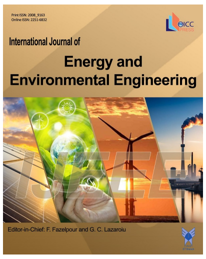

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Integrating Solar Energy and Pumped Hydro Storage for Sustainable Power Supply: A Case Study of the West Bengal Power Sector

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Original Research

Abstract:

This paper undertakes a real-world performance evaluation of the Purulia Pumped Storage Plant (PPSP) situated in West Bengal and its integration with solar photovoltaic (PV) power plant to assess the techno-commercial feasibility of the hybrid system towards mitigation of intermittency nature of solar energy which is a necessity for India's energy transition and ambitious renewable energy goals, using high-resolution real operational SCADA data instead of simulation-based approaches. Pumped Hydroelectric Plants (PHPs) are primarily utilised during peak demand periods and in instances of major power plant outages. India's very first pumped storage plant was commissioned in 1985. Presently, out of the 4.75 GW of pumped storage plants installed across the country, 3.3 GW are operational in pumping mode. However, these plants have fallen short of their projected energy generation figures due to insufficient availability of off-peak power for pumping operations, until the advent of various renewable energy sources, notably solar energy, in India. Against this backdrop, this analysis delves into the economic viability of the Purulia Pumped Storage Plant considering real solar generation profiles distributed across the West Bengal state and PPSP operational data of six representative days viz., 6th Feb., 26th April., 8th June., 24th Aug., 4th Oct., and 30th Dec. across different seasons of the year 2023 to assess critical performance indicators such as Daily Efficiency (DE), Cumulative Pumped Ratio (CPR) and Levelized Cost of Storage (LCOS) for both actual grid power operational scenario and hypothetical solar power generation driven pumping scenario matching with the actual PPSP operation. The study findings reveal that the hypothetical solar-PPSP hybrid system doesn't just slightly improve economics, it fundamentally enhances the value proposition by drastically reducing reliance on the grid electricity, achieving up to a 100% displacement on four days except 6th Feb. and 30th Dec. This substitution of high-cost grid power of up to 6.01 INR/kWh with low-cost solar energy with LCOE of 2.55 INR/kWh directly caused a dramatic surge in the CPR by 15% to 136% and halved the LCOS range to 0.31-1.05 INR/kWh, fundamentally transforming the plant's economic viability. CPR on the six representative days have increased from 159.50, 98.36, 102.20, 40.23, 137.37 and 152.18 in actual operational scenario to 182.92, 178.98, 225.64, 94.82, 294.13 and 230.83 respectively in the hypothetical scenario. On the other hand, LCOS has decreased from the range of 0.38 - 2.32 INR/kWh in case of actual operational scenario to the range of 0.31 - 1.05 INR in the hypothetical scenario. This work may therefore contribute as a data-driven evidence base on the techno-economic advantages of solar-powered pumping for PHP with varying seasonal demand and solar generation patterns, marking a significant departure from model-driven studies and would be useful for policymakers in reinforcing the role of hybridization of the existing and the upcoming PHPs in achieving India's ambitious renewable energy goal.

Keywords: Solar photovoltaic energy; Pumped hydro plant; Solar PV-pumped hydro hybrid system; Techno-commercial analysis; CPR; Purulia pumped storage plant (PPSP); Daily load curve; Peak power management; Energy storage; LCOS; LCOE; India's energy transition; West Bengal

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1. Introduction

The global energy landscape is undergoing a paradigm shift towards sustainable and renewable sources, driven by concerns over climate change and the depletion of fossil fuel resources. Among the available renewable energy sources, solar energy has gained significant traction due to its abundant availability and decreasing costs of technology. In this context, India has emerged as a key player in promoting renewable energy adoption with the ambitious national renewable energy roadmap led by the Ministry of New and Renewable Energy of deploying 500 GW of solar power by 2030 to enhance the share of renewables in the energy mix as a part of its broader commitment to sustainability and carbon neutrality [1].

The state of West Bengal, located in eastern India, presents a unique scenario in the realm of power generation and distribution. With the escalation in demand for electricity in the state, the imperative to diversify its energy sources and reduce reliance on conventional fossil fuels, West Bengal has embarked on a journey to harness solar energy potential in alignment [2] with the national energy goal and has set ambitious goals for solar plant installations to augment its power generation capacity [2].

