Techno-Economic Optimization and Financial Feasibility of A 500 MW Central Receiver CSP Plant with Molten Salt Storage in Kutch, India

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I. ABSTRACT

While India is rapidly expanding its renewable capacity, grid integration remains constrained by the steep evening drop-off in conventional solar photovoltaic (PV) generation during peak demand hours. This study evaluates a scalable mitigation framework: a 500 MW utility-scale Concentrated Solar Power (CSP) plant with thermal storage integrated within the Khavda Renewable Energy Park in Gujarat.

Departing from static photovoltaic arrays, the proposed configuration deploys five co-located 100 MW central receiver towers coupled with a 12-hour molten salt Thermal Energy Storage (TES) system. This thermal buffer **decouples thermal collection** from electricity generation, enabling dispatchable, zero-emission base-load generation during non-solar periods. The configuration provides a reliable capacity firming mechanism, operating at an optimized annual Capacity Utilization Factor (CUF) of approximately 62%

To mitigate the extreme hyper-saline atmospheric conditions and acute water scarcity of the Rann of Kutch, the plant integrates specialized anti-corrosion materials and a closed-loop dry cooling system. The total overnight project cost is estimated at **₹22,825 Crores**. Financial sensitivity modeling demonstrates that under a 30% Viability Gap Funding (VGF) mechanism paired with preferential green financing, the Levelized Cost of Electricity (LCOE) transitions to a competitive range of ₹4.80 to ₹5.50/kWh, showcasing utility-scale CSP as a viable solution for round-the-clock (RTC) clean energy requirements.

II. INTRODUCTION

India's strategic mandate to deploy 500 GW of non-fossil fuel capacity [4] introduces an operational challenge: maintaining grid equilibrium and stability during periods of zero solar resource availability While solar photovoltaic assets offer low-cost bulk energy generation, their generation profile correlates poorly with the steep evening peak electricity demand [5]. This study evaluates the techno-economic optimization and financial feasibility of a utility-scale 500 MW Concentrated Solar Power (CSP) deployment inside the Khavda Renewable Energy Park.

To maximize efficiency, this study evaluates a decentralized cluster configuration consisting of five interconnected modular central receiver blocks. Each module operates alongside a 12-hour high-temperature thermal battery loop [1]. This architecture achieves an operational availability factor equivalent to baseload fossil-fuel assets (62% CUF) [2] while retaining a zero-emission footprint.

To mitigate the high salinity and water scarcity of the Rann of Kutch, a ₹22,825 Crore plant architecture with underground storage and dry cooling is deployed [2], [3] which represents a highly capital-intensive asset deployment. Targeted fiscal mechanisms effectively bridge the near-term commercial gap, lowering the baseline generation cost from ₹7.10/kWh to a market-viable threshold. Consequently, utility-scale CSP with storage offers a viable framework to satisfy India's round-the-clock renewable energy mandates. [4]

III. TECHNICAL AND OPERATIONAL FEASIBILITY ANALYSIS

A. Civil Engineering and Structural Foundation in High-Water-Table Saline Terrain

The civil and structural engineering requirements for a 500 MW central receiver CSP facility over the Khavda salt flats necessitate highly specialized geotechnical interventions. This deployment is subject to the unique geotechnical complexities inherent to the hyper-saline Rann of Kutch terrain. The site has marine clays, loose silty sands and a very shallow saline water table that ranges from 0.5 m-1.5 m below the surface. It is also at risk of earthquakes classified under Seismic Zone V as per IS 1893:2016 [6].

1) 200-Meter Concrete Tower Foundations

The 5*100 MW modular central towers put massive vertical loads and extreme lateral forces on the foundations. This is due to monsoon wind velocities that reach up to 50 m/s [6]. Conventional shallow raft configurations are unviable due to risks of severe differential settlement and co-seismic soil liquefaction [6].

