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A Comparative Analysis of Solar Energy Technologies and Large-Scale Projects in Rajasthan: Assessing Policy Frameworks, Planning Strategies and Performance Efficiency

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ABSTRACT: The accelerating demand for energy driven by industrialization, urban expansion, and technological advancement has intensified global concerns regarding fossil fuel dependency and climate change. In this context, solar energy has emerged as a vital component of the global transition toward sustainable and low-carbon power generation. This paper presents a comparative analysis of solar energy technologies and large-scale solar projects in Rajasthan, India, with a focus on technological performance, policy frameworks, planning strategies, and implementation outcomes. The study examines the two principal solar technologies—Photovoltaic (PV) and Concentrated Solar Power (CSP)—highlighting their operational mechanisms and recent technological advancements. The declining cost of PV modules, significant improvements in system efficiency, and the integration of thermal storage in CSP systems have strengthened the feasibility of large-scale solar deployment. Rajasthan, owing to its high solar irradiance, vast desert land, and favorable climatic conditions, has emerged as a leading state in solar energy generation. Major projects such as the Bhadla Solar Park demonstrate successful implementation, while other projects remain under development, reflecting both achievements and gaps in execution. Although the state has made considerable progress in expanding installed capacity, a substantial portion of its estimated solar potential remains untapped.

KEYWORDS: Solar Energy; Photovoltaic (PV); Concentrated Solar Power (CSP); Renewable Energy; Solar Parks; Climate Change.

I. INTRODUCTION

In the twenty-first century, the pace of industrial expansion, rapid urban growth, and continuous technological innovation has led to a sharp rise in global energy demand. Energy today functions as the backbone of economic progress, social transformation, and improvements in quality of life. At the same time, excessive reliance on fossil fuels such as coal, oil, and natural gas has created serious environmental consequences, including air pollution, resource depletion, and accelerating climate change. The combined pressure of population growth, rising per capita energy consumption, and the gradual exhaustion of conventional resources has compelled countries to actively search for alternative and sustainable energy options. Recognizing the gravity of global environmental concerns, nations have engaged in collective climate action under frameworks such as the United Nations Framework Convention on Climate Change (UNFCCC). India has played an active role in these global efforts and has committed itself to expanding clean, green, and low-carbon energy generation. As one of the world's most populous countries, India faces the dual challenge of meeting increasing electricity demand while simultaneously reducing carbon emissions to ensure balanced and sustainable development (Paliwal and Dave, 2021).

Within India, Rajasthan occupies a distinctive position in the renewable energy landscape. Geographically the largest state, covering nearly 10.6 percent of the country's total area, Rajasthan has limited reserves of conventional hydrocarbons and restricted access to non-renewable energy sources such as coal and petroleum (Sukhatme and Nayak, 1997). The global connection between energy use and climate change is now widely acknowledged, with fossil fuel-based energy production identified as a principal contributor to greenhouse gas emissions. In contrast, renewable energy sources—particularly solar energy—provide a cleaner and increasingly affordable alternative. Solar power generation does not release carbon dioxide or other harmful pollutants during operation, making it central to climate mitigation strategies. As technological advancements continue to reduce costs and improve efficiency, solar energy is emerging not merely as an option but as a necessity, especially in climate-sensitive regions such as Rajasthan. The state's vulnerability to climate-related challenges, including drought, water scarcity, desertification, and agricultural stress, further strengthens the need for sustainable energy solutions. Expansion of solar infrastructure reduces



dependence on thermal power plants while simultaneously improving energy access for remote and underserved communities, thereby promoting inclusive and environmentally responsible development (Lodi and Shekhawat, 2024).