However, the intermittent nature of solar energy poses challenges in ensuring a consistent and reliable power supply [3, 4, 5, 6, 7]. To address this issue, energy storage solutions have garnered attention as essential components of the renewable energy transition [8, 9, 10]. Pumped hydro Storage stands out as one of the most mature and proven technology for large-scale energy storage [11, 12, 13, 14, 15], offering both flexibility and efficiency in balancing supply and demand dynamics.

India faces significant energy storage challenges in fulfilling the solar PV renewable energy target by 2030, given the intermittent nature of solar power. Pumped Hydro Storage is the most established large-scale storage technology, constituting over 96% of global installed energy storage capacity [16]. In India, PHS represents nearly all of the utility-scale storage capacity, with 4.75 GW operational and another 7.97 GW under construction as of February 2025 [17]. However, this is only a fraction of India's estimated PHS potential of 96.5 GW [18]. In spite of the fact that PHS constitutes almost 100% of India's total grid storage capacity as deployment of battery energy storage systems (BESS) is in the early stage and being done through tenders and pilot projects, the growth of PHS is still slow due to high capital costs, long gestation periods, and inadequate pricing mechanisms that fail to incentivize private investment or recognize the full value of storage services such as peak shaving, RE smoothing, and ancillary support.

The introduction of PHS as storage solution enables round-the-clock dispatchable renewable power, reduces curtailment, and helps DISCOMs meet Renewable Purchase Obligations (RPOs). Projects like the 1,200 MW Pinnapuram Integrated Renewable Energy Project in Andhra Pradesh, India, which combines 2,000 MW solar, 400 MW wind, and 1,000 MW PHS demonstrate the potential of such hybrids to enhance grid stability and reduce dependence on costly thermal power [18]. With supportive pricing mechanisms, financial models like viability gap funding (VGF) solar-PHS projects can play a pivotal role in India's clean energy transition.

In this context, the need for Pumped Hydro Storage as an energy storage option in West Bengal's power sector becomes evident. By utilizing the existing infrastructure of the Purulia Pumped Storage Plant 900 MW (4x225MW), the state can leverage pumped hydro technology to store excess solar energy generated during off-peak hours and release it during peak demand periods [19, 20, 21]. This not only enhances grid stability but also optimizes the utilization of renewable energy resources, facilitating a smoother integration of solar power into the existing energy grid [22, 23, 24].

While prior literatures have extensively modeled the techno-economic feasibility of integrating solar and wind power with Pumped Hydro Storage (PHS), those studies were predominantly based on simulated or theoretical annualized data with simplified operational assumptions, often overlooking the critical constraints and stochasticity of real-world plant operations of both solar PV and PSP plant. Furthermore, a comprehensive analysis within the unique and evolving renewable energy integration challenges of West Bengal's power sector, remains a significant research gap, which this study aims to address.

This work aims to explore the West Bengal power sector scenario, focusing on the integration of solar renewable energy generation and Pumped Hydro Storage as a sustainable storage solution for meeting the state's growing energy demands by increasing renewable energy share in the energy mix with the following objectives:

1. To mitigate solar intermittency by integrating Pumped Hydro Storage, supporting India's NDC target of 500 GW non-fossil capacity by 2030, aiming to enhance grid reliability and reduce dependence on conventional fossil fuel-based peaking power plants.

2. To analyze the techno-commercial viability using LCOS and CPR parameter, demonstrating the cost reduction of using solar LCOE for pumping aligning with SDG 7 by advancing affordable, clean energy through innovative storage solutions.

3. To assess the role of the Purulia PHP in daily load curve management by storing off-peak solar energy for dispatch during peak demand in driving the transition towards a more resilient and sustainable energy future for West Bengal.

4. To provide policymakers with insights on scaling Solar-PHES hybrid system, contributing to India's energy transition and socio-economic goals.