- Each tower needs a piled raft foundation configuration. This includes a high-rigidity circular concrete cap supported by 60 to 80 bored cast-in-situ concrete piles [6].
- The piles must be 1.5m to 2.0m in diameter and extend 45m to 50m deep to reach competent dense sand or bedrock [6].
- The foundation concrete must use a high-performance mix with Sulphate-Resistant Portland Cement, Ground Granulated Blast-furnace Slag (GGBS) and silica fume. This protects against chloride and sulphate attacks from the groundwater [6].
- The water-to-binder ratio must be below 0.35. High workability is maintained at low water-cement thresholds through the addition of third-generation polycarboxylate-ether superplasticizers [6].
- All reinforcing steel in the piles and pile caps must be Epoxy- Reinforcing bars or dual-phase galvanized steel [6].
- An impressed current cathodic protection (ICCP) system must be embedded in the foundation. This neutralizes chloride-ion migration [6].

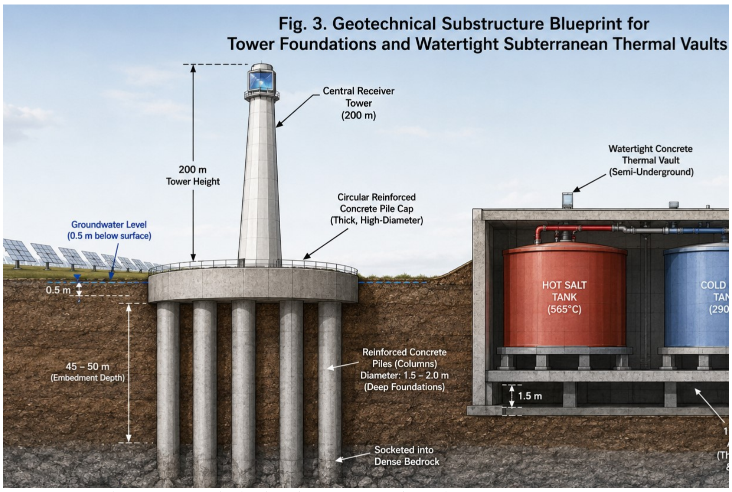

Fig. 1. Geotechnical Substructure Blueprint

2) Underground Thermal Energy Storage (TES) Tank Foundations

The 12-hour molten salt TES loop needs tanks for hot nitrate salts. These containment vessels operate continuously across an extreme thermal spectrum of 290°C to 565°C. Storing them underground in a water table introduces severe hydrogeological and thermodynamic risks [7].

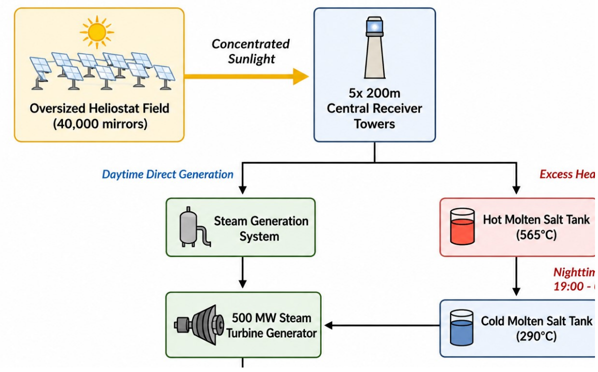

Fig. 2. System Architecture and Operational Flow of the 5x100 MW Modular Central Receiver CSP Configuration.

- The storage tanks must be in a semi-underground watertight reinforced vault [7].
- The tank base must sit on a piled slab elevated 1.5 meters above the vault floor. This isolates the ground from the downward thermal flux [8].

- The intermediate air gap must be actively ventilated with blower networks. It also needs a multi-layered insulation barrier with high-density foam glass blocks and refractory firebricks [7], [8].
- The concrete vault must be anchored with vertical tension piles. These counteract hydrostatic uplift forces exerted by the saline water table [6], [8].