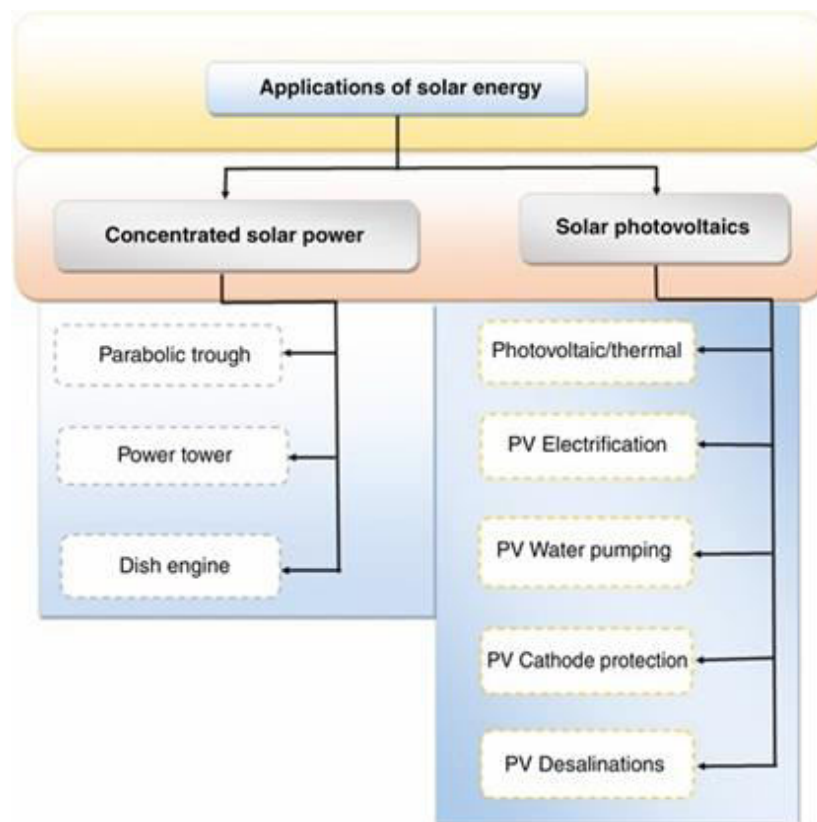
Rajasthan's natural conditions strongly favour large-scale solar energy deployment. The state encompasses approximately 208,110 square kilometres of desert terrain and receives more than 325 sunny days annually. Average solar radiation ranges between 6–7 kWh per square meter per day, while direct normal irradiation varies significantly across regions, with particularly high values recorded in western districts (Sharma et al., 2014). The western part of the state is especially rich in solar resources, supported by expansive tracts of available land that are well suited for photovoltaic installations. Key districts such as Barmer, Bikaner, Jaisalmer, and Jodhpur record some of the highest solar radiation levels in the country (Ramachandrar et al., 2011). Daily average solar radiation ranges from about 5 kWh/m² in the north-eastern hilly areas to nearly 7 kWh/m² in the western desert regions. The state's low average rainfall further enhances solar suitability by ensuring minimal cloud cover and high solar insolation. Studies have indicated that solar radiation levels in Rajasthan are comparable to those in regions like California and Nevada in the United States (Sharma et al., 2011), reinforcing its status as one of India's most promising locations for utility-scale solar development.

The benefits of expanding solar energy in Rajasthan are wide-ranging. Extensive stretches of barren and non-arable land in districts such as Jaisalmer, Bikaner, Barmer, and Jodhpur provide ideal conditions for establishing large solar parks without major ecological disturbance or displacement. High solar insolation improves plant load factors and enhances energy generation efficiency. Moreover, solar development contributes to reducing reliance on fossil fuels, lowering GHG emissions, strengthening energy security, and stimulating sustainable economic growth. The solar industry is also expected to serve as an economic catalyst by generating employment opportunities and contributing to state revenue. Government policies and incentive frameworks have further encouraged private and public sector investment, accelerating the growth of renewable energy capacity in the state. Against this background, the present paper undertakes a comparative examination of solar energy technologies and major solar projects in Rajasthan, with particular emphasis on policy mechanisms, planning approaches, and performance efficiency.

