO_2-emitting sources and increase clean and renewable energy share in the overall energy mix. The policy includes the development of various technologies such as solar, wind, biogas, geothermal, hydrogen, and storage technologies [9]. More than 350 hydrogen power plants are under development globally that could share up to 24% of global energy demand in the next 40 years, and a memorandum of understanding has been signed to install the first-ever green energy hydrogen power plant in Sindh, Pakistan [10]. Pakistan currently has two nuclear power plants with a capacity of 1100 MW and plans to add 11 new wind power plants with a total capacity of 660 MW by December 2021 [11–13]. The province of Punjab has set a target to generate 5000 MW using different clean energy sources by 2024 [14]. K-Electric has signed to build a 50 MW waste-to-energy power plant [15]. These initiatives are part of Pakistan's effort to reduce its reliance on imported fuels and protect the environment.

SWOT tool has been used for similar situations in different countries. The energy mix of ASEAN nations was also carried out using the SWOT analysis [16]. Researches from different countries, including Jordan [17], evaluated the current status of renewable in the region and the future contribution of RE in electricity production to reach about 10% by 2020. The SWOT analysis was presented to review the resources to develop sustainable energy production systems. Turkey [18] and Eastern Asia [19], including China [20, 21], reviewing the factors affecting the wind power industry in China, have used this tool widely. Research on thermal energy systems for CSPs is gaining particular attention [22]. Researchers recently studied the technical and economic aspects of CSP and PV, including a reduction in capital cost of CSP by using the latest developed equipment and different working fluids in India. The capital cost was reduced to 12.3% using a large aperture area of parabolic trough and advanced heat transfer fluid. Using molten salt as a storage medium and HTF could reduce the capital cost by 29.9% [7]. The economic analysis is carried out using system advisor model. SAM is a software package developed by the National Renewable Energy Laboratory (NREL) in the United States. It is a comprehensive tool designed to support analyzing and evaluating renewable energy systems, particularly solar power projects. Recently, it has been extensively used by many researchers. Agyekum conducted a technoeconomic comparative analysis of PV using SAM with and without storage systems in different climatic regions of Ghana [23]. Amadei et al. have simulated Spain's solar power plant GEMASOLAR in different areas of China [24]. Lashari et al. also performed a technoeconomic analysis using SAM to predict the dish/Stirling system performance in Jamshoro, Pakistan [25]. SAM was also utilized by Guzman et al. for the simulation study of a 50 MWe PT plant in Barranquilla, Colombia [26].

In a recent study, a comparison of performance and cost was carried out between 100 MW CSP (concentrated solar tower and parabolic trough) and PV for the United States of America. The results showed that CSP and PV are both complementary technologies. However, PV was found to be 3 cents/kWh cheaper than CSP, accompanied by the drawback of the unavailability of energy through solar PV systems at night. CSP integrated with a storage system was evaluated as expensive at about 6 cents/kWh [27]. Solar energy potential was assessed for Qatar for long-term and clean electricity production using kriging techniques (Gaussian process regression) [28]. A performance and cost analysis for 50 MW concentrated solar power technologies in four locations of Pakistan, i.e., Quetta, Hyderabad, Multan, and Peshawar, for PT, SPT, and LFR with evaporative and air cooling systems. The LCOEs of PT with evaporative cooling for mentioned locations were 3.69, 5.25, 6.52, and 6.28 cents/

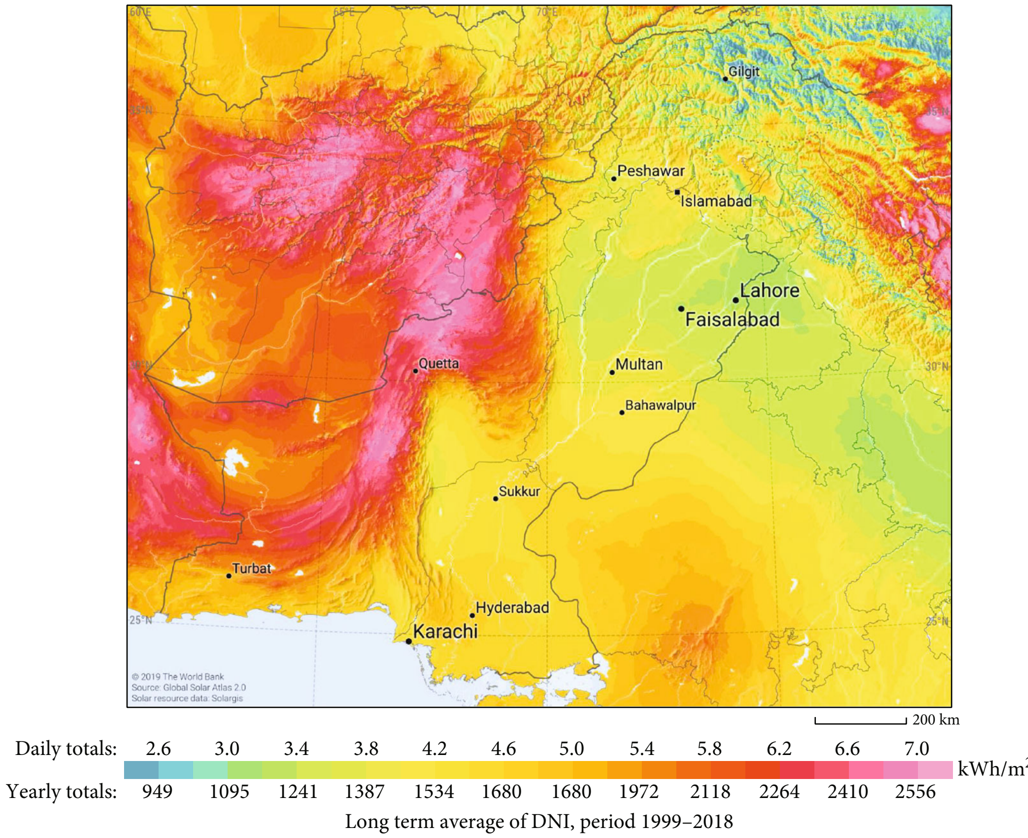


Figure 1: DNI map of Pakistan [5].

kWh, respectively, which increased by almost 11.65%, 16.76%, 18.55%, and 15.12%. For SPT with an evaporative cooling system, the LCEOs calculated were 10.98, 15.27, 19.89, and 15.57 cents/kWh, again going up by 4.1% and 3.6%, respectively, and 2.9% and 22.4%, with an air cooling system. They concluded that tower type is the cheapest and LFR is the most expensive with LCOEs of 11.29, 15.27, 18.93, and 18.18 cents/kWh, while cost increases by 11.7%, 16.4%, 17.64%, and 15.5% with the addition of air evaporative cooling in respective cities [29]. Using the analytic hierarchy process (AHP) method and geographical information system (GIS) technology, a map was presented showing the optimal locations for solar energy power plants in Malatya, Turkey, and found 34 ideal locations for photovoltaic power plants based primarily upon DHI and other siting factors [30].

This work is aimed at significantly contributing to the field of renewable energy by conducting a detailed assessment of the siting factors for both concentrated solar power (CSP) and photovoltaic (PV) systems. To the best of the authors' knowledge, no such comprehensive study has been conducted, making this research unique and novel. Pakistan was chosen as a test case, and multiple locations were analyzed. A thorough technoeconomic analysis was conducted for a 100 MW parabolic trough (PT) against a 100 MW photovoltaic (PV) system in Pakistan. In addition, an economic analysis based on the levelized cost of electricity (LCOE) was conducted for both technologies, and the results were compared. Moreover, a SWOT analysis was carried out for both CSP and PV systems, presenting an overall view of their strengths, weaknesses, opportunities, and threats in Pakistan. The study is aimed at aiding ongoing research efforts in the country and improving the development of parabolic trough and photovoltaic systems.

2. The Current Energy Mix of Pakistan

Developing countries might not have as many funds as wealthier nations; nonetheless, they have lured private investments in large-scale renewable energy projects. Algeria has produced 92.28% of its renewable energy from solar resources. Bangladesh, India, South Korea, Morocco, Ukraine, Vietnam, and Chile have generated 35.5%, 11.54%, 55.4%, 21.78%, 31.67%, 12.71%, and 17.43% of RE directly from sun rays in 2021, respectively. Countries in Africa, Asia Pacific, and North America also sustain their energy on solar resources by generating 8.37%, 14.65%, and 11.04% of their renewable energy, respectively. Egypt, Morocco, and North America get their major portion of renewable energy from wind energy, sharing 27.85%, 65.79%, and 29.84%, respectively [31]. The renewable energy mix of developing countries in 2021 is shown in Figure 2.

Demonstrating the desire of emerging nations to attain a low-carbon, sustainable energy system, in developing countries like Pakistan, the need for industrialization is immense; however, it deteriorates due to a lack of electricity. Due to

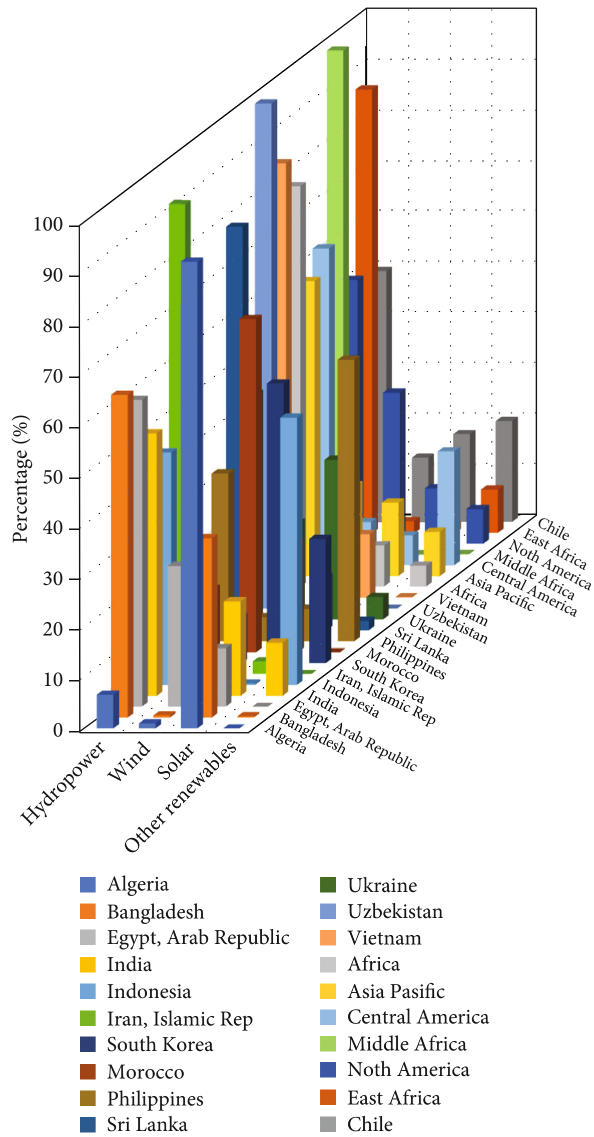


Figure 2: The renewable energy mix of some of the developing countries (2021).

electricity shortages and increased prices, some industries shifted to Bangladesh, India, and Indonesia. Pakistan ranked 37th in energy consumption and 110th among 135 countries for reliable electricity provision to its citizens and industries [32]. The estimated electricity shortage in 2013 was 2000 MW, reaching ~7000 MW in 2015. In 2017, 51 million people in Pakistan were not connected to electricity, causing many industries to shut down or lower production [33]. The electricity imported in 2018 soared to 486.80 GWh and increased by 26.94 GWh in 2019-2020, as stated by government authorities [34]. Pakistan's electricity production is 37,261 MW; the electricity shortage currently stands at 6,500 MW [35]. This shortfall prolonged 6-8 hours in urban areas and 8-12 h in rural summers compared to winters [36]. Conventional nonrenewable resources are depleting and are insufficient to meet the rising need for electricity. Pakistan is producing more of its energy from hydropower plants by 30.52%. According to recent data, in 2020, the total power production from hydropower plants was 29,799 GWh. Thermal systems include electricity production from coal, gas, and oil. Thermal power plants cover 59.42% of the total energy. These resources produce total energy of 61,003 GWh. Nuclear energy produces 7,941 GWh of energy and shares 7.82% of the full energy. On the other hand, renewable energy shares a very low percentage, about 2.83%, and produces 2,322 GWh [3]. Wind energy shares the highest portion of electricity generation through renewable energy technologies in Pakistan. Wind energy shares 2.19% of the total energy production in Pakistan. Even though Pakistan's average monthly solar irradiation intensity is 136.05 to 287.36 W/m^2 [37], it only shares 0.71% of total energy production. The share of coal, gas, and oil in thermal energy covers 20.16%, 12.04%, and 23.73%, respectively [38]. The current energy mix of Pakistan is shown in Figure 3.

The estimated installation capacity of electric power plants in Pakistan is 53,315 MW by 2030 [39]. Pakistan also needs to develop renewable energy sources other than solar energy. A recent study shows that Pakistan has rich agricultural waste sources. Biomass waste includes poultry waste manure, kitchen waste, and sugarcane bagasse. These resources are also highly underutilized [40]. Agricultural waste includes maize, rice, cotton, and wheat residues. It is also found that Punjab is the ideal location for installing BBP. It is the cheapest way to produce electricity among agricultural waste, with maize stalk having an LCOE of 6.8 cents/kWh [41].