B. Metallurgy, Coating Systems and Heliostat Reliability

The Khavda salt flats have a marine/industrial environment. This is classified under category CX as per ISO 12944-2:2018 [9]. The environment has humidity, marine salt-mist and abrasive wind-borne sand. This subjects the 40,000 tracking heliostats to erosion and chemical degradation.

TABLE II. METALLURGICAL CORROSION and MATERIAL PROTECTION SPECIFICATIONS

Component Category	Material and Environmental Condition	Protective System and Design Life
Heliostat Structures (Saline Air)	Structural Steel (IS 2062)	Hot-dip galvanizing (ISO 1461) + Polyurethane topcoat
Reflective Mirrors (Sand Scour)	Low-iron glass (ISO 9050)	Dual-layer anti-soiling hydrophobic/oleophobic film
Receiver Tube and Piping (600°C Salt)	Alloy 625 / SS347H	High-emissivity black pyro mark coating
Water and Drainage Piping	High-Density Polyethylene	Internal epoxy lining + sacrificial zinc anodes
Molten Salt Tanks (Thermal Cycling)	SS347H (Dual wall)	High-density calcium silicate block insulation

1) Heliostat Structural Frame and Tracking Mechanisms

The torque tubes, structural trusses and pedestals are vulnerable to pitting corrosion.

- Structural components must be made from high-strength low-alloy steel. They must undergo hot-dip galvanizing to ensure a zinc coating thickness of 85 µm [10].
- A multi-coat duplex painting system must be applied over the surface. This achieves a "Very High" durability classification (>25 years to first major maintenance) [10].
- The system must feature a zinc- epoxy primer, an epoxy micaceous iron oxide barrier intermediate coat and an aliphatic fluoropolymer or polysiloxane topcoat [10].
- The axis azimuth-elevation tracking slewing drives must be housed in IP66/IP67 rated cast ductile iron enclosures. These are coated with a three-layer marine paint system [10].
- Internal gearing must use fluorinated lubricants. These operate continuously up to 70°C ambient-induced temperatures [10].

2) Mirror Silver Layer and Edge Protection

Heliostat mirrors have a reflective silver layer on the rear surface. Moisture and salt ingress at the mirror perimeter can initiate corrosion of the silver film [11].

- The silver layer must be protected by a copper passivation layer. This is followed by a minimum of three coats: a lead-free polyurethane base coat, a chemically resistant epoxy intermediate coat and an acrylic UV-blocking topcoat [11].
- The perimeter of each mirror facet must be fully encased, with a automated application of a neutral-cure structural silicone or polyurethane edge sealant [11].
- The sealant must withstand a minimum of 3,000 hours without showing edge delamination in ASTM B117 salt spray testing [12].

- The front glass surface must be treated with a fused silica-based anti-reflective coating. This maximizes transmittance and combines with a permanent hydrophilic photocatalytic anti-soiling outer layer. This prevents cementation of saline dust and minimizes cleaning water demands [13].

IV. WATER CONSERVATION PERFORMANCE: ACC AND ZLD ARCHITECTURE

Operating a 500 MW utility-scale thermal facility within an arid environment necessitates highly optimized, closed-loop water management architectures.

1) Air-Cooled Condenser (ACC) System Integration

To satisfy local environmental constraints, the power block substitutes conventional wet-cooling towers with a high-capacity Air-Cooled Condenser (ACC) system [14].

- The Khavda deployment zone experiences extreme summer ambient temperatures peaking between 45°C and 48°C. The ACC array is thermally engineered to maintain functional condensation metrics across extreme ambient-to-steam temperature differentials. [14].

- The condenser configuration utilizes high-frequency welded finned tubes to optimize heat rejection performance during high-ambient periods [14].

- Elevated dry-bulb temperatures induce an increased turbine backpressure penalty, resulting in a 4% to 6% thermodynamic efficiency reduction relative to evaporative wet-cooling configurations. This thermodynamic efficiency penalty is strategically mitigated by the plant's operational dispatch profile [14].

