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Concentrated Solar Power Technologies and its Prospect in Pakistan

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Abstract- **With the ever-increasing economic development and population growth in Pakistan, there is an unprecedented increase in electricity demand. On the other hand, using fossil fuels for electricity generation is leading to severe environmental pollution. To solve the problems mentioned earlier, the use of renewable energy sources (RES) is gaining considerable attention recently. Ample solar energy resources and vast wastelands make Pakistan an ideal country for solar thermal power development. A comprehensive comparison of various CSP technologies in terms of characteristics and efficiencies is drawn. Amongst the available solar power technologies, the parabolic dish based CSP system is potentially low cost and has no environmental impact. This paper aims to analyze the prospect of electricity generation using various CSP based technologies in Pakistan.**

Index Terms-- **Concentrated solar power plants; Linear concentrator; Point concentrator; Pakistan; Renewable energy resources;**

I. INTRODUCTION

Pakistan, being a developing country, heavily relies on energy consumption for its economic growth. Presently, Pakistan ranks at 35th position in electric energy consumption in the world. From the late 1990s to around 2005, the country was self-sufficient in electricity production. The current energy crisis started in 2006-7. Ever since the supply and demand gap has only been widened. The average power outage duration ranges from 8-10 hours in urban areas and 18 hours in rural areas of Pakistan [1]. The current installed capacity is around 17,000 MW, whereas the peak demand is about 22,000 MW, resulting in an average shortfall of about 5,000 MW [2]. Pakistan's energy consumption is increasing at an annual average of 10% compared to a 7% increase in its generation capacity [2]. As per studies conducted by Pakistan Electric Power Company (PEPCO) and Planning and Development Division, electricity demand projections are shown in Fig. 1 [3]. In 2017-18, the actual installed capacity was 33,836 MW, contrary to the projected installed capacity of 52,170 MW, leading to a deficit of 18,334 MW. For the year 2024-25, the installed capacity is planned to be 90,650 MW, which needs an additional installation of 56,814 MW by that time. Therefore, it can be deduced that Pakistan is short of projected electricity demand.

In Pakistan, power generation is mainly from fossil fuels. Table I shows the mix installed capacity until 2017 [3]. Amongst it, natural gas is the most widely used exhaustible fuel available in Pakistan. However, Table II provides source-wise annual energy consumption in Pakistan from 2010-19 [3].

TABLE I
INSTALLED GENERATION CAPACITY

Type of Energy Generation	Installed Capacity (MW)	Installed Capacity (%)
Gas/LNG	8,868	33.87
Oil	6,785	25.91
Coal	810	3.09
Hydro	7,116	27.17
Nuclear	1,142	4.36
Renewables (solar/wind/biomass)	1,465	5.59
Total	26,186	100.00

TABLE II
SOURCE-WISE ANNUAL ENERGY GENERATION

Year	Natural Gas (%)	Oil (%)	Coal (%)	Hydro (%)	Nuclear (%)	Renewable (%)
2010	29.26	33.22	0.13	28.71	2.68	0.23
2011	29.21	39.22	0.13	28.71	2.68	0.08
2012	29.42	36.21	0.20	29.03	4.94	0.20
2013	32.08	35.31	0.22	28.85	3.33	0.21
2014	25.67	38.91	0.10	30.82	4.25	0.25
2015	28.60	35.89	0.10	30.24	4.90	0.27
2016	31.42	32.44	0.15	30.85	3.76	1.38
2017	33.87	25.91	3.09	27.17	4.36	5.59
2018	38.47	21.69	9.14	21.00	6.77	2.92
2019	42.92	10.10	12.57	24.15	6.67	3.59