3. Potential and Siting Factors for CSP and Solar PV in Pakistan

The leading technologies to exploit solar power can be broadly categorized into two technologies, i.e., the CSP systems and the PV systems. The former's ability to store thermal energy gives it an edge over other renewable energy technologies and attracts researchers [42], whereas advancements in materials, coatings, cleaning strategies, thermal management [43], concentrators [44], and trackers [45] keep solar PV economical. The potential of concentrated solar power and photovoltaics is dependent on numerous factors. The primary factors in deciding the potential of CSP and PV are solar resources, availability of water resources, wind velocity, land resources, availability of natural gas, meteorological conditions, weather conditions, and topography which affect the performance of both the CSP and PV technologies. Other than these factors, proximity to population/cities, road and rail transportation, land assessment, and waste disposal are not the primary determinants, however still count, and their availability aids in determining the site location. CSP technologies depend upon direct normal irradiation (DNI) and work more efficiently at higher DNI. PV works efficiently at higher direct horizontal irradiation (DHI), unlike CSP. Mensour et al. [46] conducted a study evaluating siting factors for the Souss-Massa area in southern Morocco. Cevallos-Sierra and Ramos-Martin [47] also conducted a study to assess the solar potential in Ecuador and South America. They also discussed different regions'

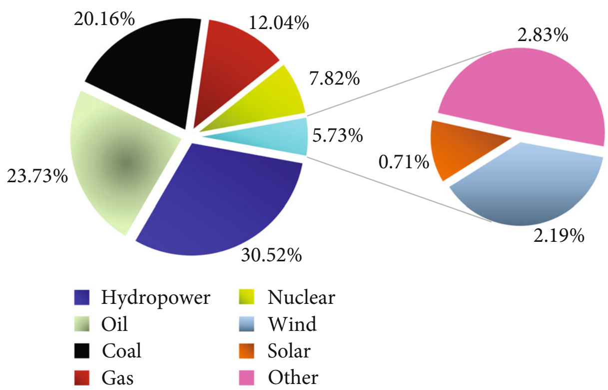
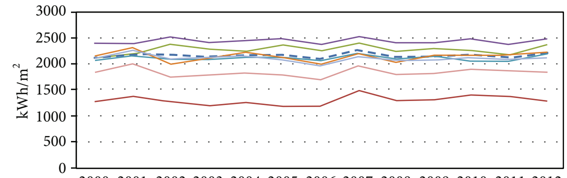


Figure 3: The energy mix of Pakistan (the extended pie-chart shows the share of renewable energy technologies except for hydropower) [38].



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Pakistan	2105	2163	2182	2123	2156	2169	2090	2258	2129	2154	2172	2111	2202
Northern Reg.	1280	1377	1273	1195	1248	1180	1191	1479	1292	1303	1399	1365	1288
Sindh	2149	2186	2357	2281	2248	2362	2255	2389	2237	2286	2251	2169	2360
Balochistan	2384	2390	2510	2399	2446	2474	2379	2518	2407	2400	2476	2367	2477
Punjab	2065	2151	2085	2082	2123	2110	2048	2196	2084	2152	2056	2054	2181
Islamabad	2147	2303	1988	2109	2219	2115	1979	2191	2028	2158	2159	2162	2217
Fata	2108	2251	2093	2123	2149	2072	1960	2144	2060	2070	2113	2090	2101
Khyber P.	1829	1998	1747	1778	1824	1782	1692	1955	1794	1819	1890	1870	1828

Figure 4: Yearly average DNI of Pakistani provinces [49].

spatial factors and solar resources for PV, wind, and CSP. Since no such studies have been done in detail about the siting factors of concentrated solar power and photovoltaic systems in the Pakistan scenario, this research has been covered in the present studies. The next section discusses the potential of CSP and PV concerning the abovementioned factors.

3.1. Solar Resource Evaluation for CSP. Solar resource evaluation is the most important among all the factors. As mentioned earlier, Pakistan possesses rich solar energy resources and suitable locations for CSP and PV. CSP primarily depends upon DNI. The average yearly DNI is around 2100 kWh/m^2 for most regions of Pakistan, as shown in Figure 4. According to the available data, Balochistan has the highest DNI yearly. Therefore, Balochistan is an ideal province for installing CSP technology in Pakistan. In contrast, the KPK, Punjab province, and federal capital Islamabad are the least suitable sites for CSP generation in DNI. The Sindh province has moderate DNI values. However, the CSP would be too expensive in Sindh. The LCOE of CSP generation drastically depends upon DNI [20]. Therefore, even moderate DNI is unfavorable for installing concentrated solar power plants. Hence, Balochistan is the most favorable province for CSP technologies. The direct normal irradiations of some of the major cities of Balochistan, i.e., Quetta, Chaghi, Khuzdar, Kalat, Panjgur, Loralai, Qila Saifullah, Toba, Qilla Abdullah, Chaman, and Qamar-ud-din Karez are 2277, 2100, 2240, 2400, 2264, 1972, 2191, 2400, 2300, 1900, and 2300 kWh/m^2, respectively. With such high DNI values, these locations in Balochistan are ideal for CSP [48].

3.2. Solar Resource Evaluation for PV. Unlike CSP technologies, photovoltaic technology is primarily affected by direct normal irradiation. The value of DHI influences PV system designs significantly. PV is more efficient at higher DHI regions. The western region of Pakistan has a maximum yearly average of greater than 2330 kWh/m^2, whereas in northern Pakistan, DHI remains higher than in high-latitude regions. The average DHI in the Northern parts of Pakistan lies between 1300 and 1750 kWh/m^2 [50], as shown in Figure 5. Solar irradiation intensity is higher in Sindh and Balochistan. The maximum solar irradiation intensity in Sindh is 331.27 W/m^2 during June which drops to 145.29 W/m^2 in December. Likewise, Balochistan possesses an average yearly solar intensity of 150 W/m^2. This value is maximum in June and reaches 329.05 W/m^2 and drops to 135.73 W/m^2 in December.

Similarly, the average DHI in Punjab is 138.73 to 286.81 W/m^2 throughout the year. It is maximum in May, reaching 315.14 W/m^2, and is lowest in December (96.11 W/m^2). The Quaid-e-Azam Solar Park, with a capacity of 100 MW, is situated in Bahawalpur, Punjab. Hence, it can be concluded that regions in Sindh, Balochistan, and Punjab are the most suitable locations for installing PV systems on a commercial scale.

4. Orographic Factors

4.1. Land Assessment for CSP and PV. Land availability is another primary factor that affects solar technologies. Generally, 1 MW requires 20,000 m^2 of land in the case of CSP. The land requirement varies with the value of DNI. Pakistan is the 5th most populated country globally, sharing 2.83% of the world population [52]. The province-wise share of Punjab, Sindh, Khyber Pakhtunkhwa, and Balochistan is 52.96%, 23.04%, 14.69%, and 5.94% of the total population, respectively. The population density of Punjab is 535.63 persons/km^2, whereas comparatively, Balochistan (35.53 persons/km^2), KP (409.40 persons/km^2), and Sindh (339.60 persons/km^2) have less population density [53], as shown in Figure 6. It concludes that all provinces have ample land resources for renewable energy power plants.

The acceptable slope for parabolic trough CSP is 2°. Punjab and Sindh have vast plains having a slope of less than 2° (please refer to Figure 7). However, as discussed earlier, Punjab and Sindh are ideal for PV systems due to the higher direct solar irradiance in these provinces. Multan, Bahawalpur, and Rahim Yar Khan are the most suitable cities in Punjab to install PV systems. Sindh has Karachi, Hyderabad, Larkana, and Sukkur as favorable locations for PV systems. The northern region of Pakistan is a mountainous and hilly area and not an appropriate location for installing PT or PV power plants on a commercial scale. There is also high certainty of landslides and risks of earthquakes which make this region unfit for renewable technologies.

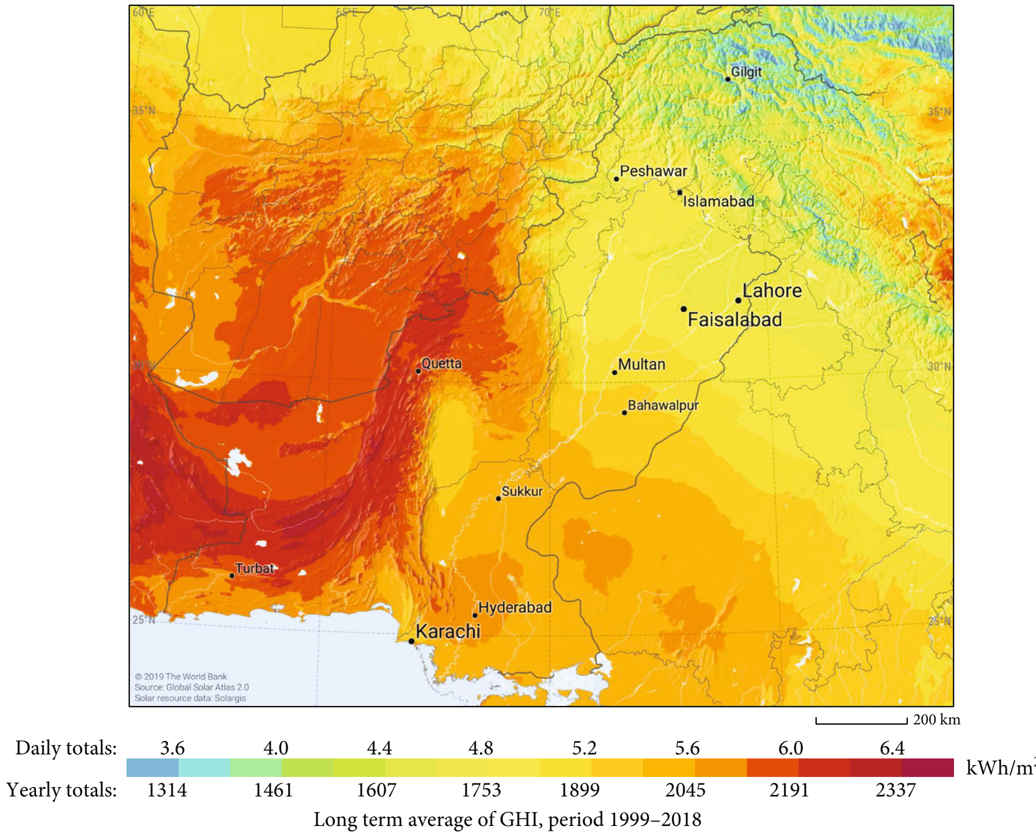


Figure 5: DHI map of Pakistan [51].

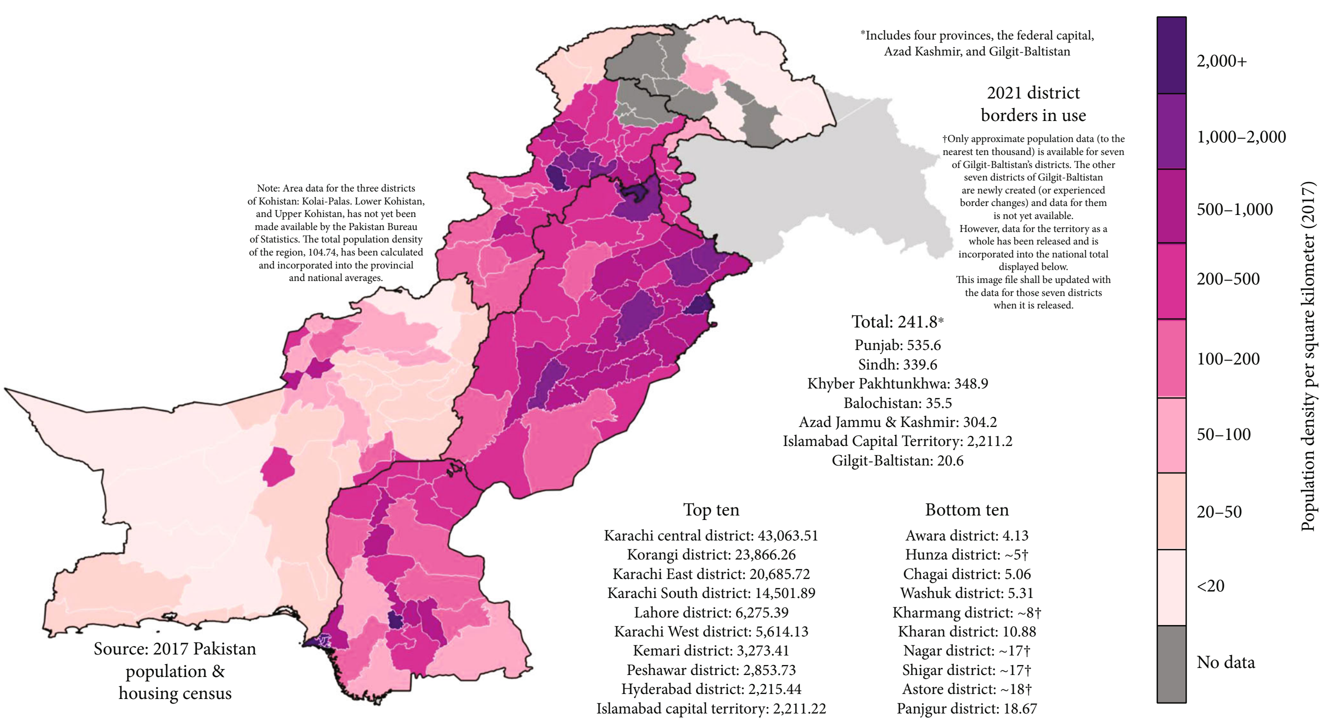


Figure 6: Population density map of Pakistan [54].