- This thermodynamic efficiency penalty is mitigated by the plant's dispatch profile. Because power generation is heavily weighted during nocturnal hours (19:00 to 07:00), the lower ambient temperatures maximize ACC performance. [14], [15].

2) Zero Liquid Discharge (ZLD) Architecture

Zero Liquid Discharge (ZLD) Architecture: To comply with environmental mandates established by the Central Pollution Control Board (CPCB), the facility incorporates a strict zero-discharge loop [16].

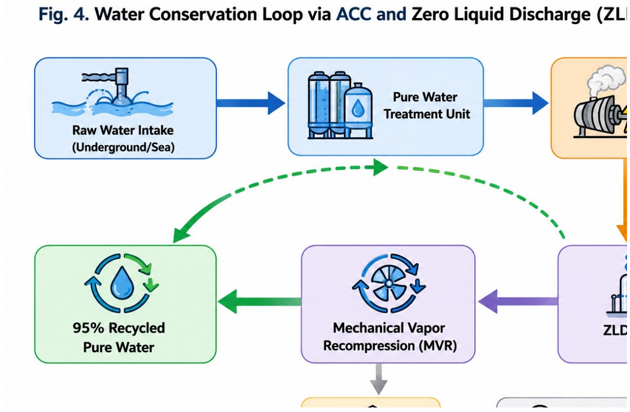

Fig. 3. Water Conservation Loop

- Raw water abstracted from saline aquifers undergoes multi-stage chemical purification to meet ultra-pure boiler feed standards. [16].

- Concentrated residual waste is processed via mechanical crystallizers into stable solid salt cakes for secure onsite disposal [16].

- A closed-loop recovery mechanism recycles mirror-cleaning effluent to minimize raw water abstraction [13], [16].

- Consequently, specific lifecycle water consumption is restricted below 0.05 m^3/MW/hr [14], [16].

V. FINANCIAL MODELING AND TECHNO-ECONOMIC EVALUATION

The technical design metrics established in Section II are converted into a comprehensive lifecycle financial matrix

A. CAPEX Allocation Model

The total overnight capital cost for the 500 MW modular tower CSP plant is approximately ₹22,825 Cr. The financial structure utilizes the international IRENA benchmark of \$5,500/kW established for utility-scale solar thermal configurations featuring deep storage (>10 hours) configurations. [14]. Capital expenditure conversions are calculated using a baseline currency exchange index of ₹83.00 per USD [14].

TABLE I DETAILED WBS CAPEX BREAKDOWN

WBS Code	Component Category	Cost (₹ Cr.)	% Share
1.0	Solar Field and Heliostat Array	9,130.00	40%
2.0	Thermal Energy Storage Loop	5,706.25	25%
3.0	Power Block and ACC	3,423.75	15%
4.0	Civil Works and Infrastructure	2,282.50	10%
5.0	Soft Costs and Financing Charges	2,282.50	10%
Total	**Project CAPEX**	**22,825.00**	**100%**

B. LCOE Analytical Formulation

The long-term economic viability of the asset lifecycle is quantified through a standardized levelized generation cost model. The asset lifecycle viability is quantified using the Levelized Cost of Electricity (LCOE) formulation [14]:

$$LCOE = \frac{\frac{\sum_{\{t=0\}}^{N} I_t + M_t - V_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}}$$

Where I_t represents the initial and lifecycle capital expenditures in year t, M_t is the operational and maintenance expenditure, V_t accounts for Viability Gap Funding (VGF) allocations, E_t is the net annualized energy yield, r is the Weighted Average Cost of Capital (WACC = 9.2%), and N represents the 30-year lifecycle.