Major highlight of this study may be described as this integration analysis of solar PV plant with the Pumped Hydro Storage plant to investigate whether intermittency nature of solar power can be mitigated by pumping water

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Authors	Data Used	Methodology Employed	Key Findings
Caralis et al. (2012) [25]	- Simulated hourly wind and Solar PV data - PHS plant configuration Data	A proprietary hourly simulation model of the Greek power system with Four Wind-PV capacity scenarios (1000-100, 3000-500, 5000-1000, 8000-2000 MW). The feasibility of 1000 MW of PHS was then analyzed for the latter three scenarios.	- PHS is necessary for large-scale RES integration - Using conventional power for complementary pumping to increase plant utilization can make PHS financially viable, as the required tariff then aligns with peak electricity prices.
Sullivan et al. (2008) [26]	- Simulated generation profiles for five wind classes (3-7) across 358 U.S. regions, including unique diurnal and seasonal patterns. - Techno-economic parameters (capital cost, O&M, efficiency, heat rate) for PHS, CAES, and batteries from literature and industry reports (EPRI/DOE Handbook, Holst 2005).	- The Regional Energy Deployment System (ReEDS) model, a high-resolution linear programming model minimizing system-wide costs.- Two pairs of scenarios were simulated from 2006 to 2050: 1) Business-as-usual (with-/without storage), 2) 20% Wind by 2030 (with/without storage).	- Storage enables higher wind penetration (+50 GW by 2050 in BAU case) by increasing its economic competitiveness and capacity value. - The value of storage increases with higher wind penetration, but significant investment only becomes viable after substantial wind capacity (~200 GW, 15% of energy) is on the grid. - In a 20% wind scenario, storage reduces overall electricity system costs, lowering electricity prices by over $2/MWh by 2050.
Zeng et al. (2013) [27]	- Installed capacity and growth rate statistics for wind and solar power in China from 2004-2011 - This paper is a policy review; it does not collect or use specific PHS pumping or generation data.	- Analysis of policy achievements and identification of limitations across legal, planning, administrative, pricing, and technical standard domains. - Development of a prospective framework for China's renewable energy policy system and provision of policy recommendations	- China established a comprehensive renewable energy policy system after the 2005 Renewable Energy Law, leading to massive growth in installed capacity (e.g., wind power from 0.76 GW in 2004 to 62.73 GW in 2011). - Key policy limitations identified include: inconsistent planning between national/local levels and with the grid, inadequate grid connection subsidies, lack of tailored technical standards, and ambiguous administrative regulations. - Recommendations included amending laws, clarifying planning, implementing a Renewable Portfolio Standard (RPS), improving pricing mechanisms, and establishing a policy supervision system.
Ma et al. (2014) [28]	- Real-world performance data from an existing 19.8 kWp PV system on the island. - Techno-economic specifications of PHS from manufacturer quotes (pumps, turbines) and engineering assumptions (efficiencies, head).	- Sizing models for battery storage and Pumped Hydro Storage (PHS) systems. - Comparison of 4 storage options: advanced battery, conventional battery, PHS + battery, and PHS only.- Sensitivity analysis on key parameters (energy demand, sun hours, discount rate, PV cost).	-PHS options are significantly more economical than battery-only options, with LCC as low as 29% of the advanced battery option. - Advanced deep-cycle batteries outperform conventional batteries in long-term LCC. - PHS becomes economically favorable for daily consumption > 25 kWh and autonomy days ≥ 3.
Jurasz et al. (2017) [29]	- Hourly solar irradiation data for Poland (2015) from the SoDa service. - Hourly energy demand and price data (2010-2015) from the Polish Balancing Market (PSE S.A.). - PHS Technical parameters (efficiencies, capacities) were based on literature values and assumptions.	- Developed a mixed-integer mathematical model to simulate and optimize the operation of a PV-PHS hybrid system. - Conducted sensitivity analysis on PHS generating capacity and PV nameplate capacity	- Increasing PV capacity (from 100 kW to 344 kW) increased revenue by 360%, demonstrating the model's scalability. - The economic viability of a PV-PHS system on the balancing market is promising, but a full techno-economic analysis including capital costs is needed for a definitive conclusion.