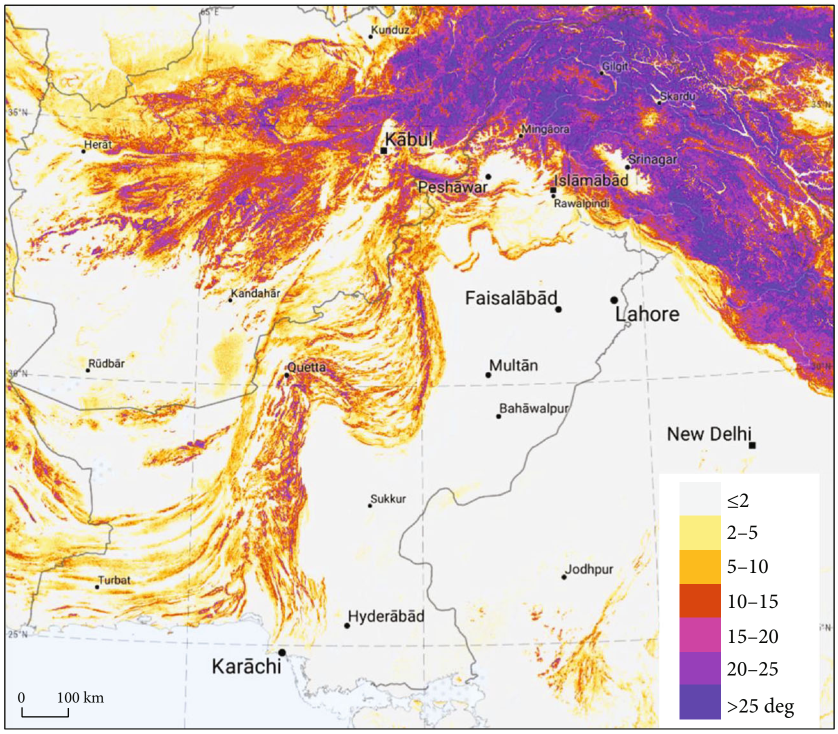


Figure 7: Terrain slope map of Pakistan [56].

On the other hand, Balochistan possesses plains, bare soil, plateaus, dunes, shrublands, and rangeland [55]. Regarding land assessment, we can conclude that Balochistan is the only province with the potential for both CSP and PV technologies and receives a large amount of solar energy. Quetta, Toba, Khuzdar, Loralai, Qila Saifullah, Qilla Abdullah, Chaman, and Qamar-ud-din Karez are ideal locations for CSP and PV.

4.2. Assessment of Water Resource Availability. Steam is used in CSPs operating on the Rankine cycle for power production. However, water is also used as HTF in some plants. Moreover, water is also used to wash/clean heliostats at regular intervals and for cooling purposes. The need for water could be higher for CSP as it is used to cool steam turbine systems. Therefore, regions with water availability are preferred over dry regions for installing CSP generation at a commercial scale [57]. Three types of cooling systems are used, i.e., dry cooling, wet, and hybrid. A water cooling system is more beneficial than dry and hybrid cooling systems. The water cooling method is 7-9% more economical and 5% more efficient than dry cooling system. Hence, water cooling is preferred [58]. In the context of Pakistan, water resource availability is directly related to the irrigation system, as Pakistan has one of the best irrigation systems. The beneficial average irrigation efficiency is 30%, most of which is found in Punjab and Sindh, including some regions of Balochistan.

The rivers and water reservoirs in Pakistan are shown in Figure 8. Fortunately, the rivers' network is also spread across the country except for Balochistan. Four rivers, Ravi, Chenab, Jhelum, and Sutlej, pass through Punjab and fall into Indus River in Punjab. The Indus River enters Sindh and divides into many streams and canals. A river from FATA, named Gomal, enters Balochistan through the Taunsa Barrage and Sukkur Barrage. At the same time, the Indus River passes through KPK. However, unfortunately, KPK does not possess high solar potential. Availability of water resources has a positive impact and thus lowers the LCOE. In Punjab, the regions of Multan, Bahawalpur, and Rahim Yar Khan and cities closer to the Indus River are most suitable for plant installation regarding water resource assessment.

In Sindh, the Indus River splits into several small rivers and canals. The metropolitan city of Hyderabad (and Jamshoro) is also near the Indus River. Although the Hub River passes through different regions of Balochistan and the Kulachi River passes through Khuzdar, Balochistan remains the driest province of Pakistan. The water stress in Balochistan is 80% [59]. Water withdrawal is much higher than replenishing water resources. However, Balochistan's water demand is less because of the lower population.

Pakistan is extracting groundwater for irrigation at a high level and stands 3rd worldwide [60]. Ahmed et al. researched the changing characteristics of groundwater sustainability and found a trend of depletion of groundwater resources in Pakistan. They used GRACE and discovered that the water storage varied from -20.5 to 29.3, -25.4 to 18.1, and -5.3 to 4.6 cm/month for the grids $36.5\circ\mathrm{N}\times 74\circ\mathrm{E}$, $30.5\circ\mathrm{N}\times 73\circ\mathrm{E}$, and $26\circ\mathrm{N}\times 62.5\circ\mathrm{E}$, respectively. Where the negative sign indicates a decrease in water storage, they concluded that the water storage is decreasing by -16.87 to -12.58 cm/year in the north and central east [61]. The groundwater shortage in other regions of Pakistan is

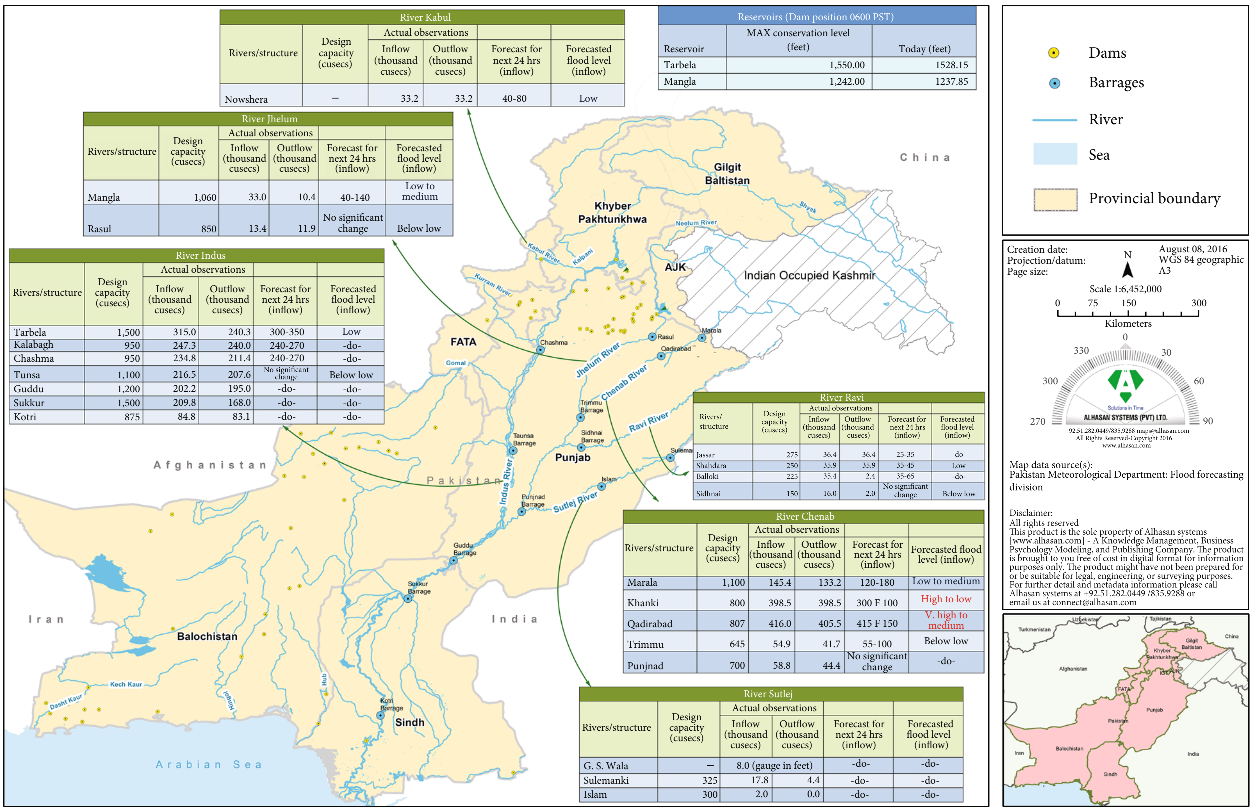


Figure 8: Water reservoirs and river map of Pakistan [63].

shown in Figure 9. The groundwater storage depletion in the eastern side of Pakistan is immense due to the intensive use of groundwater for irrigation [62]. However, in the south-eastern part of Pakistan, annual precipitation is quite low, and the water stress is 80%, as mentioned earlier.

The groundwater level has already begun to deplete. The period from 2002 to 2016 has shown a great groundwater deficiency in Pakistan's agricultural area [61]. Therefore, groundwater is not favorable for developing renewable energy power plants in upper Punjab. However, the cities of lower Punjab, i.e., Multan, Bahawalpur, Rahim Yar Khan, and Sadiqabad, are the ideal locations for PV power plants concerning the availability of water resources. In Sindh province, Guddu, Sukkur, Jamshoro, Kotri, Hyderabad, and Kashmore are the best PV locations near rivers and canals, while in Balochistan, the situation is challenging and water resources are scarce. Natural water resources are almost depleted due to high levels of water stress. Therefore, there is no water available for RE power plants in Balochistan. Although Balochistan has the highest land area and maximum solar DNI and DHI, Khuzdar, Quetta, Toba, and Qilla Abdullah are the ideal locations for the selection based on solar resources, which poses a challenge due to water shortage.

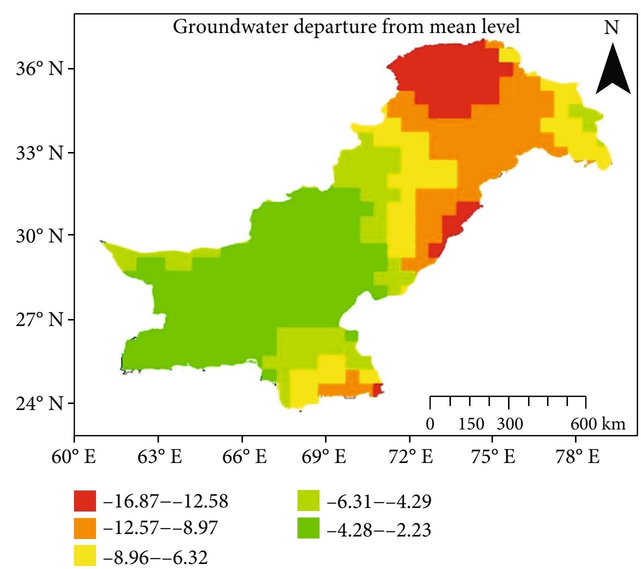


Figure 9: Groundwater shortage departure from the mean level in Pakistan (2002-2016) [58].

5. Meteorological Assessment

5.1. Wind Effect and Assessment. Wind speed, temperature, direction, and peak wind speed are important factors to consider before selecting the location for plant installation. High-speed wind can severely affect the infrastructure and structural parameters. High-velocity wind could reduce the optical efficiency of the solar panel. It could also break the heliostat in the case of CSP plants. Wind gusts in Pakistan vary from 1 m/s to 7 m/s, and the peak value is observed in Balochistan's southern and western regions. The wind gust map of Pakistan is shown in Figure 10. Heliostat shape,

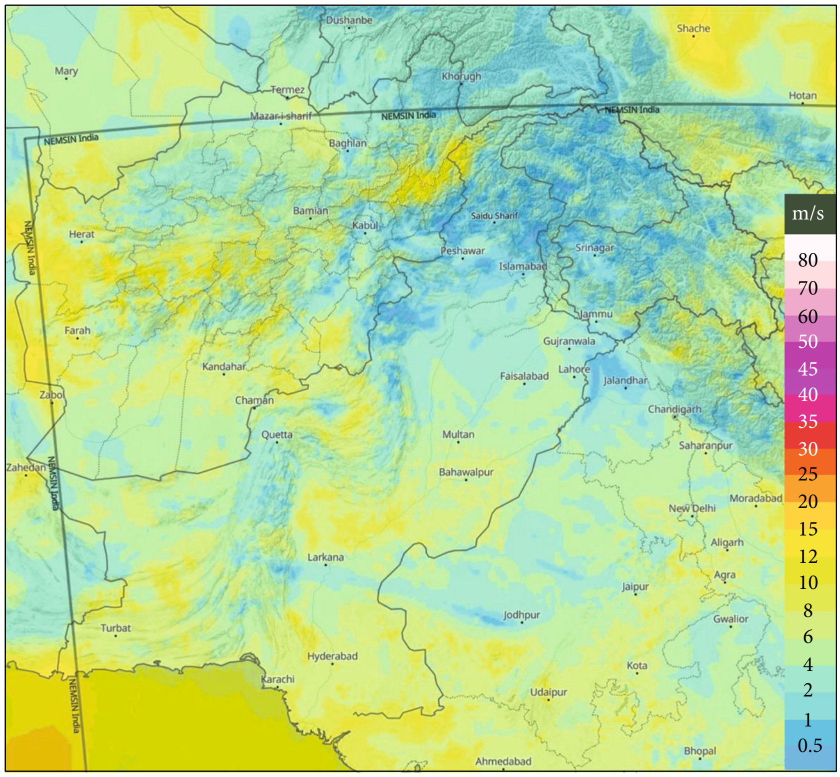


Figure 10: Wind gust map of Pakistan [69].

design, interpanel gap, inclination angle, ground clearance, and structural strength may change wind velocity and its effect [20]. High-speed wind increases heat losses due to convection, which reduces plant efficiency [64]. In the desert, sand particles mix in the air and cause soiling. It makes the mirror's surface rough by brushing sand particles on the heliostat's surface. The sand particles are stuck in different components and reduce their functional efficiency. Maintenance, washing, or cleaning in deserts may be needed weekly to maintain efficiency. Wind, without contaminants (sand/dust), is beneficial for PV power plants.