II. SOLAR ENERGY TECHNOLOGIES: TYPES AND PERFORMANCE ANALYSIS

Solar energy technologies are generally grouped into two principal categories: non-concentrated PV systems and CSP systems. Non-concentrated PV systems generate electricity directly from sunlight through the photovoltaic effect. In this process, semiconductor materials—most commonly silicon—absorb incoming solar radiation and release electrons, producing DC electricity. This DC power is subsequently converted into AC with the help of inverters, making it suitable for household, commercial, and grid applications. PV technology includes different types of modules such as monocrystalline, polycrystalline, and thin-film panels, each differing in material composition, efficiency levels, production cost, and structural characteristics. Additionally, since these systems have no moving mechanical components, they require comparatively low maintenance. Their flexibility and adaptability make them particularly appropriate for regions that receive high levels of solar radiation and have extensive open land resources. Compared to PV installations, CSP plants typically involve higher capital investment and are more commonly deployed in large-scale power generation projects. However, a significant advantage of CSP technology lies in its capability to integrate thermal energy storage systems, enabling electricity production even during evening hours or periods without direct sunlight. Both PV and CSP technologies contribute meaningfully to the advancement of solar energy infrastructure, and the choice between them depends on multiple considerations such as economic feasibility, land and water availability, grid connectivity, and supportive policy frameworks (Kumar and Mchinnapandian, 2017).

Fig 1: Taxonomy of solar energy applications

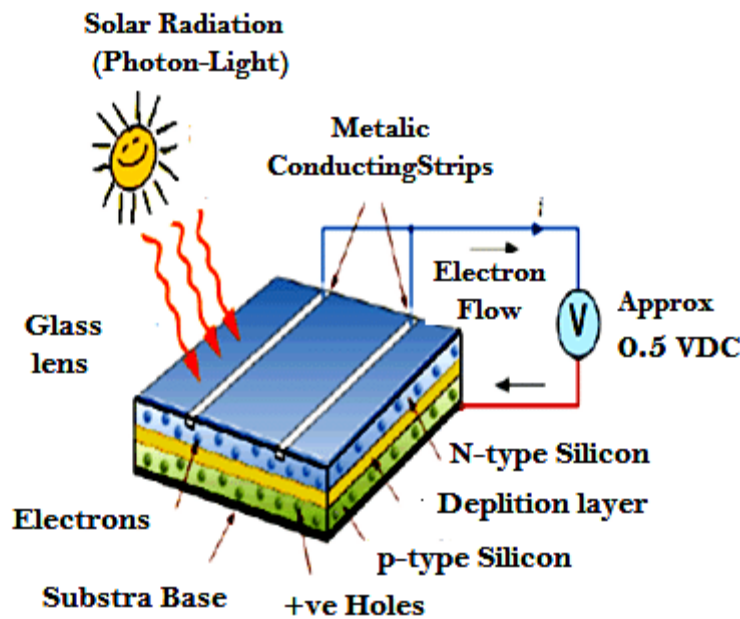


Source: Maka and Alabid (2022)

III. PHOTOVOLTAIC (PV)

In recent years, solar photovoltaic (PV) technologies have expanded more rapidly in the energy market than solar thermal systems. One of the main reasons for this growth is their capability to convert sunlight directly into electrical energy without intermediate mechanical processes. Additionally, PV systems generally offer a lower levelized cost of electricity (LCOE), making them economically attractive for large-scale deployment. Future projections indicate that by 2030, solar PV is expected to contribute nearly 69.6% of total electricity generation from solar-based sources, highlighting its dominant position in the renewable energy sector. Despite these advantages, conventional PV panels face inherent efficiency limitations. Typically, only about 20% of the incident solar radiation is converted into usable electricity, while the remaining 80% is lost as heat. This excess heat accumulates within the PV modules, leading to a rise in cell temperature that negatively influences their performance. Even a minor temperature increase of 1°C can reduce electrical output by approximately 0.1% to 0.5%. Over extended periods of continuous solar exposure, such reductions become significant, ultimately lowering the overall efficiency and productivity of the system. Furthermore, elevated temperatures increase the internal resistance of PV circuits, which slows the movement of charge carriers (electrons). This directly affects key electrical parameters, particularly the open-circuit voltage, and results in noticeable degradation in overall cell performance. Recognizing these challenges, researchers have devoted considerable attention over the past few decades to exploring and developing various cooling strategies aimed at regulating PV cell temperature and improving operational efficiency (Alami et al., 2024).