C. Revenue Architecture and Tariff Capture

While the baseline unsubsidized financial model yields an LCOE of ₹7.10/kWh, the integration of strategic regulatory frameworks alters project economics [14]. Adding a 30% funding support under VGF reduces the electricity cost by ₹1.15/kWh [16]. Concessional debt financing secured via Sovereign Green Bonds provides an additional generation cost reduction of ₹0.70/kWh [16].

Also, the Ministry of Powers waiver on transmission charges cuts down the wheel costs by ₹0.35/kWh. This results in an electricity cost of ₹4.90/kWh [16].

VI. COMPARATIVE PERFORMANCE ANALYSIS: CSP VS. SOLAR PV IN KUTCH

A. Operational Capacities and Generation Windows

While conventional solar PV tracking configurations provide efficient bulk energy harvesting during diurnal hours, their generation profile drops to zero during nocturnal windows, yielding a regional Capacity Utilization Factor (CUF) of only 21% to 23% [14], [15].

Conversely, the proposed modular tower CSP configuration decouples generation from real-time solar resource volatility through its integrated 12-hour thermal storage system, sustaining an elevated, baseload-equivalent CUF of 62% [14], [15]. This represents a significant operational advantage. It means they can make a lot of energy that is always available. The **CSP power block** can generate approximately 2,715.6 GWh of energy annually [15].

$$E_{annual} = P_{cap} \times CUF \times 8760 = 500\ MW \times 0.62 \times 8760\ h = 2{,}715{,}600\ MWh\ \{2\}$$

B. Grid Interaction and Evening Peak Demand Mitigation

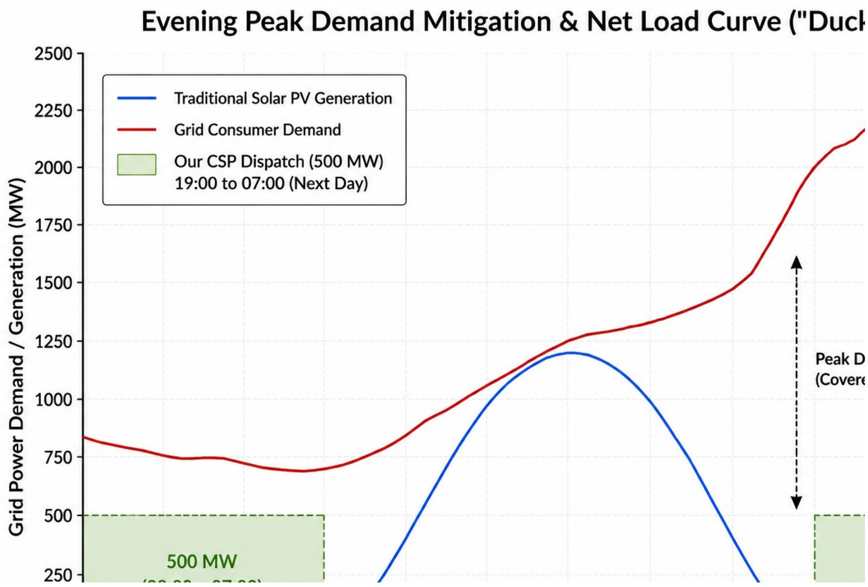

Fig. 4. The Evening Peak Demand Mitigation and Net Load Curve ("Duck Curve Plot")

Solar PV arrays make the Western Regional Load Dispatch Centre grid unstable. This happens when solar power decreases rapidly between 17:00 and 19:00 [15]. At the time Indias power demand increases sharply. A 12-hour storage system helps. It stores energy during the day when sunlight's strong. Then it supplies electricity at capacity in the evening when power rates are high from 19:00 to 23:00 hrs. [15]. This setup replaces coal-fired power. It earns tariffs under the SECI Round-The-Clock plan up to ₹10.00/kWh of electricity [15].