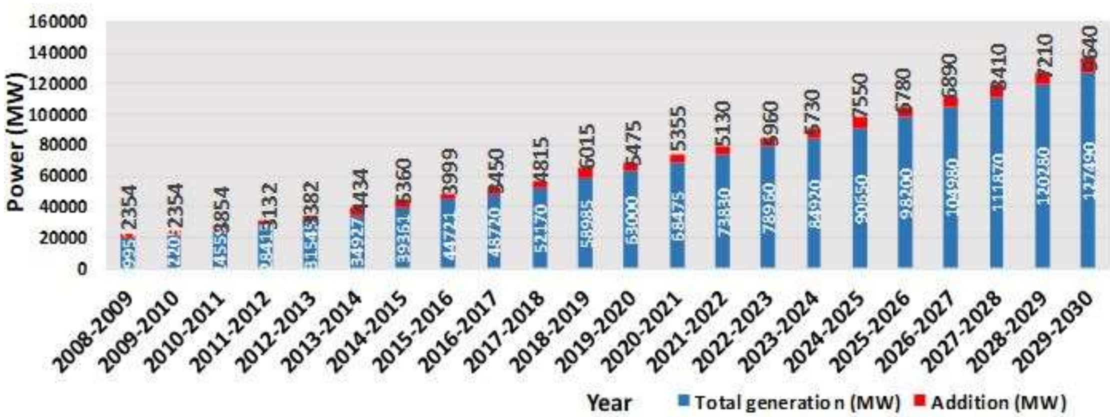

FIGURE 1. Electricity supply projections 2009-30

Hydro-based generation capacity is planned to increase up to 33% in the overall installed generation capacity by constructing small to medium-sized dams [3]. However, from Table II, it is evident that the nation's fossil fuel-based energy infrastructure, the majority of which is imported, is an indisputable fact and will remain the same for a considerably long time. This is mainly because the government is keen to adapt to coal-based technologies for electricity generation. Thus increasing the share of coal-based electricity generation capacity up to 20%. This is planned to be achieved through coal-based power plants, which are recently built and those under construction such as the Thar coal power plant, Qadirpur coal power plant, etc. Upon their completion, not only the installed energy capacity of the country will increase, but air pollution will also increase. Fossil fuel-based power plants, mostly coal power plants, are not only responsible for direct emissions such as NO_2, SO_2, CO_2, SO_2 but also for particulate matter (PM) such as PM1, PM2.5 leading to detrimental effects on humans, wildlife, and vegetation [4].

When the world is moving away from fossil fuel for energy generation, increasing the coal mix for electricity generation is not reasonable both economically and environmentally. Carbon dioxide, a greenhouse gas, is thought to contribute more than 50% human-made greenhouse effect. Therefore, using high proportions of fossil fuels in the energy mix implies high CO_2 emissions. In 2014, Pakistan's CO_2 emissions were about 175 Mt., which is nearly 0.48 % of the entire world. However, this percentage is likely to increase due to Pakistan's power generation's total future energy mix. An ideal solution towards energy and environmental problems is to evolve the country's renewable energy industry. There is immense scope for renewable energy resources in the total energy mix of Pakistan. Amongst them, solar energy in the form of concentrating solar power (CSP) has a promising future if appropriately used. As Pakistan is located in the sunbelt, it receives global horizontal insolation of 4.45-5.83 kWh/m^2 per day, which is considerably higher than the worldwide average of 3.61 kWh/m^2 day [5].

II. INTRODUCTION TO CSP TECHNOLOGIES

Concentrated solar power is a kind of solar thermal technology with tremendous potential. It has very few environmental impacts and causes no greenhouse emission. In regions with high direct solar radiation, each kilometer of the land area is enough to generate 100-120GWh of energy per year [6]. CSP plants incorporating heat storage systems or those who have the provision of using fossil fuel as an alternative fuel source can reliably be used during low radiation periods and at night time. Thus, the significant benefit of using solar energy is free, abundant, and an endless supply of fuel.

Concentrating solar power technology provides relatively low cost and the highest bulk of solar electricity amongst all other solar power technologies currently available. Apart from this, CSP plants can both generate and store energy. Therefore if the grid system experiences fluctuations due to the interconnection of variable renewable energy resources with that grid or during the peak demand, these types of plants can help to mitigate these fluctuations[7].

The electricity generation process in a CSP plant is almost similar to that of a conventional fossil fuel-based thermal power station with a difference in fuel consumption, i.e., they utilize sunlight as a fuel source instead of fossil fuels.

The solar radiations are concentrated to produce high-temperature steam, which drives a turbine. CSP plants generally comprise a receiver, a concentrator, transport or storage media, and an electrical generator. The position of the sun is continuously tracked by glass mirrors and is concentrated onto the desired point. A specially designed receiver absorbs this focused sunlight energy and transfers it to heat transfer flowing through them. This high-temperature fluid is then used to generate high-temperature steam, which drives a turbine. Fluids used to transfer heat can be air, water, or oil. However, recently molten salts are being used in modern CSP plants [9].