In this case, the solar panel works more efficiently in a cool environment, where the wind provides the cooling effect [65]. In the case of CSP, since no cooling is required, wind decreases the power output as it increases heat losses [66, 67]. The maximum wind speed limit for heliostat and parabolic troughs is 22 m/s [68]. Beyond this limit, the heliostat is stowed, and plant function is paused. The wind velocity map of Pakistan is shown in Figure 11. The average wind velocity of Pakistan is less than 10 m/s. The wind velocity is slightly higher in lower Punjab than in upper Punjab.

In the case of PV, lower Punjab has better options than cities of upper Punjab. KPK is not a suitable province for solar power plants, whereas in Balochistan, wind speed is about 8 m/s in sun-belt regions. It is a positive factor for PV panels. On the other hand, high-speed wind regions in the south of the Afghanistan border and east of the Iran border are not recommended locations for CSP. Only sun-belt regions, i.e., Quetta, Chaghi, Khuzdar, Kalat, Qila Saifullah, Loralai, and Toba, are suitable for CSP plants.

5.2. Assessment of Humidity, Rainfall, and Flood Risks. Rainy weather and humidity are strongly unfavorable for CSP and PV power plants. Regions with unpredictable rainfalls, high-intensity rain, and long rainfall duration are not recommended. Cloudy weather and humidity in the air decrease the efficiency of PV panels and heliostats. Humidity in the air settles as water droplets on the panel's surface. When light falls on water droplets, the light may refract, diffract, and reflect, degrading the efficiency of solar panels in the case of PV power plants [71].

Predictable rainfalls are helpful for CSPs as it aids in washing the dust off the heliostats. However, the moisture on the mirror's surface may reflect the light at a different angle and deviate it from falling on the thermal receiver. Humidity varies depending on the season; the maximum average humidity in Pakistan is 60.3% in January. Humidity starts decreasing in an irregular pattern and observed minimum in June and November at 28.8% and 28.6% and increasing till January [72]. The relative humidity in Punjab, Sindh, and some regions of KPK is almost the same and varies from 10% to 15%, whereas in Balochistan, humidity varies from 20% to 30%, as shown in Figure 12. According to the observation, average humidity is minimum from March to November.

Therefore, Punjab, Sindh, and Balochistan are ideal provinces for RE power plants in summer in perspective of humidity factor, except for locations with lower DNI and DHI values.

Pakistan faces a cycle of rainfall during summers known as the monsoon. The average rainfall in Pakistan is less than 200 mm annually [74]. Upper Punjab and KPK are the most

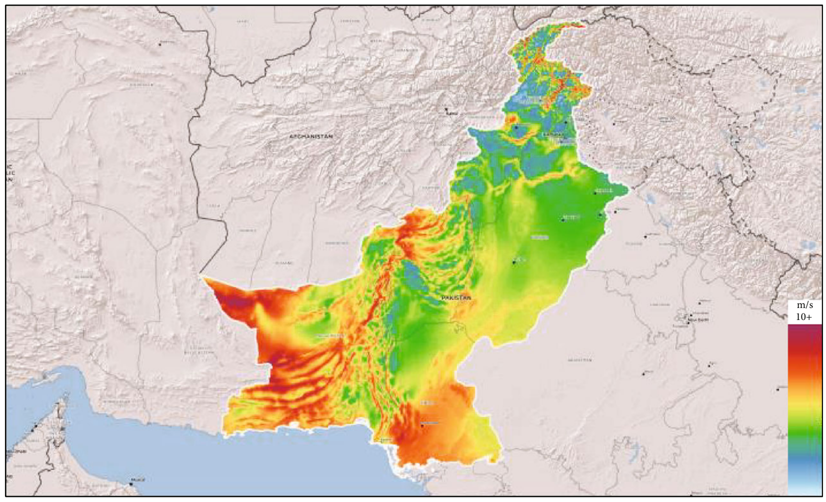


Figure 11: Wind velocity map of Pakistan [70].

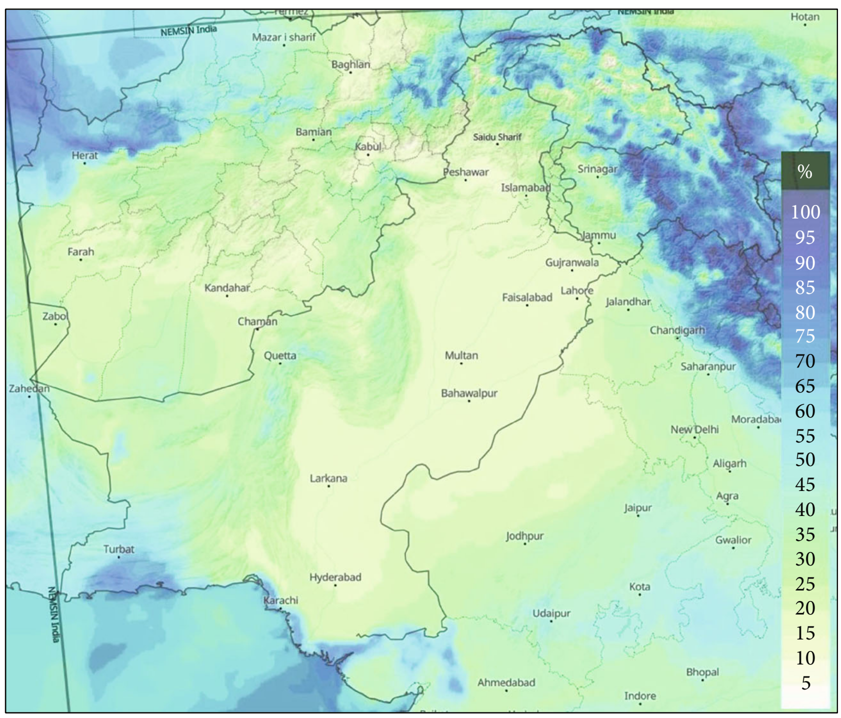


Figure 12: Relative humidity map of Pakistan [73].

affected regions during the monsoon. These regions receive about 500 mm of rainfall per annum. In the northern areas, annual precipitation is up to 750 mm, i.e., much less in south Punjab, Sindh, and Balochistan. In south Punjab and Sindh, yearly rainfall is limited to 250 mm. In contrast, the average rainfall is 50-125 mm per annum, which decreases to 25-50 mm in the southern and eastern regions of Balochistan [75]. It is way less than Sindh and south Punjab; the overall precipitation statistics are shown in Figure 13. The precipitation map of the country is available on the website [76].

Flood risk is very high in regions of South Punjab, including Multan, Rajanpur, D.G. Khan, Muzaffargarh, and Jhang. Ghotki, Thatta, Khairpur, and Jamshoro in Sindh face floods frequently. Besides these cities, Bahawalpur and Rahim Yar Khan are suitable locations for PV in Punjab. There are no severe flood risks in Balochistan except in Washuk and Kharan. Besides these cities, Balochistan is a highly favorable location for CSP and PV in climatic conditions. The flood hazard map of Pakistan is shown in Figure 14.

Under consideration of rainfall, humidity, flood risks, and other meteorological factors, cities in lower Punjab, i.e., Bahawalpur, Khanpur, and Rahim Yar Khan, are recommended locations for PV. Despite having good solar energy resources, Multan is still not an ideal location due to the high risk of floods annually. Rainfall, humidity, and other factors

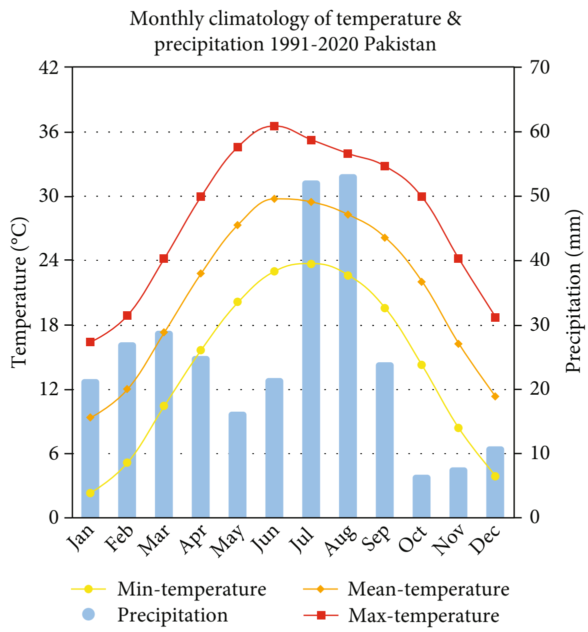


Figure 13: Annual rainfall in Pakistan [76].

are bearable. Sindh bears even more significant flood risks than Punjab. Sukkur and Hyderabad are the only locations with fewer flood risks. Although Sindh has planned to plant the first-ever solar park capacity of 400 MW, flood risks are very high in Jamshoro [78]. Therefore, safety should be considered beforehand. High flood risk locations, i.e., Ghotki, Khairpur, and Thatta, are not recommended. Flood risks are less in Balochistan compared to Sindh and Punjab. Balochistan is the safest province from flood and is suitable for installing RE technologies.

Moreover, no unpredictable high rainfall is expected in Punjab and Sindh, and humidity is also low during summers, whereas in Balochistan, sun-belt regions are recommended. Although predictable rainfall is essential to renew the water resources, the rain shortage in Balochistan is also a drawback for RE power plants.

6. Proximity to the Power Grid

Proximity to the power grid is a critical and essential factor for the power plants to transfer the generated electricity through electric transmission lines and power stations. Power stations then supply the electricity to the consumers. Currently, a total of 45 grid stations of 220 kV and 16 grids with the capacity of 500 kV are working in Pakistan. 11 grids of 250 kV and two grids of 500 kV in Islamabad, 19 grids of 220 kV and five grids of 500 kV in Lahore, five grids of 220 kV and four grids of 500 kV in Multan (MEPCO), five grids of 220 kV and 500 kV in Hyderabad, and only five grids of 220 kV in Quetta are working [79]. Over 5900 km and 11322 km transmission lines are connected to these 16 grids of 500 kV and 220 kV, respectively. The 500 kV grid station Sheikh Muhammadi in Islamabad is connected to Tarbela. The installed capacity of 1350 MVA feeds the major regions of Khyber Pakhtunkhwa [80].

In contrast, the Rawat grid is connected with Ghazi Barotha powerhouse and provides utilities in Islamabad. Nokhar grid station of 500 MV and Tarbela powerhouse are also connected to Rawat GS [81]. Grid stations in Attock, Sheikhupura, Faisalabad, Nokhar, Lahore, and Sahiwal, including 220 MV GS (Sialkot, Gujrat, Gakhar, Kala Shah Kaku, Okara, Sargodha, and Wapda Town Lahore), are making sure the transfer of electricity from sources to the important regions of Punjab. In short, upper Punjab has strong interconnectivity of grid stations. Multan, Muzaffargarh, Rahim Yar Khan, and D.G. Khan have operational 500 MV grid stations in south Punjab. In Bahawalpur, 220 MV GS is fully operational and connected to Quaid-e-Azam Solar Park. Four big grid stations, Guddu, Dadu, Jamshoro, and NKI grid stations of 500 kV, are working in Sindh. These are also interconnected with each other, respectively [79], whereas in Balochistan, only two grid stations of 220 kV are working in Quetta industrial area and Sibbi. Electricity comes from Guddu to Sibbi and then is transmitted to Quetta industrial area. Despite the national electrification rate of 72%, Balochistan is restricted to only 26%, whereas the main supply is limited to one supply line from Guddu-Sibbi-Quetta. Therefore, an alternate route was proposed from Dadu to Khuzdar to improve the voltage [82].

Accessibility to grid stations is an additional advantage for site selection. Most regions of upper Punjab have strong grid connections, which could be used if solar power is installed in those regions. Lahore, Sahiwal, and Faisalabad, including small grid stations, are useful for this purpose. Grid stations in Multan, Bahawalpur, and Rahim Yar Khan could provide utilities if the solar power plant is installed in these locations. Therefore, these are the ideal locations for connecting transmission lines to transmit electricity from power plants, whereas in Sindh, Guddu, Jamshoro, and NKI grid stations cover many regions of Sindh. RE plants could be installed nearby these locations, whereas Jamshoro grid station is fed with Dadu and NKI. In Balochistan, only two grids work in Quetta industrial area and Sibbi. If the power plant is installed in Balochistan, only two locations (Quetta and Sibbi) will give an advantage to a power plant. Other than these cities, transmission lines will have to be installed. Transmission lines and grids of Pakistan are shown in Figure 15.