TABLE III. HEAD-TO-HEAD FEASIBILITY COMPARISON: MODULAR CSP VS. TRADITIONAL SOLAR PV IN KHAVDA

Operational Metric	500 MW Central Receiver CSP Asset	Traditional Utility-Scale Solar PV
Annualized Capacity Factor (CUF)	62% with Baseload Delivery Profile	21%–23% with Intermittent Generation
Annual Electricity Yield	2,715.6 GWh	Lower 24-Hour Energy Yield
Thermal Storage Capability	Integrated 12-Hour Molten Salt Storage	No Integrated Storage; Requires Batteries
Peak Demand Support (19:00–23:00)	Fully Dispatchable at 500 MW Output	0 MW After Sunset
Grid Stability Contribution	High Mechanical Inertia from Turbine Rotors	Zero Inertia; Inverter-Based Injection
Lifecycle Design Horizon	30–40 Years	20–25 Years with Gradual Degradation

VII. ENVIRONMENTAL, GRID STABILITY, AND RESOURCE CONSERVATION ASSESSMENT

A. Mechanical Inertia and Grid Stabilization

Unlike static inverter-based solar PV systems, the proposed CSP configuration integrates five synchronous steam turbine generators [15]. These high-mass rotating turbine assemblies contribute significant mechanical inertia to the regional electrical grid, providing vital frequency stabilization and synthetic frequency response to counteract the volatility of non-synchronous solar and wind injection arrays farms around the Khavda hybrid park can be unstable. The heavy parts in the turbines help reduce the changes in frequency that these farms can cause. The 500 MW CSP configuration is good because it uses these heavy turbine rotors. The 500 MW CSP configuration helps keep the power grid stable [15].

B. Dry-Cooling ACC Integration

This plant uses an A-frame dry ACC system to save water [14], [15]. The ACC is designed to work with a temperature difference of 18 K-22 K. It uses oval-shaped tubes with aluminum fins. The plant's efficiency drops by 4%-6% during the day because of the hot summer temperatures. This is not a big problem because the plant stores energy for 12 hrs. and generates power at night when its cooler [14], [16].

The cooler nighttime temperatures help to optimize the turbine vacuum pressure. This helps to restrict the plant's water usage to **less** than 0.05 m³/MWh [14], [15]. The ACC and ZLD system works together to help the plant save water. The plants' water usage is very low because of these systems. Operating a power plant in an arid zone needs careful water management.

TABLE IV: DETAILED FINANCIAL ENGINEERING and ROI LIFECYCLE MATRIX

Financial Parameter / Metric	**Baseline (No Support)**	**Optimized (With VGF)**
CAPEX BREAKDOWN		
Total Initial CAPEX	₹22,825 Cr.	₹22,825 Cr
Heliostat and Receiver Field (45%)	₹10,271.25 Cr	₹10,271.25 Cr.
Storage and Power Block (35%)	₹7,988.75 Cr.	₹7,988.75 Cr.
Civil Works and BOP (20%)	₹4,565.00 Cr.	₹4,565.00 Cr.
Government VGF Grant (30%)	**₹ 0.00**	**₹6,847.50 Cr (30% Grant)**
Net Developer CAPEX	**₹22,825.00 Cr.**	**₹15,977.50 Cr.**
Financing Framework (70:30)		
Project Debt Outlay (70%)	₹15,977.50 Cr.	₹11,184.25 Cr.
Required Equity Infusion (30%)	₹6,847.50 Cr.	₹4,793.25 Cr.
Cost of Debt (Annual)	10.5%	8.2%
Weighted Cost of Capital (WACC)	11.40%	**9.20%**
Mean Debt Coverage Ratio (DSCR)	1.12x	**1.65x)**
Annual Operations		
Net Energy Yield (GWh)	2,715.60	2,715.60
Contracted PPA Tariff (₹/kWh)	**₹7.10**	**₹4.90**
Gross Annual Revenue (₹ Cr.)	₹1,928.07	₹1,330.64
Based Annual O&M Cost (₹ Cr.)	₹456.50 Cr.	₹456.50 Cr.
Corporate Income Tax Relief	Standard	10-Year Holiday
Lifecycle ROI Targets (30 Years)		
Levelized Cost (LCOE)	**₹7.10 / kWh**	**₹4.90 / kWh**
Project IRR (%)	**6.18%**	**14.76%**
Equity IRR (%)	**4.35%**	**18.22%**
Net Present Value (₹ Cr.)	- ₹3,412.80 Cr. (Loss)	**+ ₹4,105.45 Cr. (Profit)**
Simple Payback Period	14.2 Years	**7.1 Years**
Discounted Payback Period	Infeasible	**10.4 Years**
Plant Operational Asset Lifecycle	30 Years	30 Years