Two variations in CSP technology are available, linear concentrator and point concentrator technology. Amongst them, the most promising are the parabolic trough collector, the central receiver is also referred to as a solar power tower, and lastly parabolic dish collector.

A. Linear Concentrator

1) Parabolic Trough Collector

In parabolic trough collector technology, as shown in Fig. 2 [7], long parabolic trough-shaped mirrors are employed that concentrate sunlight onto a receiver tube passing through its linear optical focus. The receiver tube's function is to collect the concentrated sunlight, transfer it to the thermal fluid, usually a synthetic oil, and circulate it towards the heat exchangers. To improve the reflection properties, the mirrors employed are either silver coated or polished aluminum. These receiver tubes are made thermally efficient by encapsulating them in a vacuum glass cover. The full sun's rays heat the fluid to an approximate temperature of 400°C [9]. This heated oil is then passed through heat exchangers to generate superheated steam, which is then used to drive turbines to generate electricity. The troughs track the sun on a north-south axis for maximum utilization of sunlight. This type of plant's efficiency ranges from 17-18%, making it the most widely used solar thermal technology [8]. This is evident by its use in large scale power plants like 354 MW SEGS plants located at the Mojave Desert in California, 280 MW Solana generating station Gila Bend, Arizona, and Andasol I in Andalusia, Spain, etc. [6].

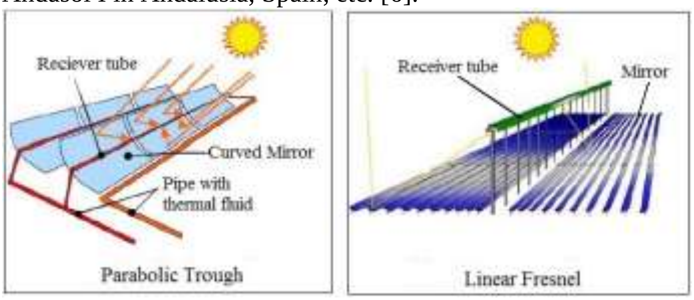

FIGURE 2. Types of linear concentrators

2) Linear Fresnel

Among the two practical CSP technologies, Linear Fresnel collector (LFC) based CSP technology is superior to parabolic trough designs in terms of its simplicity, robustness, comparatively low initial cost, and more utilization of land area leading to compact plant size. Linear Fresnel collector consists of an array of individual flat low-profile mirrors, forming roughly a parabolic shape, acting as primary reflectors, as shown in Fig. 2. The receiver tube assembly is fixed. In some plants, a second optional set of reflectors may also enhance its reflective properties. During day time, these flat mirrors track the sun and reflect the sunlight onto the receiver tube, through which a thermal fluid is circulated in the same manner as in the parabolic trough system. The receiver design may constitute of single-tube receiver or multiple tube receiver [11].

TABLE III
COMPARISION BETWEEN PARABOLIC TROUGH AND LINEAR FRESNEL

Plant Type	Unite Capacity (MW)	Concentration	Operational Temperature Range ^{0}C	Land required per MWh/y (m^2)	Annual Solar Efficiency Efficiency (%)
Parabolic Trough	10-200	70-80	300-550	6-8	17-18
Linear Fresnel	10-200	25-100	250-500	4-6	9-11

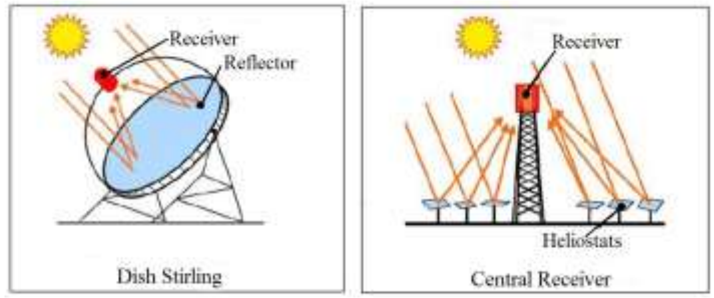

FIGURE 3. Types of point concentrator

The single tube design offers reduced manufacturing and hardware cost but requires a secondary reflector to increase collector optical performance. The multi-tubular strategy involves several parallel tubes that are placed horizontally, forming a trapezoidal arrangement with hollow spaces in between. These tubes are enclosed in a vacuum glass cover that decreases convection losses, enhancing receiver performance. Besides, it protects the tube coating, which is responsible for reducing losses due to radiation. These plants can achieve a temperature range from 300°C to 400°C [10]. However, LFC based plants offer lesser efficiency as compared to other typical CSP plants, but the generation cost of electricity of these types of plant is less [12].