Authors	**Data Used**	**Methodology Employed**	**Key Findings**
Sivakumar et al. (2014) [30]	- Real-world historical operational data (1996-2013) for multiple Indian PHS plants, including annual energy generation, pumping consumption, and capital costs. Data was collected from plant authorities and official reports (e.g., CEA).- Mention of installed wind capacity (7000+ MW in Tamil Nadu) but no specific generation time series used.	- An economic analysis based on historical performance and financial data from existing Indian PHS plants. - A detailed techno-economic assessment of the Kadamparai PHS plant, calculating net benefit using a formula that incorporates generation revenue, pumping energy cost, and annual fixed charges.	- Case study of Kadamparai PHS showed it became economically beneficial post-2003, with its energy cost proving lower than that of gas or diesel peaking plants. - Despite high potential (96,500 MW identified), the development of PHS in India is hampered by underutilization of existing plants, often due to a lack of surplus off-peak power for pumping. - The study argues PHS is crucial for integrating renewables and meeting peak demand, but its economic feasibility depends on supportive regulatory mechanisms and sufficient off-peak power availability.
Jacob et al. (2021) [31]	- Hourly load profiles for Uttarakhand (2015-16), extrapolated to 2022. Hourly solar generation profiles based on a 900 MW target capacity. Precipitation data. - Technical specifications (head, capacity) and financial data (Initial Capital Cost breakdown) for the proposed 1000 MW Tehri Pumped Storage Plant.	- A techno-economic model using hourly data to simulate analyzing daily and seasonal peaking operation. - Calculation of the Levelized Cost of Storage (LCOS) incorporating capital cost, O&M, and a discount rate, assuming charging cost is zero (uses excess solar).	- The Levelized Cost of Storage (LCOS) for the proposed Tehri PHS plant, when charged solely by excess solar energy, is calculated to be between 6.7/kWh and 28.5/kWh, with a central estimate of 6.7/kWh. - The analysis showed that PHS can effectively shift excess solar generation from midday to meet evening peak demand, reducing curtailment. During high-solar seasons, the plant charges quickly, indicating potential for even more storage capacity.
Bamoshmoosh et al. (2025) [32]	- Real-world hourly irradiance, temperature, wind speed (PVGIS, ERA5).- Real plant parameters (capacity, head, basin volume, surface area) from Italian PHS plants (Bargi, Capriati, Taloro).	Mixed-Integer Linear Programming (MILP) optimization simulation model using real-world Historical DAM electricity prices (2019, scaled).	- FPV integration increases NPV up to 6x. - Reduces evaporation by 0.5–5.2 Mm^3/year. - PHS equivalent hours increase with FPV integration.
Agajie et al. (2023) [33]	The paper reviewed numerous other studies which used a mix of:- Simulated meteorological data. - Technical specifications of PHS. Predominantly simulation-based studies, with some case studies validated against real-world scenarios.	- Categorizing and analyzing existing research based on components, objective functions, and optimization methods. - Evaluating Energy Storage Systems (ESS) integration, with a focus on techno-economic criteria.	- Hybrid Renewable Energy Systems (HRES) are crucial for reliable, cost-effective, and clean energy, especially for remote/off-grid areas. - Pumped Hydro Storage (PHS) is highlighted as a superior large-scale ESS option due to its long lifespan, high efficiency, low energy cost, and rapid response capabilities compared to batteries and other storage technologies
Amoussou et al. (2023) [34]	- Using real-world meteorological Solar & Wind and load data. - PHS Technical specifications and cost data from literature;	- Developed a detailed numerical model in MATLAB to simulate the hourly energy balance, PHS pumping/generation, and system operation over one year.	The PV-Wind-PHS hybrid configuration was the most cost-effective.

Authors	Data Used	Methodology Employed	Key Findings
Agajie et al. (2023) [35]	- Simulated solar radiation and temperature data (NASA).- Simulated pumping and generation data. - Simulated hourly load profile (1668–1707 kW peak).	Opposition-based Whale Optimization Algorithm (OWOA) tuned Fractional Order Fuzzy PID (FO-Fuzzy-PID) controller for frequency and power regulation in a hybrid PV-Biogas system with SMES and PHES storage.	FO-Fuzzy-PID with OWOA reduced frequency deviation by 1.05%, 2.01%, and 2.73% compared to QOHSA, TLBOA, and PSO, respectively. The controller showed robustness under parameter variations and load disturbances
Amoussou et al. (2024) [36]	- Hourly solar radiation and temperature data for Bafoussam, Bamenda, Yaoundé, Douala, Limbe (from SoDa-Pro). - Simulated water consumption, pumping, and generation based on reservoir dynamics.	Multi-Objective Bonobo Optimizer (MOBO) and five other metaheuristics (MSSA, MOALO, MOPSO, SPEA2, MOAVOA) for optimal sizing and siting of PV/PHES/ultra-capacitor system to replace HFO/LFO plants.	MOBO achieved the lowest TAC (52.78×10 €) at LPSP=0%. Bafoussam was the optimal location for PV installation. System profitability required an energy selling price of 0.12 €/kWh. Ultra-capacitors provided fast response during PHES start-up.