Fig 2: Basic structure of a PV cell



Source: Makhloufi et al. (2016)

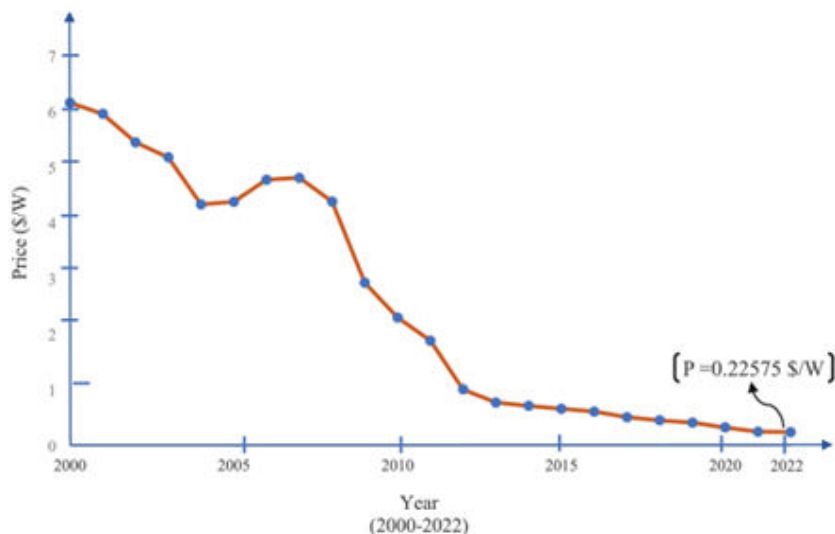
Solar PV technologies convert sunlight directly into electricity through the photovoltaic effect. Solar cells are the basic units of PV modules and are widely used in power generation and light-sensitive applications. PV technologies are broadly classified into three generations (Sarah et al., 2020):

- **First-generation** (wafer-based) technologies include monocrystalline and polycrystalline silicon cells. Monocrystalline cells, made from a single silicon crystal, offer higher efficiency, while polycrystalline cells are more cost-effective but slightly less efficient due to crystal defects.
- **Second-generation** technologies consist of thin-film solar cells such as amorphous silicon (a-Si), Cadmium Telluride (CdTe), and Copper Indium Gallium Di-Selenide (CIGS). These technologies require less material, are cheaper to manufacture, and perform better under diffuse light conditions. CdTe and CIGS cells have achieved competitive efficiencies, with lower energy payback time and reduced environmental impact compared to conventional silicon cells.
- **Third-generation** solar technologies are emerging and largely under research and development. These include nanocrystal (quantum dot) cells, polymer solar cells, dye-sensitized solar cells (DSSC), and perovskite solar cells. They focus on improving efficiency, reducing production cost, enhancing flexibility, and enabling new applications such as lightweight and building-integrated solar systems. Among these, perovskite solar cells have shown rapid efficiency improvements and hold strong potential for future large-scale deployment.

Figure 3 illustrates the declining trend in solar photovoltaic (PV) electricity prices from 2000 to 2022, measured in US dollars per watt (\$/W). The overall pattern clearly demonstrates a substantial and continuous reduction in solar power costs over the past two decades. At the beginning of the period (around 2000), solar PV prices were approximately \$6/W. During the early 2000s, prices showed a gradual decline with minor fluctuations, falling to around \$4–5/W by 2005–2007. This phase reflects the initial stage of technological development and limited large-scale deployment, where production volumes were still relatively low and manufacturing processes were less optimized. A sharp and accelerated decline is observed between 2008 and 2012. During this period, prices dropped dramatically from above \$4/W to nearly \$1/W. This steep reduction can be attributed to rapid technological advancements, economies of scale, improvements in manufacturing efficiency (particularly in crystalline silicon modules), increased global competition, and strong policy support mechanisms in major markets such as Europe, China, and the United States. After 2012, the rate of decline becomes more gradual but continues steadily. Between 2013 and 2022, prices decreased from around \$0.8/W to approximately \$0.22575/W. This phase represents market maturity, where cost reductions are driven by incremental technological improvements, supply chain optimization, automation, and large-scale project implementation.