A comparison between the various characteristics of a linear Fresnel and parabolic concentrators is illustrated in Table III [8].

B. Point Concentrators

1) Central Receiver

As shown in Fig. 3 [7], a central receiver, also referred to as solar tower power, consists of a circular field of flat mirrors known as heliostats, a receiver (absorber) tower, and a power conversion system and a storage system. The computer-controlled heliostats individually track the sun on a dual-axis and reflect the sunlight onto a receiver situated at the top of a tall tower. Generally, the receiver consists of several absorber tubes. A working fluid absorbs the concentrated radiation reflected from the number of heliostats and transports it to a thermal storage tank. The working fluid may be steam, air, or molten salts. This heat energy is then used to generate steam in a heat exchanger, which drives a steam turbine for electricity generation. These plants concentrate sunlight 500-1000 times to attain an operational temperature range of 250 to 1000 ºC [13]. A significant advantage of this type of CSP plant is operating the plant at high steam temperature conditions, resulting in increased efficiency ranging from 20% [8]. This Concept is successfully demonstrated in an American pilot project, Solar Two. Presently, various central receiver solar power plants in operation like 1.5 MW Beijing Badaling plant, 19.9 MW Gemasolar plant in Spain, etc.

2) Parabolic Dish

Also known as Sterling dish (SD), this type of system consists of a small concentrator (reflector) unit in parabolic shaped dishes and a power conversion system coupled through a heat exchanger. These dual-axis concentrator dishes reflect and concentrate the sunlight onto a receiver situated at the focal length of a concentrator. In this case, the receiver unit acts as the heat exchanger, absorbing the concentrated solar radiation beam to heat the working fluid or gas like air or helium. The maximum operating temperature may reach 700 ºC or even above [14]. This heated fluid is then utilized to drive a Sterling engine or a small turbine. An electrical generator coupled to the crankshaft of the generator converts the mechanical energy to electrical energy. These dishes are equally effective in decentralized power supply units or standalone systems, with an individual unit rating from 5-50 kW. Currently, various parabolic/Sterling dish systems are operational in America and Spain.

III. COMPARISION OF VARIOUS CSP TECHNOLOGIES

Among all the CSP technologies, the parabolic trough is the most advanced technology commercially implemented in many solar thermal plants [15].

However, if mass production is achieved, there can be a significant cost reduction in parabolic dish technology. This technology is particularly suitable for water-scarce areas like deserts, in the form of standalone or modular units, due to no water required for cooling purposes. Various characteristics of major CSP technologies are compared in Table IV [6,8,15].

TABLE IV
COMPARISION BETWEEN MAJOR CSP TECHNOLOGIES

Characteristics	Plant Type			
	Parabolic Trough	Linear Fresnel	Central receiver	Parabolic/Sterling Dish
Relative cost	Low	Very Low	High	Very High
Unite Capacity (MW)	10-200	10-200	10-150	0.01-0.4
Operational Temperature (ºC)	400	300-400	250-1000	700
Peak solar efficiency (%)	21	20	20	29
Grid Connection	Yes	Yes	Yes	Yes (In case of clustered unites, forming a dish park)
Standalone Capability	No	No	No	Yes
Commercial Availability	Yes	Yes	No	Yes
Modularity	Yes	Yes	No	Yes
Land Use Factor ($m^2MWh^{-1}y^{-1}$)	6-8	4-6	8-12	8-12
Hybrid Operation	Yes	Yes	Yes	Yes
Storage Capability	Yes	Yes	Yes (only at high temperatures)	Yes
Reliability	Average	Good	Good	Low
Cooling Water (L/MW h)	3,000 /dry	3,000/dry	1,500/ dry	None
Comments	The moderate steam quantity due to oil base heat transfer.	Plant efficiency needs to be improved	For commercial plants, investment and operating costs are required to be improved.	Due to its low reliability, mass production has not yet been achieved.

IV. POTENTIAL OF CSP IN PAKISTAN

There are two main factors, geographical and climatical, that are considered in this paper for accessing the suitability of developing CSP technologies in Pakistan.