VIII.CONCLUSION AND FUTURE SCOPE

This paper evaluated the techno-economic performance of a 500 MW Concentrating Solar Power facility sited across the geotechnically challenging and highly corrosive terrain of the Khavda salt flats in Kutch, Gujarat.

- A structural analysis was done to check the design. The shallow water table and Seismic Zone V make it hard. A special piled raft configuration can solve these problems [6].
- The configuration uses 45-to-50-meter concrete piles. These piles are made with sulphate-resistant concrete. An impressed current cathodic protection framework is also used [6].
- The molten salt thermal energy storage loop is isolated. It is placed in semi-underground concrete vaults. These vaults are watertight. This setup reduces risks from water and heat. The evaluation covered operational and economic aspects [7], [8].

The 500 MW Concentrating Solar Power facility represents a highly viable utility-scale framework that leverages molten salt thermal energy storage. The big problem of corrosivity that the 40,000 dual-axis tracking heliostats face is completely solved [9]. This is done by using strength low-alloy steel and protecting it with a special coating. The steel is protected with a process called hot-dip galvanizing that's 85 µm thick [10]. It also has a painting system that is made up of several layers. These layers include zinc- epoxy and micaceous iron oxide and a top layer made of aliphatic fluoropolymer [10].The dual-axis tracking heliostats and the whole system are designed with the environment in mind. The system uses dry-cooling ACC [14] and a Mechanical Vapor Recompression (MVR) driven ZLD water recycling system [16], optimizing process water conservation.

This system helps to save water. The amount of freshwater used in the lifecycle of the dual-axis tracking heliostats and the system is very low. It is less than 0.05 m^3/MWh of freshwater per unit of electricity produced [14], [16].

The configuration successfully mitigates the intermittency challenges inherent to utility-scale PV solar profiles. The configuration utilizes a 12-hour thermal energy storage loop, enabling deferred power dispatch during peak evening and nocturnal hours (19:00 to 07:00) [15]. This operational profile exploits diurnal temperature variations to optimize daytime thermal capture while bypassing daytime ambient thermal degradation. Unlike traditional solar PV arrays that suffer from ambient temperature-induced efficiency degradation, the proposed facility maintains robust thermodynamic conversion efficiency, yielding an annualized energy output of 2,715.6 GWh (approximately 2.715 billion units) [14], [15]. It also helps keep the power grid stable. This is important for the Western Regional Load Despatch Centre. These high-inertia steam turbine-generator units provide essential mechanical synchronicity to stabilize the regional grid network [15].

The cost of setting up a project is very high at ₹22,825 Cr. [14]. This is because it needs a lot of money to start. The government can help by giving some money to make the project work. If the government gives 30% of the money needed and the project gets an interest loan and does not have to pay some fees then the cost of electricity will be lower [16]. The cost will go down from ₹7.10/kWh to ₹4.90/kWh [14], [16]. This optimized tariff structure enhances the commercial viability and market competitiveness of utility-scale CSP procurement. The CSP project with storage is very important for India. This is because India wants to use renewable energy and the CSP project can help [15]. In the future we will do research on how the wind affects the CSP project, in the Khavda basin [6]. We will also study how the mirrors used in the project get damaged over time when they are exposed to sand and water [11], [12], [13].

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