7. Spatial Factor

7.1. Transportation. A critical criterion for investment is the to-and-from transportation system from the location. The stronger the transport system, the easier it is to access the site and the lower transportation expenditures. Roads need to be built before commissioning the power plant to transport the necessary components to install any power plant. If there is no road linkage to the selected locations, new roads will have to be constructed, and it will cause additional expenses [30]. The China-Pakistan Economic Corridor (CPEC) project fulfills essential road needs. KKH Phase II (Havelian-Thakot) 40 km long motorway and 80 km long highway are constructed in KPK. The 1100 km long

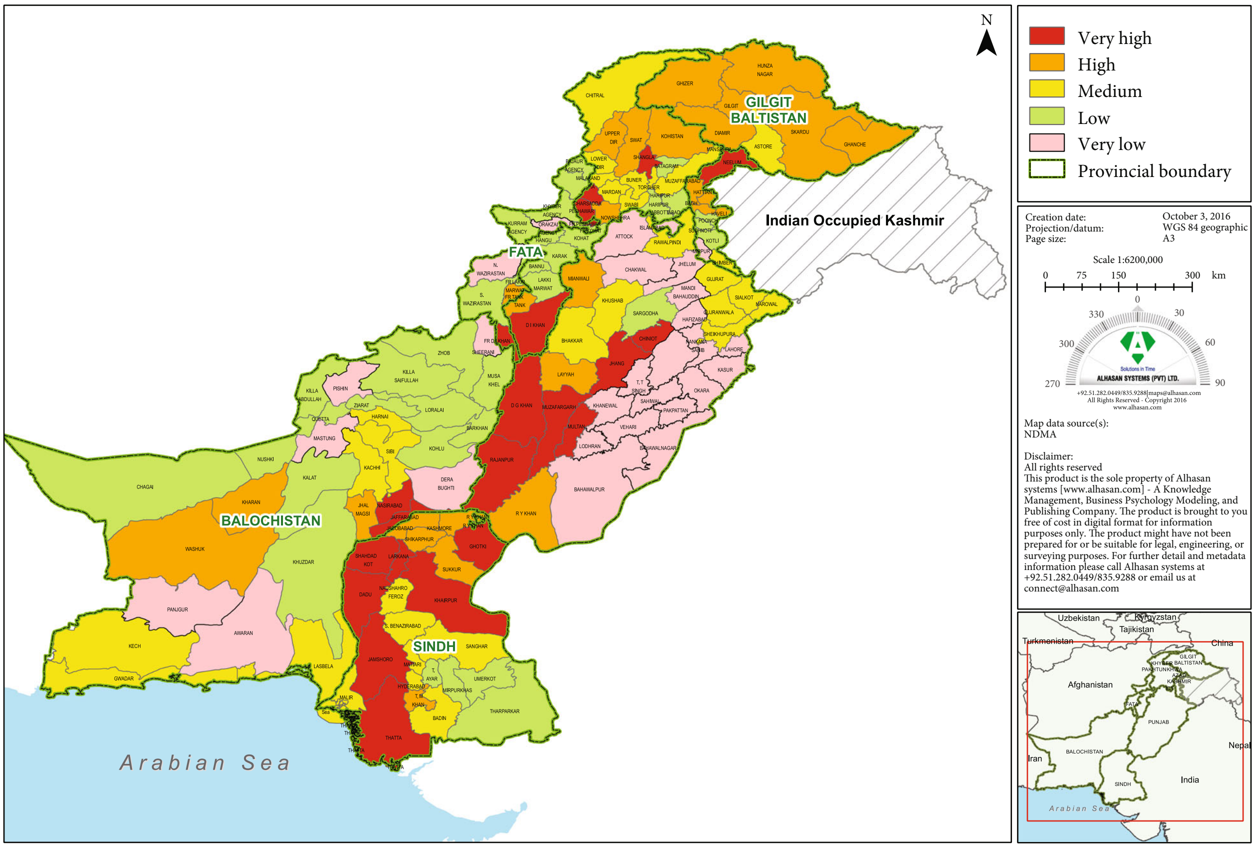


Figure 14: Flood hazard map of Pakistan [77].

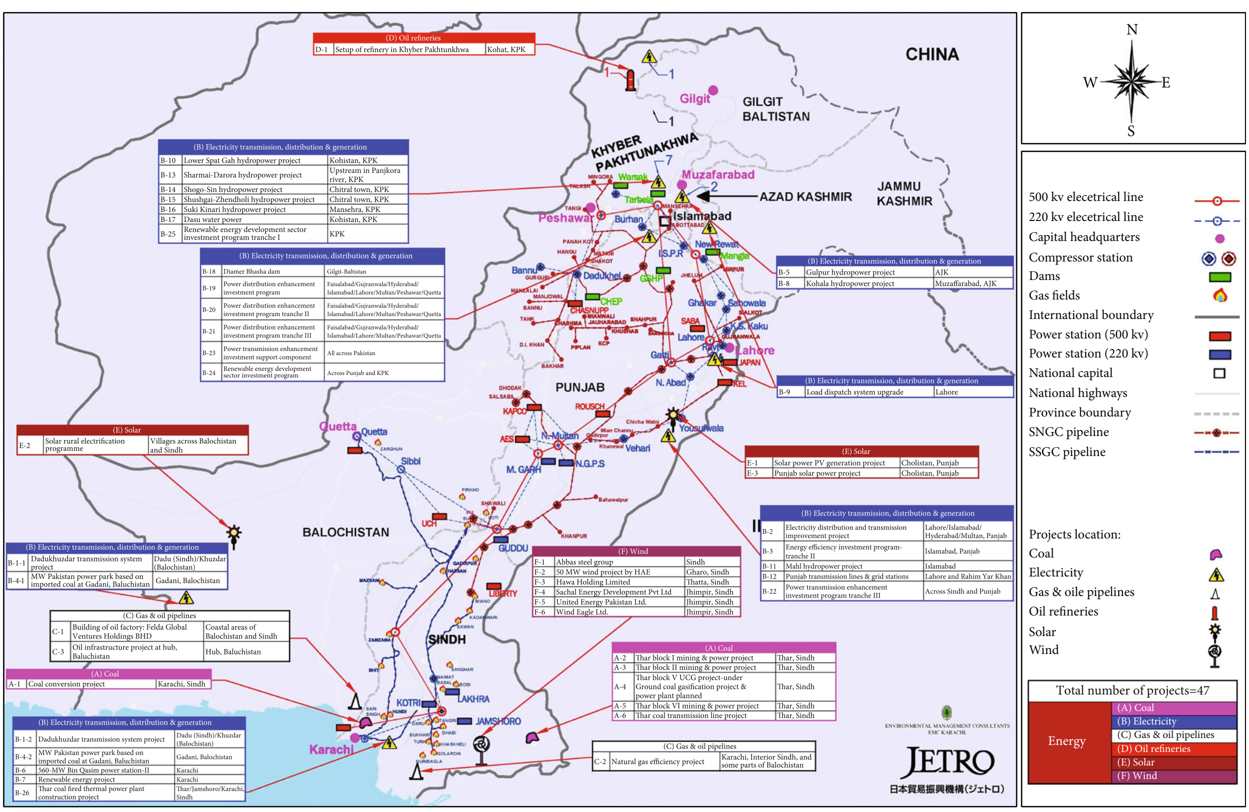


Figure 15: Grid map of Pakistan [83].

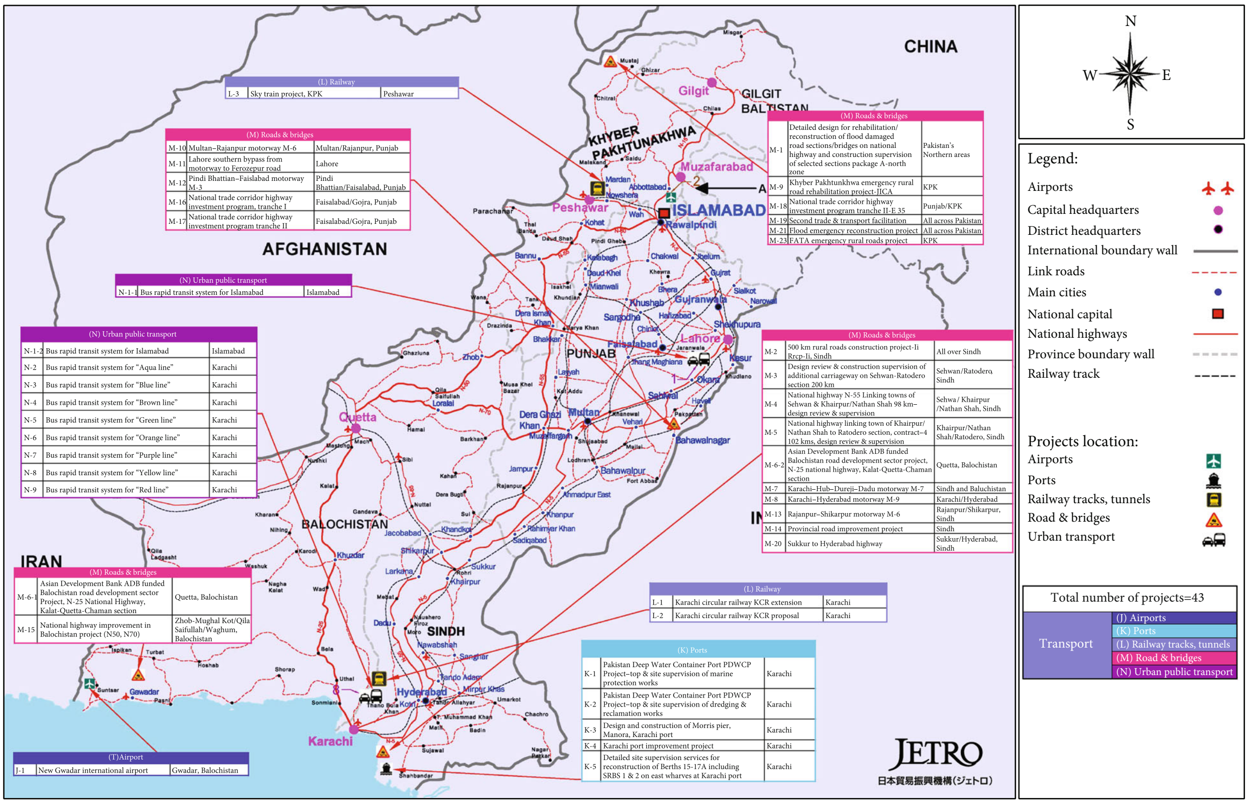


Figure 16: Road map of Pakistan [88].

Peshawar-Karachi motorway (Multan-Sukkur section) from Karachi passes through Hyderabad and Sukkur and ends in Multan [84]. National Highway 50 (NH-50) is restored and upgraded from D.I. Khan, passing through Kuchlak and valley Zhob, Balochistan [85]. Highway N-85, 449 km long, originates from Hoshab to Surab; passes through Panjgur, Mugalgori, Nag, Shireza, Basima, and Gidar; and ends at Surab [86]. N-25 is 813 km long, connecting Karachi with Quetta, passing through Kalat, and extending to Chaman from Quetta [87]. Other than motorways and highways, linkage roads are also there to connect different regions to the highways and motorways, as can be seen in the roadmap of the country in Figure 16 [88]. Therefore, transportation facilities are available, and it is easy to access the selected locations in Punjab, Sindh, or Balochistan.

8. SWOT Analysis for PT and PV in Pakistan

SWOT analysis is a widely used planning technique for structural management to determine the strengths, weaknesses, opportunities, and threats of a system, country, organization, society, site selection, or industry for a particular project. It is categorized into two factors, namely, external and internal. Internal factors include strengths and weaknesses, and external factors include opportunities and threats. As mentioned in the introduction section, various researchers have used the SWOT technique to decide renewable energy technologies at specific sites. In line with the current study, it has been used by Erdil and Erbıyık to assess the sustainability of renewable energy in Turkey [89]. Sharvini et al. conducted a SWOT analysis to determine the opportunities and challenges to East and Southeast Asian countries in the linkage between energy consumption and RE [90]. Therefore, this work carries a SWOT analysis for RE policies and locations.

8.1. Assessment of Strengths. Pakistan has abundant natural solar resources and the potential for RE energy in the hour of need. In recent years, Pakistan has started working on climate change and moving towards RE. In 2018, the Prime Minister of Pakistan launched Clean Green Pakistan Movement (CGPM) [91]. The Pakistani government is showing great interest in developing renewable and sustainable systems, a strength for Pakistan. Another advantage is that Pakistan has sought political stability for the last 15 years.

In contrast, a proper framework for development in RE systems is under construction. It is encouraging that several NGOs are working in Pakistan to develop and promote renewable energy [92]. In 2001, the Pakistan Council of Renewable Energy and Technologies was founded by merging two institutes, NIST and PCAT, which are working under the Ministry of Science and Technology to promote different renewable technologies [93]. With Pakistan's strength, the researchers have performed exceptionally well, keeping in mind the limited financial resources for developing renewable Energy in Pakistan. Moreover, the cheap labour [94] and workforce in Pakistan are more economical than in western countries, significantly affecting capital, LCOE, and maintenance costs.

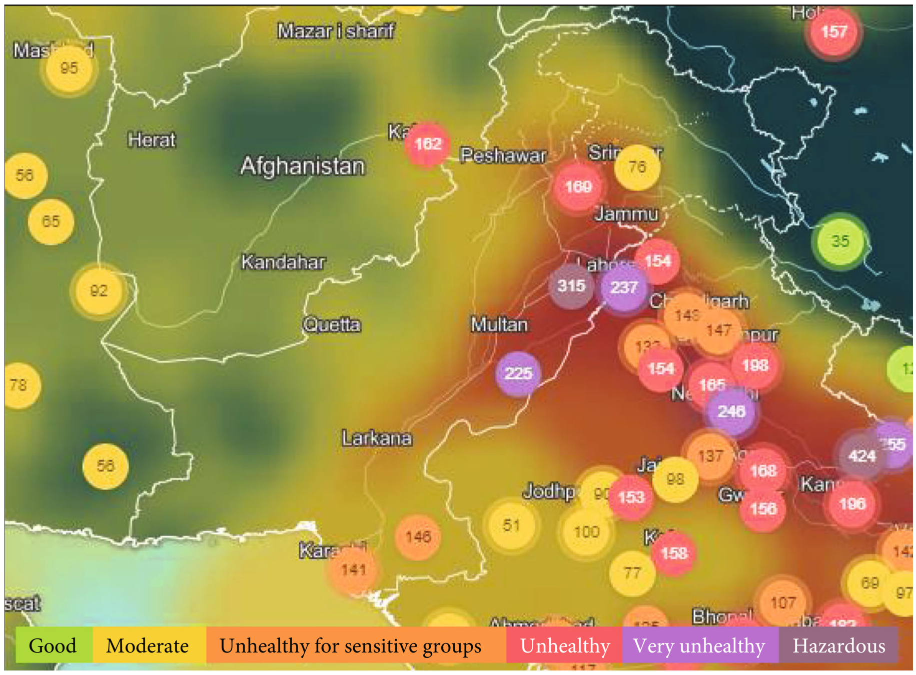


Figure 17: Air quality map of Pakistan [108].