A. Solar radiation resource assessment

The major climatic factor that affects the performance of a CSP plant is solar irradiation. Pakistan has sufficient solar resources. It is estimated that Pakistan's three-fifth land receives high-intensity horizontal radiations of 5.2 to 6.4 kW h/m2 per day, which is 3000 hours more than the annual average sunshine [16]. Fig. 4 shows the solar radiation resource in Pakistan. It is evident from Fig. 4 [17] that parts of central Baluchistan, southern Punjab, and Northern Sindh receives maximum irradiation.

Due to current CSP technology's inherent optical characteristics, only the direct normal component of irradiation (DNI) is being used to heat the working fluid to generate electricity [6]. DNI refers to the fraction of undeviated sunlight that reaches the earth's surface in the form of a parallel beam of light that can be concentrated by a solar plant's mirrors. Fig. 5 [17] shows the distribution of direct average irradiation in Pakistan.

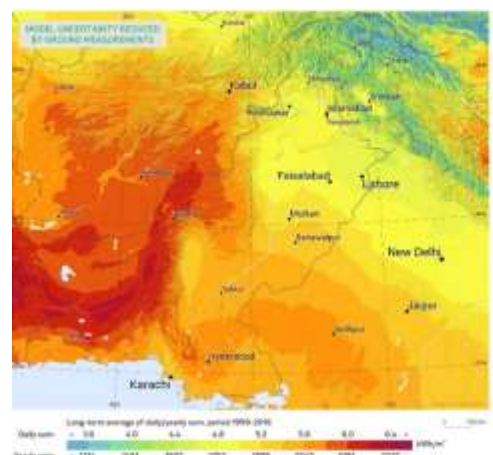

FIGURE 4. Global horizontal irradiation map of Pakistan

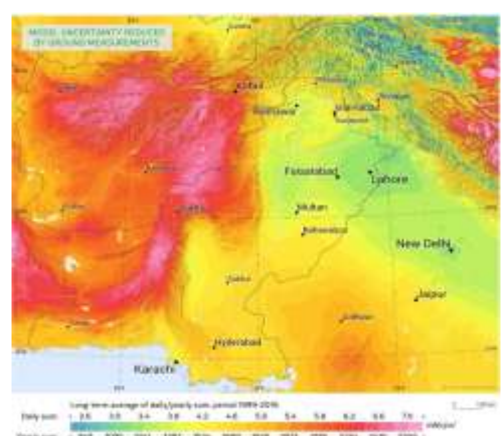

FIGURE 5. Direct normal irradiation map of Pakistan

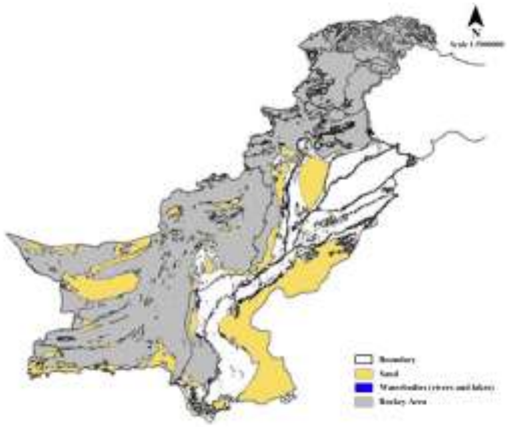

FIGURE 6. Wasteland map of Pakistan

In general, the DNI level is directly proportional to the land area required for a given power plant capacity. One of the most important economic factors for a solar power plant is solar field cost. For example, the solar plant's field cost comprises 50% of the total cost for the Rankine cycle steam power plant-dependent solar heat source [18]. In literature, CSP plants' economically feasible sites have a DNI level above 6 kW h/m^2 per day while receiving a minimum of 2,000 kW h/m^2 of sunlight radiation annually [6]. As seen from Fig. 5, the best-suited sites are situated in the province of Baluchistan, especially surrounding Quetta valley, with some areas having a DNI level similar to a typical desert region.

B. Land feasibility in Pakistan

The fundamental consideration in the planning of a CSP power plant project is land availability. As a general rule, the CSP plant requires an average of 1,000 m^2 of land area per 50 MW of the installed plant capacity [8]. Pakistan has a high population density, therefore agricultural or forest land cannot be utilized for power plant construction, as food and biomass for the growing population is produced on these types of land. Pakistan has approximately 285,000 km^2 of wastelands that accounts for 34.2% of the total land area [19]. The wasteland distribution of Pakistan is shown in Fig. 6 [19]. It can be seen that most of the wasteland area is rugged, rocky, or comprised of deserts.