into the upper reservoir using excess daytime energy for later use, dependency on grid power for pumping operations can be reduced, grid stability can be enhanced, feasible levelized cost of the storage can be achieved or not etc., has been conducted using real operational data of PPSP and solar PV plants without depending on any simulation model as real data based analysis will boost the confidence of the policymakers and implementers in future adoption of such system towards achieving the renewable energy goal. However, due to lack of data of evaporation and precipitation from and on the upper reservoir and the unutilised stored water quantity from prior pumping operations, this analysis faces limitation and may impact the calculated DE, ACPR and HCPR to some extent.

2. Case Study Presentation

2.1 Description of the PHP System

Pumped Hydro Plant operates as a dual-reservoir system comprising upper and lower reservoirs. Energy is stored in the upper reservoir in the form of water, which is subsequently pumped from the lower reservoir, located at a lower elevation. During periods of excess demand, power is generated using turbines by releasing water from the upper reservoir. Conversely, during low-demand periods, the upper reservoir is replenished by pumping water from the lower reservoir. This pumping process, known as charging, occurs during off-peak periods when electricity costs are lower. Pumped-hydro storage is the most economic option for storing large amount of electrical energy. The design of a pumped-hydro storage power plant is intricately linked to site-specific characteristics. Sites with ample water resources, favourable topography, and geology are deemed ideal for the development of pumped-hydro storage plant [31].

The Purulia Pumped Storage Plant 900MW (4 x 225MW) is located at Purulia district, West Bengal, India with Latitude 22.194° N and Longitude 86.096° E is a significant energy storage facility designed to enhance grid stability and meet peak power demands in the state. The plant features an upper reservoir with a maximum level of EL 518.39 m and a lower reservoir with a maximum level of EL 337.00 m, providing a substantial hydraulic head differential. The system operates with four Francis-type reversible pump-turbine units, each capable of generating up to 225 MW under a net head of 214.5 m in turbine mode and consuming 250 MW in pump mode, with a maximum turbine discharge capacity of 150 m^3/s and pumping discharge capacity of 142 m^3/s. The synchronous generator-motors, rated at 250 MVA (generator) and 255 MW (motor), operate at 16.5 kV and 250 rpm, ensuring efficient energy conversion. The plant includes four 280 MVA, 400/16.5 kV power transformers with forced oil and water cooling, facilitating high-capacity power transmission. With an upper reservoir discharge capacity of 77 m^3/s and lower reservoir discharge capacity 150 m^3/s, the facility ensures rapid response to load variations, making it a critical asset for renewable energy integration and grid balancing. The plant's design emphasizes operational flexibility, enabling seamless transitions between generation and pumping mode to optimize energy storage and dispatch. The Plant location and construction details of the plant have been shown in Figure 1, Table 1 and Table 2 below.

2.2 Description of the PV Plants

In order to derive the average solar generation potential of the whole state, five Solar PV Plants viz., Teesta Canal Top, Dhaka-I, Bhajanghat, Salboni and Sankrail PV plant distributed in various regions with variation in solar resources have been chosen. Among the above, Teesta Canal Top plant is situated in the northern region, Bhajanghat in the eastern region, Dhaka-I in the western region, Salboni and Sankrail PV plant are situated in the southern region of the West Bengal state. Geo-locations are shown in Figure 2 below.