Fig 3: Solar PV module price



Source: Ahmed et al. (2025)

IV. CONCENTRATED SOLAR POWER (CSP)

Concentrated Solar Power (CSP) technology operates by using a network of mirrors to concentrate direct normal irradiation (DNI) onto a central receiver, where the captured solar energy is transformed into high-temperature thermal energy. This heat is then utilized to generate steam, which drives a conventional turbine connected to an electrical generator, similar to the working principle of traditional thermal power plants. A distinctive feature of CSP systems is their ability to incorporate thermal energy storage, commonly through materials such as molten salts. This stored heat can be used to continue electricity production during cloudy periods or after sunset, thereby enhancing grid reliability and stability. The principal CSP configurations include parabolic trough systems, central receiver or solar tower systems, linear Fresnel reflector systems, and parabolic dish systems. Among these, parabolic trough and linear Fresnel technologies employ linear focusing mechanisms, concentrating sunlight along a receiver tube. In contrast, solar towers and parabolic dish systems utilize point-focus concentration, which allows them to achieve significantly higher operating temperatures. Parabolic trough and central tower systems are typically deployed in large-scale utility projects, generally ranging from 10 to 200 MW in capacity, while parabolic dish systems are more suitable for smaller-scale or decentralized applications. Although CSP installations involve substantial upfront capital costs, their capability for integrated thermal storage and bulk electricity generation makes them particularly advantageous for large, grid-connected solar power plants (Silva et al., 2024).

Table 1: Recent Technological Advances in PV and CSP Systems

Research	Methodology	Key Findings	Reference
Self-cooled ventilated PV panel	Experimental & CFD modelling	Better performance at 30° tilt and white soil; lower operating temperature improved output	Echarfi et al. (2018)
CSP-based solar still with Fresnel lens	Experimental study (Malaysia)	92% increase in condensate production; potable water quality achieved	Ho & Bahar (2019)
Polycrystalline PV temperature effect	Experimental analysis	Increase in panel temperature reduced power and efficiency	Sidharthan & Mathiazhagan (2021)



100 MW PV vs CSP (Kuwait)	Techno-economic analysis	PV lower capital cost (\$100M) & 5-year payback; CSP higher revenue but 13-year payback	Althuwaini & Philbin (2021)
Water-cooled PV panels	Experimental comparison	Exergy efficiency increased from 2.91% to 12.76% with cooling	Chanphavong et al. (2022)
50 MW Parabolic Trough CSP	Seasonal simulation (Mongolia)	Best performance in June; reduced efficiency during winter and part-load	Shagdar et al. (2022)
4 kW Grid-connected rooftop PV	PVsyst simulation	17.8 kWh/day generation; 113 tons CO ₂ reduction	Yadav et al. (2023)
Bifacial PV-Trombe Wall	Theoretical & experimental	17.46% higher power; PV efficiency increased to 16.17%; reduced wall temperature	Su et al. (2024)
Vertical Bifacial PV (VBPV)	One-year empirical study (UK)	Up to 26% higher output than tilted monofacial PV; strong seasonal gains	Badran & Dhimish (2024)
10 MW Solar Tower CSP (Leh)	SAM simulation	CF 56.9%; efficiency 16.35%; LCOE \$0.1202/kWh	Vennila et al. (2024)
CSP optimization (cooling methods)	SAM & RSM modelling	Hybrid cooling most cost-effective; 47% land reduction with minimal energy loss	Mdallal et al. (2024)
CSP site comparison (Egypt)	SAM & GIS analysis	Solar tower higher output but 25% more land; lower LCOE than trough	Bayoumi et al. (2024)
PV tilt angle & dust impact	Outdoor experiment (Oman)	24.5% efficiency with daily cleaning; 18.8% loss due to dust; optimal tilt 25°	Chala et al. (2025)
Molten Salt CSP towers (Algeria)	SAM techno-economic study	Optimal SM 1.8 & 10h TES; CF 51.49%; LCOE \$0.097/kWh	Mohamed et al. (2025)