It is quite evident from Fig. 6 that the majority of the wastelands lies in the parts of Balochistan province, where the areas receiving the highest DNI values are situated too. In addition to the factors mentioned above, the land's slope and orientation also play an important role in site selection of CSP plants. Ideally, the land's exposure should be north-south, with some degree of slope allowed towards the equator. A slope of less than 2% is ideal for plant location; however, some plants can cope with less than 5% of the slope but at a higher grading cost [18].

However, if the land is exceptionally rocky or hilly with a more than 5% slope, it would not be suitable for a solar power plant. Therefore, vast land areas in Baluchistan, especially near Quetta, can be utilized for small to medium scale solar thermal plants.

C. Land feasibility in Pakistan

For optimum CSP plant operation, water availability is one of the critical factors. In a typical CSP plant, water is mainly used for three purposes, namely: (i) steam generation, (ii) cooling (iii) washing mirrors. Two types of cooling technologies are usually employed in a CSP plant for cooling purposes, i.e., wet or water-cooling and air or dry-cooling. The water requirement for a water-cooled-based CSP plant is about 3.3 m^3/ MWh, while a dry-cooled-based CSP plant is 3 m^3/MWh [20]. A majority of this water, around 95%, is used for cooling purposes. The remaining is used for steam generation and for the washing of mirrors to prevent soiling effects, which may reduce plant efficiency. For regions having abundant water resources, water cooling technology can be utilized. On the contrary, in areas where water availability is scarce, air cooling is the preferred type of technology. However, air cooling technology increases the capital cost of a CSP plant and an annual reduction of 3%-10% in plant efficiency but provides greater flexibility in terms of plant location [1, 20].

In Pakistan, the primary source of water is its rivers. Currently, all major power plants are situated near the river due to easy water accessibility. From Fig. 7 [1], it can be deduced that the Indus river plain compromising much of Sindh and Punjab province have a majority of the river network. Thus, this area is suitable for wet cooling CSP plants. Whereas Baluchistan does not possess much river network, therefore dry cooling is ideal for CSP plants near Quetta valley.

FIGURE 7. Water bodies in Pakistan

V. CURRENT STATE POLICY TOWARDS CSP

In general, Pakistan lags behind other Asian countries in terms of effectively utilizing renewable energy technology. The main reasons are lack of supportive policies, deficiency in the allocation of budget for renewable energy technologies (RET's), and lack of research and development efforts. By implementing RETs, specifically, small to medium energy generation plants through proper research can enable Pakistan to follow its sustainable goals of increasing renewable energy, particularly CSP, in its total energy mix. The 2006 policy for the development of RETs states that by 2030 contribution of RET's in the total energy mix would be increased by 10,000 MW [21]. According to the German Advisory Council on Global Change (WBGU), by 2050, half of the world's primary energy requirement would have to be derived from renewable energy sources [22].

In recent years several meteorological stations at various potential sites across Pakistan have been set up in collaboration with the World Bank and Alternative Energy Development Board of Pakistan (AEDB) [23]. These stations' purpose is to record and map various ground-based solar energy parameters like direct normal irradiance, global horizontal irradiance (GHI), and diffuse horizontal irradiance (DHI) to develop solar radiation maps. These types of studies will provide ease for any feasibility studies related to the development of initial small-scale prototype CSP plants by providing actual ground-based measurements.

The solar thermal application is currently limited to solar water heaters, solar geysers, solar desalination, solar cookers, and dryers. However, the true potential of solar thermal energy for electricity generation for CSP is yet to be examined and utilized.

VI. CONCLUSION

This paper presented the prospects of concentrated solar power technology in Pakistan. A detailed comparison of various CSP technologies in terms of characteristics and efficiencies is outlined. It is found that the parabolic dish based CSP is a promising technology, given that the obstacles in its mass production are overcome.

Pakistan has ample solar energy resources and sufficient wasteland availability, especially in Western and South-Western Baluchistan. Initially, these wastelands are best suited for the construction of small scale off-grid parabolic dish plants. If deemed successful, they can be clustered together to form an on-grid dish park in the future. Hence, increasing the share of renewable energy through CSP in the total energy mix of Pakistan, as stated in the 2006 policy for the Development of Renewable Energy Technologies

Lastly, the government has to show a sincere will to design and plan the policies for CSP development in Pakistan.

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