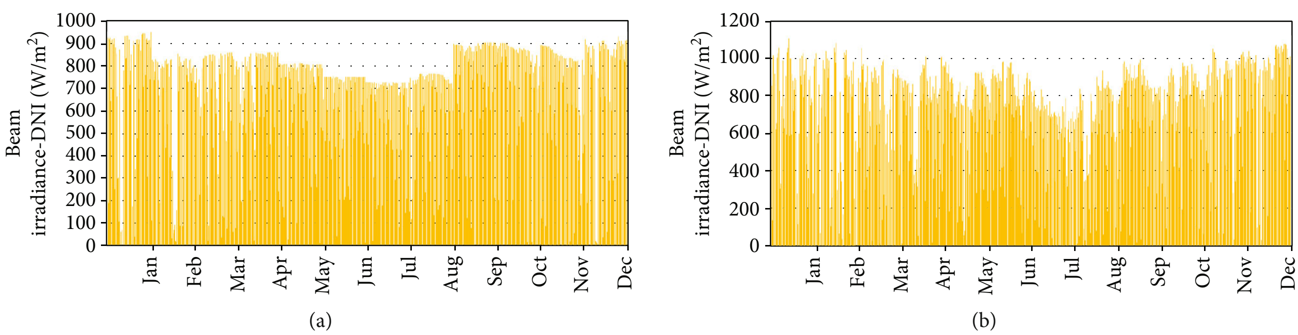


Figure 18: DNI of (a) Quetta and (b) Toba.

Pakistan is an agricultural country. Punjab is the central crop-producing province, followed by Sindh and Balochistan, i.e., 12.58, 5.03, and 3.26 million hectares, respectively [95]. Therefore, it would be the strength of the PV system if PV and agricultural land were colocated. It has been observed that agricultural efficiency is enhanced under PV panels [96]. Agrivoltaics reduce water evaporation, and cooler microclimate under panels provides cooling, increasing PV efficiency and reducing operational and management costs [97]. PV is not much restricted, even where the population density is high. Unlike CSP, photovoltaic panels can be installed on rooftops in a highly populated Punjab region. A recent survey on household energy choices in rural areas of Pakistan in three districts of KPK (Dera Ismail Khan, Tank, and Bakkar) showed that 20.21% of 532 houses own PV systems to produce electricity [98]. Therefore, the compatibility of solar panels on rooftops is the PV system's most prominent strength due to its gaining social acceptance. Moreover, no grids or particular power station is required but just a storage system in the house.

In the present studies, it is observed that the foremost strength of PV is low LCOE and capital cost in south Punjab and Sindh. It decreases further if PV plants are set up in Balochistan. Solar PV can be installed in Pakistan anywhere due to rich solar irradiation and has the potential to work efficiently except in the KPK province, whereas CSP parabolic trough lacks this.

Considering the strengths of a parabolic trough, this technology produces 1800 MW globally and holds 94% market share of CSP [99]. Only a single-axis mechanism is required for parabolic collectors to track the sun radiations from east to west if the receiver design is based upon linearity [100]. The foremost strength of PT lies in being the most mature and popular system to be used in the hybrid combined cycle. A parabolic trough is less expensive than other CSP technologies. Due to high modularity, parabolic troughs of different sizes can be installed in solar fields. The low land use factor of PT is cost-friendly. In contrast, low material demand affects the cost-effective manner [101]. CSP provides significantly high efficiency only in the

Table 1: Technical parameters for simulation of parabolic trough power plant [29].

Description	Technical parameter	Value
Solar field parameters	Solar multiple	2 [113]
	Row spacing	15
	Number of field subsections	2
Heat transfer fluid	Field HTF	Therminol VP-1
	Field HTF min operating temperature	12°C
	Field HTF max operating temperature	400°C
Solar field design point	Single loop aperture	3762.4
Collectors	Collector type	Solargenix SGX-1
	Reflective aperture area per solar collector assembly	470.3 m^2
	Aperture width	5 m
	Length of the collector assembly	100 m
	Number of modules per assembly	12
	Mirror reflectance	0.935
	Length of a single module	8.33 m
Receivers	Receiver type	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	304 L
Power cycle	Design gross output	100 MW
	Estimated gross-to-net conversion factor	0.9
	Estimated net output at design	90 MW
	Rated cycle conversion efficiency	0.3774
	Boiler operating pressure	100 bars
	Design loop outlet temperature	391°C
	Design loop inlet temperature	293°C
	Condenser type	Evaporative
	Reference condenser water dT	10°C
Thermal storage	Full load hours of TES	12 h
	Storage volume	45311.3 m^3
	Storage HTF fluid	Hitec solar salt
	Tank diameter	69.3374 m
	Tank loss coefficient	0.43 W/m^2.k
	Parallel tank pairs	1
Mirror washing	Water usage per wash	0.7 L/m^2, aper.
	Washes per year	63

sun-belt regions of Balochistan. Since no CSP power plant is working in Pakistan, further CSP strengths in Pakistan are yet to be explored.

8.2. Assessment of Weaknesses. The lack of industrial support is a major RE development weakness. Only a few companies and industries provide solar energy solutions [102]. Fabrication of new RE technologies is a hard nut to crack in Pakistan. Therefore, in the case of plant installation, technology is imported from foreign companies at high costs, including shipping expenses [103]. However, these expenses can be avoided by manufacturing RE technologies locally. The reason is the lack of financial support for the researchers to conduct an advanced search and test and scale up the new development.

On the other hand, the overall budget of Pakistan is insufficient to launch new solar technology manufacturing companies, nor has Pakistan been an ideal location for foreign investors, keeping in view the geopolitical scenario in the last decade, where solar energy has grown multiple folds globally. The foremost weakness is the reliance on economically viable nonrenewable energy resources. Thermal energy sources are cheaper to produce energy, which industries prefer. Production plants rely on thermal-based nonrenewable energy sources for their high and continuous demand for energy 24/7. Therefore, initiatives encourage economic sources like coal and gas [104, 105].

Among the weaknesses of solar PV, it is reported that the solar PV system is not a carbon-negative technology. Solar PV system releases 14 to 73 g CO_2 eq/kW during their lifetime [106], but their after-life disposal remains challenging. Although this amount of CO_2 is significantly lower than thermal energy sources, Pakistan suffers from the worst air quality index in its major cities, mainly its more populated province of Punjab. The air quality is very unhealthy in major parts of Pakistan. Therefore, CO_2 emission from PV systems will increase the GHG concentration of air, as shown in Figure 17. Pakistan hosts five deserts, and the Cholistan desert is rich in resources required for solar PV (Bahawalpur, Rahim Yar Khan, and Bahawalnagar districts) [107]. If PV is installed in these locations, as aforementioned, the weakness remains as the efficiency of PV panels reduces due to the soiling effect of sand mixed in the air.

Unlike PV, although PT systems have less land-to-use factor, they could perform better away from a populated area. Moreover, Balochistan is the only province with excellent potential for CSP plants. Unfortunately, Balochistan is the least developed province of Pakistan as well. The human development index of Balochistan from 1990 to 2019 has improved only from 0.382 to 0.475, the least of all provinces [109]. Sadly, the Balochistan province has been ignored despite having rich natural resources. The infrastructure of the province has not yet been developed enough. New roads are needed throughout the Balochistan province. The largest province of Pakistan by land area has only one power transmission line and faces acute water shortage. Moreover, unfortunately, this semiarid province is steeper than the allowed limit of 2 for the PT system. Therefore, despite having solar potential, much development and advancement are required in the province to move towards installation, adding to the weaknesses of PT systems in the country.

8.3. Assessment of Opportunities. Pakistan is among the most populous countries, with a continuously growing population. Therefore, the annual electricity demand is increasing by approximately 8%. Thus, Pakistan is taking steps to meet the need for electricity. The Pakistani government has proposed 616 billion rupees in subsidies for overall energy sectors in the upcoming fiscal year 2021-2022 [110]. Moreover, the government has also decided to eliminate the taxes associated with manufacturing renewable energy technologies for five years. It will help boost RE technologies manufacturing and overcome the energy shortfall [111]. Production companies must implement the latest research to take advantage of tax exemption and manufacture highly efficient and less expensive RE technologies. Also, this is an opportunity for the researchers to develop more advanced techniques and improve existing equipment.

Table 2: Performance parameters of PT system.

Parameters	Unit	Quetta	Toba
Annual electricity generated	GWh	341.514	388.665
Gross-to-net conversion	%	90.1	90.5
Capacity factor		43.3	46.7
Cooling water requirements	m^3/year	1,235,318	1,186,590

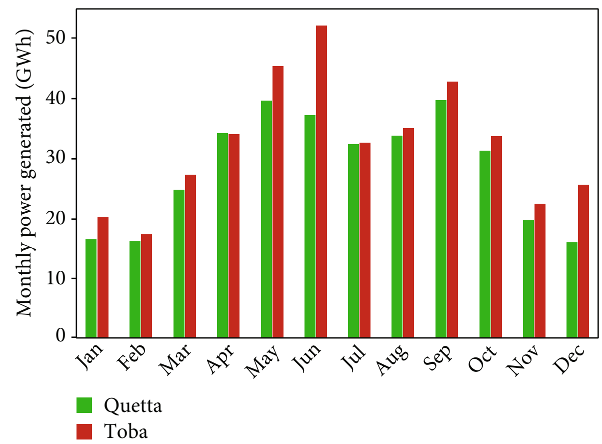


Figure 19: Monthly power generated by 100 MW PT power plant.

Canal capacity is the most significant opportunity in the context of PV systems. India generates 10000 MW of electricity from PV panels installed over canals to reduce evaporation [112]. Statistical data shows that the usable water loss through canals could be 20% to 25% due to evaporation, transpiration, and seepage [113]. Therefore, evaporation-induced useable water in a water-deficient and agricultural country can be stopped by installing photovoltaic arrays to cover canals in Punjab and Sindh.

Moreover, solar panels do not require water to operate. It means that the performance of the solar panels will not be impacted by seasonal fluctuations in water levels, including when the canals dry up during the winter months. As a result, solar panels installed on canals can provide a reliable source of electricity without impacting the surrounding water resources. It serves as an opportunity for Pakistan to decrease the load on national grid stations. As mentioned before, there is a shortage of electricity in Pakistan. Therefore, it is an opportunity for Pakistan's government to install PV plants to produce enough electricity to meet the need. The need for electric power should be fulfilled using green energy technologies in Balochistan.

Industries in Pakistan are primarily located in Punjab and Sindh due to the availability of coal/gas to produce power. Since only a few industries operate in Quetta, there is a need to build more industries in Balochistan for development and job opportunities. These industries can be powered by CSP parabolic troughs for a clean and continuous electricity supply.

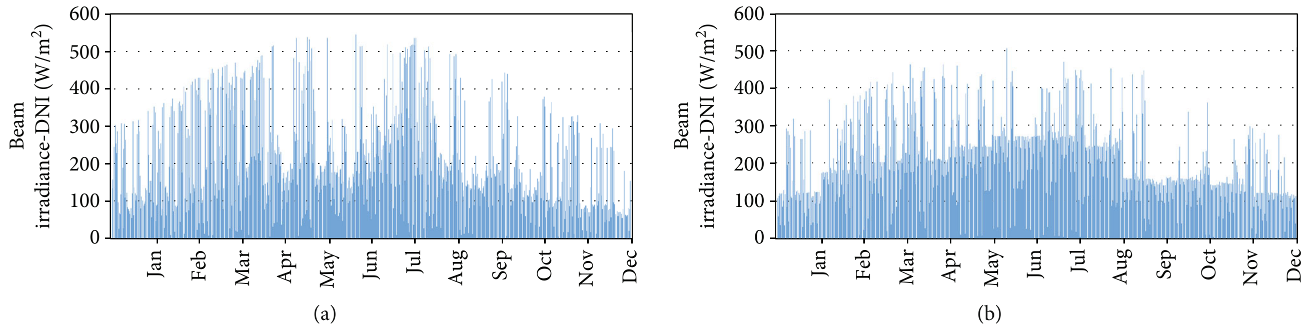


Figure 20: DHI of (a) Toba and (b) Quetta.

8.4. Assessment of Threats. The government of Pakistan recently proposed a finance bill (minibudget) and increased the customs duty tax on the importation of plants and machinery by up to 17% [114]. It could threaten RE development since there is no significant fabrication of RE technologies in Pakistan. Therefore, Pakistan has to import RE technology at a higher cost. Another drawback is the lack of infrastructure and uneven distribution of resources, which hinders the implementation and development of RE in Pakistan. Among the threats to PV, the ideal locations to implement PV commercially are near or inside desert regions. It has been observed that during a sandstorm, efficiency is reduced by about 60% per module at the Quaid-e-Azam Solar Park (QASP) [115]. Therefore, sandstorms could threaten such locations on the eastern side of lower Punjab and Sindh.