Source: Author

V. LARGE-SCALE SOLAR PROJECTS IN RAJASTHAN: POLICY, PLANNING AND PERFORMANCE

Global efforts to address climate change have gained momentum since the adoption of the Kyoto Protocol, marking a significant step toward coordinated international climate action. Within the broader shift toward low-carbon energy systems, photovoltaic (PV) solar power has emerged as a vital component in reducing greenhouse gas emissions (Song



and Wang, 2023). Solar energy contributes not only to emission reduction but also to diversification of the energy portfolio, enhancement of energy security, and decreased dependence on imported fuels. As a renewable resource that is widely available and freely accessible, solar power presents a cost-effective and sustainable alternative for countries seeking long-term energy stability (Pichou et al., 2023; Meflah et al., 2024).

In India, policy support for distributed generation photovoltaic (DGPV) systems began taking shape after 2003. A major turning point came with the launch of the Jawaharlal Nehru National Solar Mission (JNNSM) across its three phases, which significantly stimulated growth in the distributed solar market. Despite these early efforts, DGPV capacity expansion remained modest until 2013, when installed capacity reached 150 MW and system prices began to decline noticeably. Subsequent policy measures—including the introduction of feed-in tariffs in 2014, rooftop solar net-metering regulations in 2015, and the Grid Connected Solar Rooftop Programme in 2016—further accelerated adoption. During this phase, installation costs fell by approximately 44%, while total installed capacity increased to 1.3 GW. The implementation of Renewable Purchase Obligations (RPOs) in 2019 provided an additional boost, expanding DGPV capacity to 5.4 GW and reducing installation costs by another 21%, reaching historically low levels. By 2022, India's installed DGPV capacity had grown substantially to 15.2 GW, reflecting sustained policy-driven momentum (Schetinger and De Lucena, 2025).

Rajasthan represents a strong example of how renewable energy policy and natural resource advantages can align. Blessed with high solar irradiance and vast arid landscapes, the state has adopted the Integrated Clean Energy Policy 2024, setting an ambitious target of 125 GW of renewable energy capacity by 2030, of which 90 GW is expected to come from solar power. A landmark achievement in this direction is the Bhadla Solar Park, covering approximately 56 square kilometres and generating 2,245 MW, making it the largest solar park in India. Urban centres such as Jaisalmer and Pushkar are being developed as solar cities, integrating rooftop solar installations, solar street lighting, solar water pumping systems, solar-powered drip irrigation, and electric vehicles to meet local energy needs sustainably. In rural areas, programmes such as PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mah Abhiyan) aim to promote solar-powered irrigation. Of the national target of 17.5 lakh solar pumps, Rajasthan holds a major share, with more than 1.25 lakh pumps installed and subsidies covering up to 60% of the cost for farmers. Special emphasis has been placed on districts such as Barmer, Jalore, Bikaner, and Jaisalmer. Additionally, schemes like Saubhagya have delivered solar kits to remote tribal households in districts including Dungarpur, Banswara, and Pratapgarh, where standalone systems are deployed in areas lacking grid connectivity. As both urban and rural regions continue to expand, integrating solar solutions into infrastructure development is essential to achieving sustainable development goals and promoting environmentally responsible growth (Beniwal and Tyagi, 2025).