8.5. SWOT Analysis Summary. SWOT analysis aided in a bird's-eye view of the current situation, potential, and challenges with particular emphasis on geographical strengths and weaknesses, focusing on the strengths and weaknesses of parabolic trough and photovoltaic power systems. The SWOT analysis illustrated reasons for developing RE technologies in suitable geographical locations. The analysis points out that Pakistan has ample solar resources to deplete the CO_2-producing power plants and alternate the course of power production plants towards clean and green energy. Fortunately, the current government in Pakistan has also realized that the need for clean energy has become essential to construct a sustainable infrastructure of power sources for the country's needs in the long run. Therefore, legislators in the country have diverted their focus towards renewable energy sources and making favorable policies for climate, depletion of natural resources, and country development. On the other hand, SWOT analysis provides locations for a specific technology. The conclusions drawn regarding locations are provided in the subsequent section.

9. Site Selection and Simulations for 100 MW PT and PV Power Plants

The analysis concludes that only the Balochistan province is most suitable for setting up parabolic trough power plants. However, to set up a PV power plant, the number of locations is higher, and various locations in Sindh, Balochistan, and Punjab are selected for further consideration. Calculations based on LCOE were conducted for economic analysis for 100 MW parabolic trough and solar PV power plants. As stated above, only regions of Balochistan, i.e., Toba and Quetta, were selected to calculate LCOE for the parabolic trough power plant. Similarly, these locations were deemed suitable for PV plants from Balochistan, along with Bahawalpur and Rahim Yar Khan (Punjab) and Hyderabad (Sindh). The selection process was based on a SWOT analysis that focused on various factors, including the sun-belt region, climate, spatial considerations, and environmental factors. The annual DNI maps of Quetta and Toba are expressed in Figures 18(a) and 18(b) as concentrated solar power (CSP) technology relies on direct sunlight, i.e., DNI only, to generate electricity efficiently.

The simulations for comparison compare were conducted on system advisor model (SAM) developed by NREL. Quetta and Toba are selected for the LCOE analysis of 100 MW for the PT plant. The simulations are performed for a 100 MW parabolic trough with 12 h of the storage system. The technical parameters are obtained from previous literature and summarized in Table 1. The optimal solar multiple is 1.94 [116], considered 2 in the present cases. The power plants simulated were equipped with a thermal storage capacity of 12 hours consisting of a two-tank storage system. In the case of Quetta and Toba, the total land requirement is 2,456,529 m^2 and 2,561,751 m^2, respectively. For 100 parabolic trough power plants in Quetta, there are 234 loops, while in Toba, there are 244 loops.

The simulation results show that the electricity production in Toba is higher than that in Quetta due to higher DNI in Toba. Table 2 summarizes the performance parameters of 100 MW parabolic troughs in both Quetta and Toba. The simulation results have shown that Toba and Quetta are the ideal locations to install parabolic trough power plants. However, it is observed that Toba has a higher annual power production compared to Quetta. The yearly net electrical energy production is 388.665 GWh in Toba against 341.514 GWh in Quetta. The gross-to-net conversion factor is almost the same for both cases, while Toba has a better capacity factor of 0.46 than 0.43 for Quetta. As shown in Figure 19, the simulation results depict that for both cases, the electricity production is maximum from June to

Table 3: Technical parameters of SAM to simulate PV system [23].

Description	Parameters	Value
Module characteristics	Manufacturer	Sunpower SPR-E19-310-COM
	Cell temperature	25°C
	Max power (P_{mp})	310.15 Wdc
	Maximum power voltage (V_{mp})	54.70 Vdc
	Maximum power current (I_{mp})	5.7 Adc
	Open circuit voltage (V_{oc})	64.4 Vdc
	Short circuit current (I_{sc})	6.0 Adc
	Nominal efficiency	19.016%
	Module area	1.631 m^2
	Number of cells	96
	Module aspect ratio	1.7
	Module length	1.63 m
	Module width	1 m
System design	Modules per string in subarray	12
	Strings in parallel in subarray	26,869
	Number of modules in subarray	322,428
	Nameplate DC capacity	100 MW
	Total AC capacity	83.16 MW
	Ground coverage ratio	0.3
	Tilt angle for fixed tracking	30°
Inverters	Number of inverters	108
	Type	SMA America SC750CP-US
	DC to AC ratio	1.20
	Total inverter DC capacity	85.5 MW
	Maximum AC power	770,000 Wac
	Maximum DC power	791,706 Wdc
	Maximum DC voltage	820 Vdc
	Maximum DC current	1289.42 Adc
	Minimum MPPT DC voltage	545 Vdc
	Maximum MPPT DC voltage	820 Vdc
Battery	Battery	Lithium ion: nickel manganese cobalt oxide (NMC/graphite)
	Desired bank capacity	4000 kWh
	Desired bank power	1000 kWh
	Cell capacity	2.25 Ah
	Nominal bank capacity	4000 kWh (DC)
	Nominal bank voltage	500.4 V (DC)
	Cells in series	139
	Strings in parallel	3553
	Maximum discharge power (DC)	1000.08 kWdc
	Maximum discharge power (AC)	960.077 kWac
	Maximum charge current	1998.56 A

September during summer, as evident, while in winter, sun hours decrease, decreasing electricity production. Furthermore, Toba is considered the preferred site for installing commercial-scale parabolic trough power plants due to its higher production capacity.

On the other hand, these locations are also ideal for PV power plants. The simulations for a duration of 25 years were performed for a 100 MW photovoltaic power plant. The DHI map of Toba and Quetta is shown in Figures 20(a) and 20(b) as photovoltaic (PV) technology utilizes the total solar radiation received on a horizontal surface. The technical parameters for simulation are summarized in Table 3. The annual energy production in Quetta is 179.47 GWh, whereas in Toba, it reaches 184.80 GWh annually.

Figure 21 illustrates that the 100 MW photovoltaic power plant at both locations achieves its highest production levels from April to October. However, monthly production is higher in Toba excluding February, July, and August. Based on the higher monthly production levels, Toba is considered more favorable than Quetta. Moreover, a PV power plant could be installed at both locations to meet Balochistan's electricity needs. The capacity factor, energy yield, and other performance parameters are shown in Table 4.

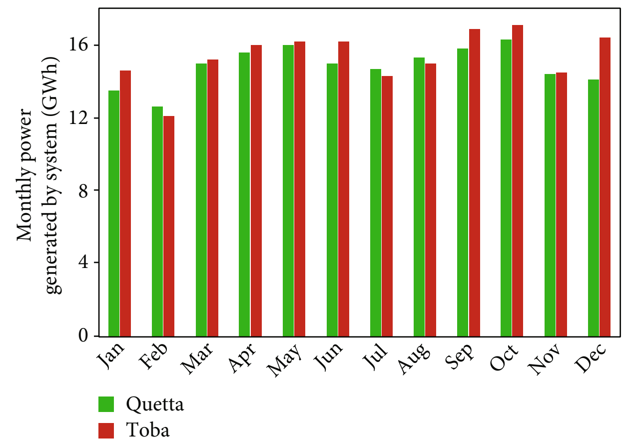


Figure 21: Monthly power generation by 100 MW PV power plant at Quetta and Toba.

Table 4: Performance parameters of 100 MW PV.

Parameters	Unit	Quetta	Toba
Annual electricity generated	GWh	179.47	184.80
Capacity factor		0.20	0.21
Energy yield	kWh/kW	1,795	1,848
Performance ratio		0.74	0.78

10. Simulations of 100 MW PV Power Plant in Other Proposed Locations

This section examines the performance evaluation of a 100 MW photovoltaic power plant in Punjab and Sindh's proposed locations. The technical parameters for simulations on SAM are kept the same and given in the above section. The weather files for the proposed locations were obtained from the National Solar Radiation Database (NSRDB) [117]. The DHI maps of the proposed locations are shown in Figure 22. The plotted graph in Figure 23 shows that the power produced in March is maximum in all selected locations due to high solar irradiance. However, due to the lower solar irradiance value, the minimum productivity can be predicted in December for Bahawalpur and Rahim Yar Khan and July for Multan and Hyderabad. The maximum power obtained is 14.3 GWh, 14.4 GWh, 14.7 GWh, and 14.5 GWh in Bahawalpur, Multan, Rahim Yar Khan, and Hyderabad. However, the minimum electric power is 11.6 GWh and 10.8 GWh in Bahawalpur and Multan, respectively.

In contrast, Rahim Yyar Khan and Hyderabad share the same minimum value of 12.0 GWh. A detailed description of the performance parameters is provided in Table 5. The performance parameters show that Hyderabad is preferred for the 100 MV photovoltaic power plant, followed by Rahim Yar Khan, Bahawalpur, and Multan.

A validation model is also provided for SAM simulations. Before performing the simulations on proposed locations, the LCOE comparison of Quaid-e-Azam Solar Park (QASP) in Bahawalpur is carried out with available literature. Khosa et al. [118] analyzed a 100 MW QASP photovoltaic power plant using the Monte Carlo simulation method for a lifespan of 25 years, and the results are compared in this study. The LCOE of QASP calculated using SAM simulation software is 7.82 cents/kWh. Simultaneously, LCOE calculated by Khosa et al. is 7.91 cents/kWh. The first year of power production is calculated using SAM as 14 GWh and 13.7 GWh. The comparison reveals a 1.14% difference between the LCOE calculated using SAM and the results obtained from Monte Carlo simulations. Such slight differences may arise due to the assumption of fixed values or the unavailability of precise data in the literature. However, the 1.15% difference is negligible and can be disregarded, thereby validating the methodology employed in this study.

11. LCOE Parameters and Comparison

The simulation results gave us the levelized cost of energy for all the above-selected locations for 100 MW parabolic trough and photovoltaic systems. The LCOE of 100 MW parabolic trough is 10.8 cents/kWh and 12 cents/kWh in Toba and Quetta, respectively, as shown in Figure 24. It indicates that Toba is a better location than Quetta for implementing a parabolic trough system at a commercial scale in Balochistan. Additionally, photovoltaic systems can be installed at both locations. The LCOE of a 100 MW photovoltaic power plant in Quetta is 6.04 cents/kWh and 5.95 cents/kWh in Toba. There is a slight difference in LCOEs of PV plants in Quetta and Toba. Therefore, both locations are ideal for PV plant installation.

In Punjab, simulations for 100 MW photovoltaic power plants are carried out for Bahawalpur, Multan, and Rahim Yar Khan. As a result, the LCOEs of locations in Punjab are 7.21 cents/kWh, 7.36 cents/kWh, and 7.01 cents/kWh, respectively. Rahim Yar Khan has a lower LCOE, followed by Bahawalpur and then Multan, as shown in Figure 25. It indicates that LCOE increases as we move from lower Punjab to upper Punjab. In Sindh, LCOE is calculated in only one location. The LCOE calculated for 100 MW photovoltaic system in Hyderabad is 6.82 cents/kWh. The LCOE in Hyderabad clearly states Sindh's superiority in terms of solar resources. The government of Pakistan will provide the

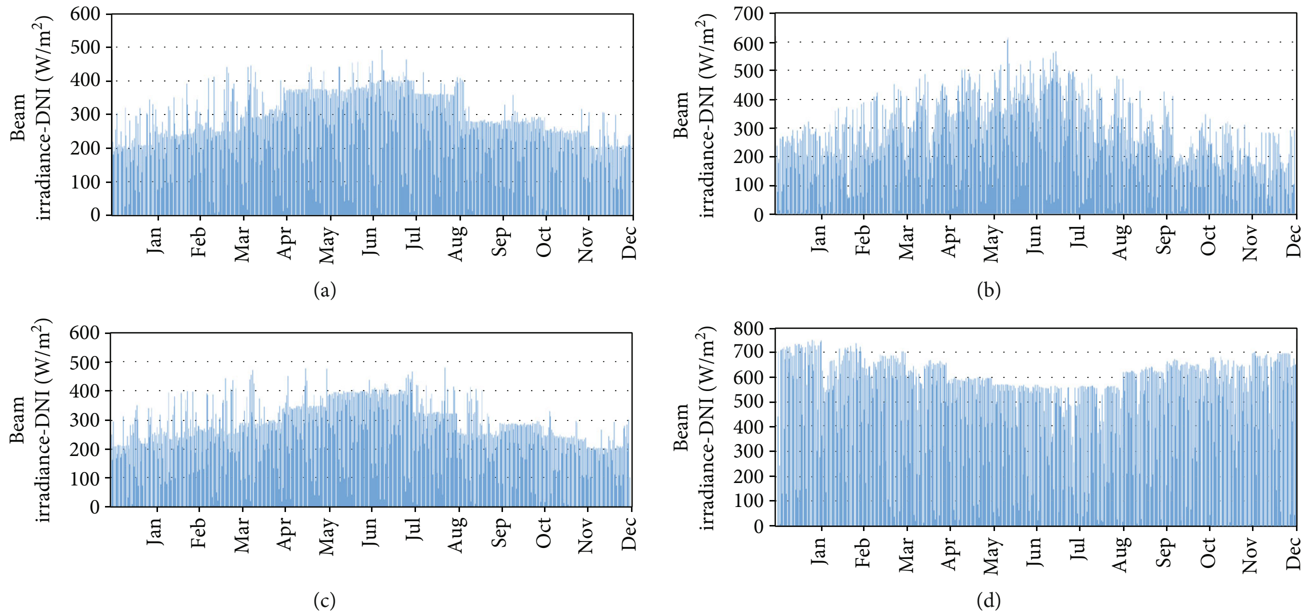


FIGURE 22: DHI maps of Bahawalpur (a), Multan (b), Rahimyar Khan (c), and Hyderabad (d).

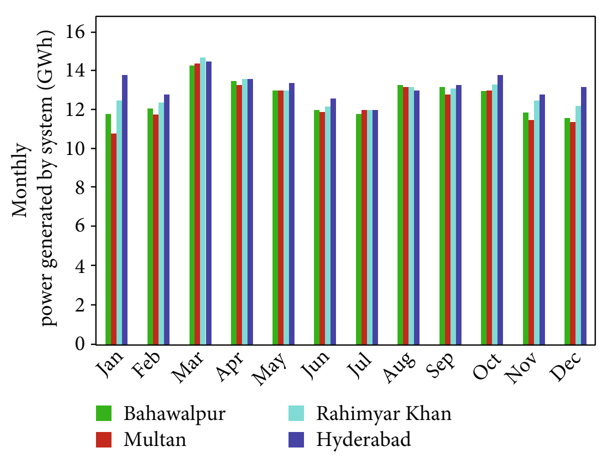


FIGURE 23: Monthly power generation by 100 MW PV power plant at Bahawalpur, Rahim Yar Khan, Multan, and Hyderabad.

required land. Therefore, it is essential to mention that the necessary land and water costs are ignored during the evaluation. The significant effect on LCOE of power plants is caused by solar resources (DHI and DNI), while the other factors are the additional positive points that could help reduce the solar field's expenses, engineering, cleaning, and labour costs. Orographic and spatial factors could reduce the capital cost if they are favorable to power plants and could save transportation expenses if roads are built and water costs if there are predictable rainfalls; power transmission would be cost-effective if the power plant has utility to connect to the existing grid station. That is how the climate, orography, or availability of water resources can improve economics.

The input parameters are summarized in Tables 1 and 3, and the LCOEs of selected locations are given. These parameters are used in SAM and HOMER (Hybrid Optimization of Multiple Energy Resources) developed by NREL, USA, to carry out technoeconomic analysis of hybrid energy systems in rural areas in Pakistan [119]. These calculations are performed using the LCOE calculator in SAM, and Equation (3) is the governing equation to calculate LCOE.

11.1. Total Lifecycle Cost (TLCC). The LCC model used in SAM considers both initial capital and operating costs, the value of energy or other products generated by the system, and any applicable tax credits or incentives. TLCC, or total lifecycle cost, is an important part of calculating LCOE (levelized cost of energy) as it provides a comprehensive estimate of all costs associated with the system over its lifetime, allowing for a more accurate assessment of the true cost of energy production.

$$\sum_{n=1}^{N} \frac{Q_n \times \text{LCOE}}{(1+d)^n} = \text{TLCC}. \tag{1}$$

The equation can also be written as

$$\text{TLCC} = \sum_{n=0}^{\text{N}} \frac{C_n}{(1+d)^{\text{n}}}, \tag{2}$$

$$\text{LCOE}^{22} = \text{TLCC} \div \left\{ \sum_{n=1}^{N} \left[Q_n \div (1+d)^n \right] \right\}. \tag{3}$$

LCOE can be calculated if TLCC is known. Equation (2) can be used to calculate the total lifecycle cost. In this

Table 5: Performance parameters of 100 MW PV in the proposed locations.

Parameters	Unit	Bahawalpur	Multan	Rahimyar Khan	Hyderabad
Annual electricity generated	GWh	15.1	14.8	15.4	15.8
Capacity factor		0.173	0.17	0.176	0.181
Energy yield	kWh/kW	1,513	1,490	1,546	1,590
Performance ratio		0.70	0.70	0.70	0.71

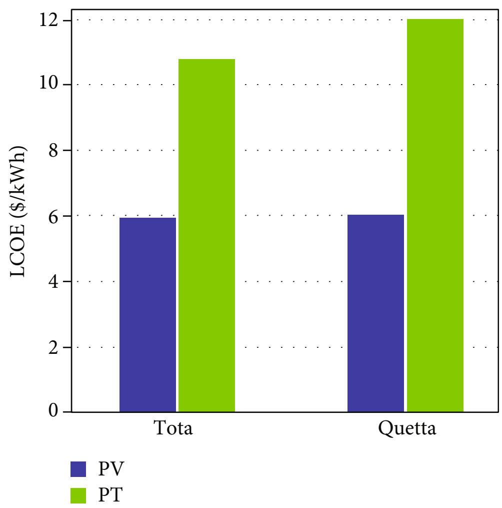


Figure 24: LCOE comparison of 100 MW PV and PT in Quetta and Toba.

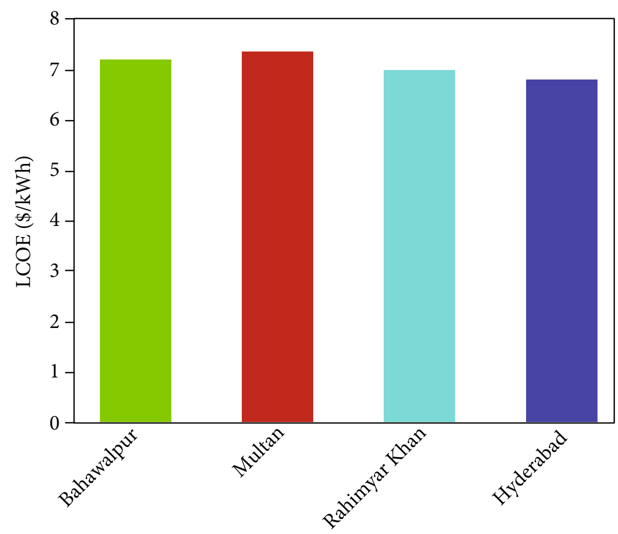


Figure 25: LCOE comparison of 100 MV PV plant in the proposed locations.

equation, the periodic cost n such as repair costs, replacement costs, maintenance costs, and energy costs is denoted by C_n. In Equation (3), total lifecycle cost is denoted by TLCC, with the assistance of weather data file and performance parameters collectively, the energy output Q_n is determined, N stands for the analysis period, and d is the nominal discount rate.

11.2. Nominal Discount Rate. The discount rate calculates the present value of future cash flows associated with the renewable energy system, including capital and operating costs. The present value is then divided by the total expected energy production over the system's lifetime to calculate the LCOE. The user customizes the nominal discount rate used in SAM, but the default value is 7% per year, a commonly used rate in the renewable energy industry.

$$d = \left[\left(1 + \frac{\text{real discount rate}}{100}\right) \times \left(1 + \frac{\text{inflation rate}}{100}\right) - 1\right] \times 100. \quad (4)$$

11.3. Inflation and Real Discount Rate. The inflation rate is used to adjust the nominal discount rate in the LCOE calculation to account for the expected change in the purchasing power of money over time. SAM allows specifying an inflation rate, which is used to calculate the real discount rate. The real discount rate is the nominal discount rate adjusted for inflation and reflects the true cost of borrowing or the opportunity cost of investing. It is calculated as the nominal discount rate minus the inflation rate. The inflation and real discount rates significantly impact the LCOE calculation, especially over long-time horizons. The values of the inflation rate and real discount rate can be specified in SAM and affect the nominal discount rate, which is used to calculate the LCOE. Therefore, the nominal discount rate can be calculated using Equation (4). By substituting Equation (2), the levelized cost of energy can be calculated, whereas the values of the inflation rate and real discount rate are specified in Table 6.

11.4. Net Present Value (NPV). The net present value (NPV) is a financial metric used in SAM to evaluate renewable energy projects by measuring the current value of all cash inflows and outflows associated with an investment, discounted to their present value using a discount rate. NPV determines a project's financial viability and compares investment opportunities. A positive NPV indicates financial viability, while a negative NPV indicates that the project is not economically feasible. The magnitude of the NPV also indicates the project's profitability, with a higher NPV indicating greater profitability. It can be calculated using Equation (5). The discount rate used in the NPV calculation is typically the same as the nominal discount rate used in the

Table 6: Economic analysis of 100 MW PV and PT power plants.

Parameters	Unit	Values
100 MW PT plant-net capital cost in Quetta	$	646,144,640
100 MW PT plant-net capital cost in Toba	$	655,716,032
100 MW PV plant-net capital cost in Multan	$	112,103,800
100 MW PV plant-net capital cost in Bahawalpur	$	111,035,656
100 MW PV plant-net capital cost in Rahimyar Khan	$	109,967,520
100 MW PV plant-net capital cost in Hyderabad	$	109,967,456
100 MW PV plant-net capital cost in Quetta	$	109,966,744
100 MW PV plant-net capital cost in Toba	$	109,947,536
Inflation rate	%/year	2.5
Real discount rate	%/year	5.5
Nominal discount rate	%/year	8.14

Table 7: LCOEs of 100 MW PV and PT at different locations in Pakistan.

Parameters	Units	Locations	Parabolic Trough (100 MW)	Photovoltaic (100 MW)
		Multan		
LCOE	cents/kWh		—	7.36
		Bahawalpur		
LCOE	cents/kWh		—	7.21
		Rahimyar Khan		
LCOE	cents/kWh		—	7.01
		Hyderabad		
LCOE	cents/kWh		—	6.82
		Quetta		
LCOE	cents/kWh		12	6.04
		Toba		
LCOE	cents/kWh		10.8	5.95

LCOE calculation, with the option to adjust for inflation and real discount rate. A summary of LCOEs for various locations is shown in Table 7.

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{C_n}{(1+d)^n}. \tag{5}$$

12. Conclusions

The present work analyzed various factors throughout Pakistan that affect renewable energy technology's performance and LCOE. Orographic, spatial, and environmental factors are included. After studying these factors, locations were shortlisted for the LCOE evaluation for 100 MW photovoltaic and parabolic trough systems. The detailed overview of affecting factors showed that Balochistan is ideal for parabolic trough and PV systems. In contrast, the lower Punjab and Sindh are ideal provinces for photovoltaic systems. The levelized cost of energy (LCOE) has been determined for 100 MW parabolic trough and photovoltaic systems. The analysis shows that Toba is a superior location compared to Quetta for implementing a parabolic trough system in Balochistan, with LCOEs of 10.8 cents/kWh and 12 cents/kWh, respectively. However, both Toba and Quetta are suitable for photovoltaic installations, with LCOEs of 5.95 cents/kWh and 6.04 cents/kWh in Toba and Quetta, respectively. For Punjab, simulations have been conducted for a 100 MW photovoltaic power plant at three locations, namely, Bahawalpur, Multan, and Rahim Yar Khan. The analysis reveals that Rahim Yar Khan has the lowest LCOE, followed by Bahawalpur and Multan, indicating that LCOE increases as we move from lower to upper Punjab. In Sindh, the LCOE for a 100 MW photovoltaic system has only been calculated for Hyderabad, with a value of 6.82 cents/kWh. Although Punjab and Sindh are both the best options for PV, the PV system of 100 MW in Sindh is 2.71% cheaper than the lower Punjab and Balochistan, which is 12.76% cheaper than Sindh. The parabolic trough system is only economical in Balochistan, where the evaluation is carried out in Quetta and Toba, showing that the PT system of 100 MW in Toba is 10% cheaper than in Quetta. Therefore, it is proved that Balochistan is an ideal province for PV and

PT power plants, followed by Sindh and lower Punjab for PV systems only.

Based on the above factors, Balochistan's ideal locations for parabolic troughs are Quetta, Khuzdar, Panjgur, Qila Saifullah, Toba, and Qilla Abdullah. The ideal locations for PV and PT are Quetta, Toba, and Qilla Abdullah, whereas in Punjab, cities in south Punjab are ideal for PV and the preferred locations are Bahawalpur, Multan, and Rahim Yar Khan. In Sindh, Hyderabad, Jamshoro, and Guddu are the preferred locations for photovoltaic power plants. These locations are preferred due to the rich solar resources, water availability except Balochistan, grid connections, better infrastructure, and favorable weather conditions. It is essential to state that Balochistan's infrastructure, water deficiency, and lack of grid connections may not benefit power plants. However, Balochistan receives more solar irradiance than any other province of Pakistan. Therefore, selecting sites for evaluation in Balochistan is based on solar resources.

Research indicates that Pakistan possesses abundant solar resources and has the potential to transition towards sustainable, ecofriendly energy sources. Solar energy has emerged as a cost-effective means to generate electricity, surpassing the conventional methods of energy production that have failed to mitigate the electricity crisis in Pakistan. Hence, policymakers must devise favorable regulations that facilitate the adoption of affordable and clean energy production methods.

Nomenclature

AHP: Analytic hierarchy process
CGPM: Clean Green Pakistan Movement
CPEC: China-Pakistan Economic Corridor
CSP: Concentrated solar power
DHI: Direct horizontal irradiation
DNI: Direct normal irradiation
GWh: Gigawatt hour
GIS: Geographical information systems
GRACE: Gravity Recovery and Climate Experiment
GS: Grid station
HTF: Heat transfer fluid
IEA: International Energy Agency
LCOE: Levelized cost of energy
LFR: Linear Fresnel
MW: Megawatt
NIST: National Institute of Silicon Technology
PCAT: Pakistan Council for Appropriate Technologies
PV: Photovoltaic
PT: Parabolic trough
QASP: Quaid-e-Azam Solar Park
RE: Renewable energy
SAM: System advisor model
SWOT: Strengths, weaknesses, opportunities, and threats.

Data Availability

Data can be asked from the corresponding author, where applicable.

Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and publication of this manuscript.

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