However, implementation challenges remain. According to the Ministry of New and Renewable Energy (MoNRE, 2025), although 6,550 MW has been sanctioned under the PM-KUSUM scheme, only 329.75 MW has been installed to date—representing roughly 5% of the approved capacity. This considerable gap between sanctioned capacity and actual commissioning indicates delays in execution and highlights the need for improved coordination, streamlined procedures, and stronger monitoring mechanisms. At the same time, Rajasthan possesses an estimated solar energy potential of 142.31 Gwp, underscoring its significant natural advantage. The state's cumulative installed solar capacity has reached 26,489.65 MW (26.49 GW), reflecting meaningful progress in large-scale solar development. Nevertheless, this installed capacity represents less than 20% of the total estimated potential, indicating substantial room for expansion. Overall, while Rajasthan has demonstrated notable achievements in advancing solar energy, accelerating project implementation—particularly under schemes like PM-KUSUM—remains crucial to fully harness its solar resources and ensure sustained, long-term renewable energy growth.

Table 2 show considerable variation in the installation and operational status of major solar parks in Rajasthan. The Bhadla Solar Park phases—Bhadla-II (680 MW), Bhadla-III (1000 MW), and Bhadla-IV (500 MW)—are fully commissioned, indicating successful project execution and reflecting Rajasthan's strong position in large-scale solar development. Similarly, Fatehgarh Phase-1B Solar Park, with 421 MW under CFA support, is fully operational. In contrast, Phalodi-Pokaran Solar Park has an installed capacity of 750 MW, but only 450 MW is operational, showing partial commissioning. Nokh Solar Park also exhibits a significant gap, with only 190 MW operational out of 925 MW capacity. More notably, Pugal Solar Park (Ph-I and Ph-II), RVUN Solar Park, and Bodana Solar Park, despite having substantial planned capacities of 1000 MW, 2000 MW, and 2000 MW respectively, have not yet commissioned any capacity. This indicates that while Rajasthan has achieved full operationalization in some flagship projects like Bhadla, several other large projects are still in developmental or pre-commissioning stages. Overall, the table reflects both the state's achievements in solar infrastructure and the considerable scope for future expansion once the pending projects become operational.



Table 2: Installed and Operational Capacity of Major Solar Parks in Rajasthan (in MW)

Solar Park	Capacity (MW)	Operational / Commissioned (MW)
Bhadla-II Solar Park	680	680
Bhadla-III Solar Park	1000	1000
Bhadla-IV	500	500
Phalodi-Pokaran Solar Park	750	450
Fatehgarh Phase-1B Solar Park (1500 MW but 421 MW under CFA)	421	421
Nokh Solar Park	925	190
Pugal Solar Park Ph-I	1000	0
Pugal Solar Park Ph-II	1000	0
RVUN Solar Park	2000	0
Bodana Solar Park	2000	0

Source: MoNRE (2025)

VI. CONCLUSION

With fossil fuels contributing significantly to global GHG emissions, the transition toward renewable energy sources—particularly solar—has become imperative. Among solar technologies, photovoltaic (PV) systems have experienced rapid market expansion due to declining costs, modular design, and ease of deployment, while concentrated solar power (CSP) offers the advantage of thermal storage and grid stability for large-scale applications. Continuous technological innovation, improved efficiency, and falling module prices have further strengthened the competitiveness of solar power in the global energy mix. Rajasthan stands out as a strategic hub for solar energy development due to its abundant solar radiation, extensive arid land, and supportive policy environment. Landmark projects such as the Bhadla Solar Park demonstrate the state’s capability in executing large-scale solar infrastructure successfully. However, the analysis also reveals disparities between sanctioned and commissioned capacities in several projects and schemes such as PM-KUSUM, indicating implementation bottlenecks and coordination challenges. Despite achieving an installed capacity exceeding 26 GW, Rajasthan has utilized less than one-fifth of its estimated solar potential of 142.31 GWp, signifying vast opportunities for expansion. Overall, while Rajasthan has made commendable progress in advancing solar energy infrastructure, sustained efforts are required to bridge the gap between planning and execution. Strengthening institutional coordination, streamlining regulatory procedures, enhancing grid integration, and accelerating pending projects will be crucial in maximizing the state’s renewable energy capacity. A balanced integration of technological advancement, policy support, and efficient project implementation can position Rajasthan as a global model for large-scale solar energy development and sustainable growth.

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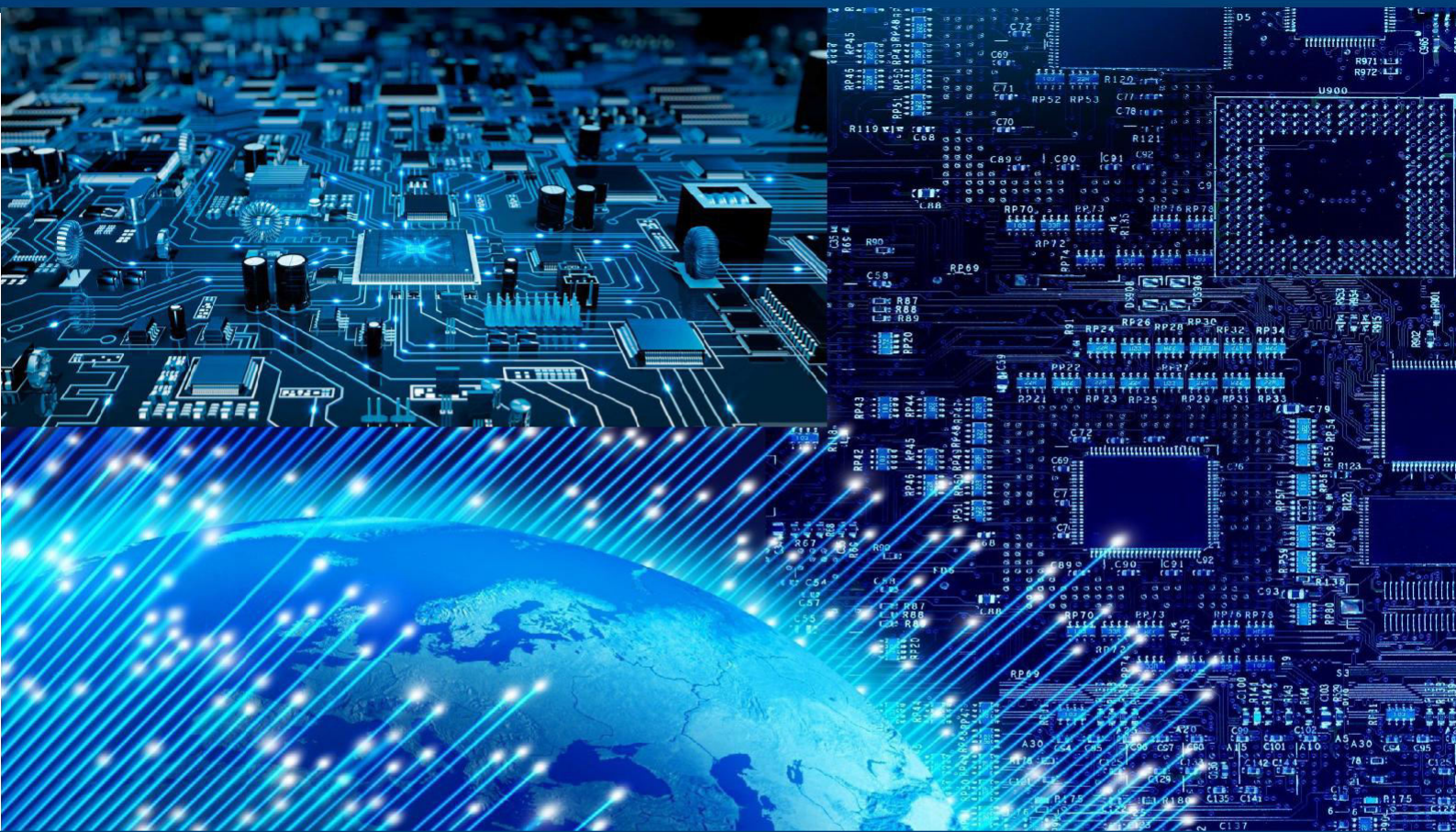
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