The Solar PV plants at Teesta Canal Top, Dhaka-I, Bhajanghat, Salboni and Sankrail consists of poly-

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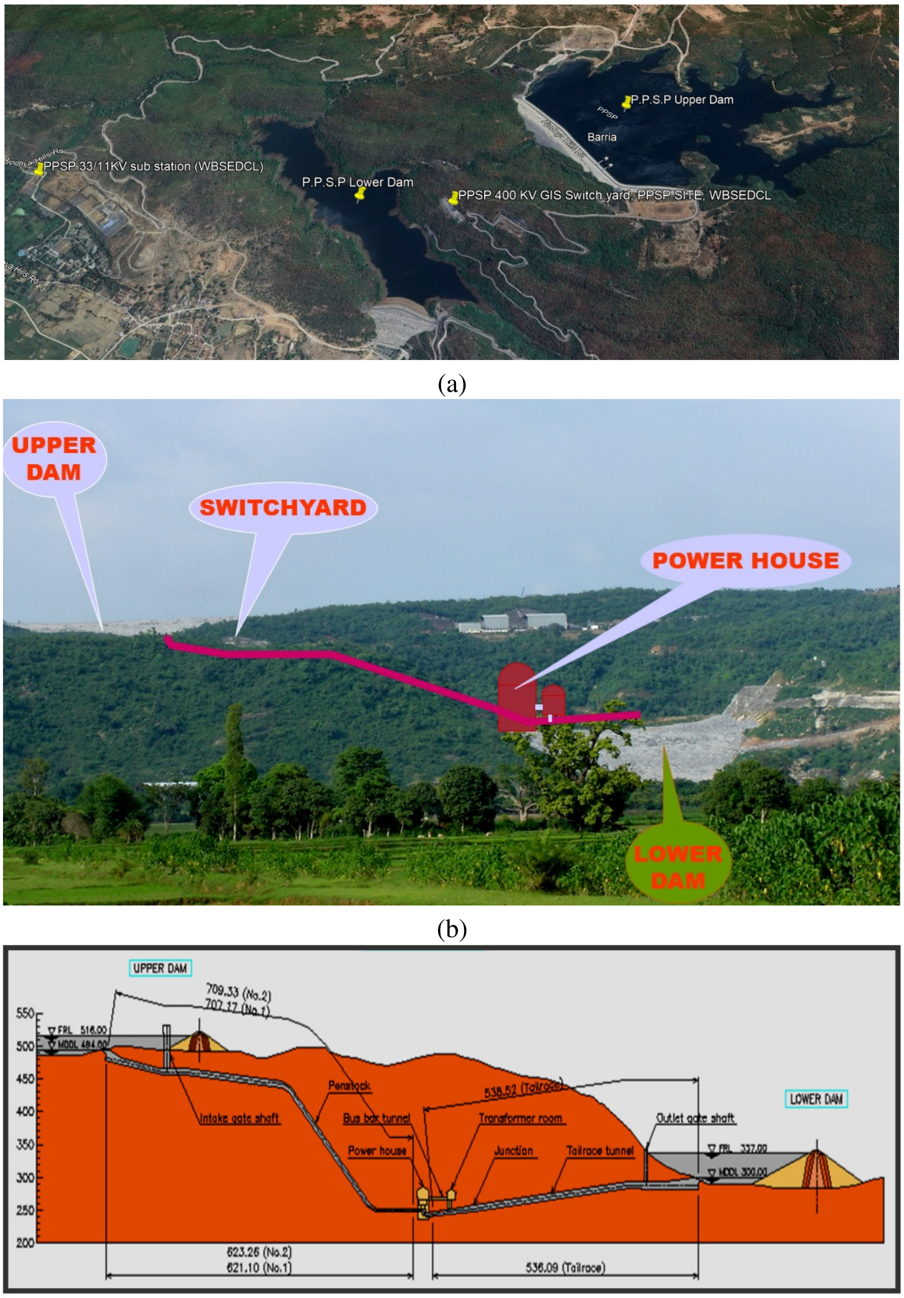

(a)

(b)

(c)

Figure 1. (a) Geo-location top view; (b) Real side view; and (c) Graphical view of the PPSP

Table 1. Reservoir elevation levels and Power Transformer specifications of PPSP

Upper Reservoir		**Lower Reservoir**	
Maximum Reservoir Level	EL 518.39 m	Maximum Reservoir Level	EL 337. 00 m
Full Reservoir Level	EL 516.00 m	Full Reservoir Level	EL 337.00 m
Minimum Drawdown Level	EL 494.00 m	Minimum Drawdown Level	EL 300.00 m
Discharge Capacity	77 cum/sec	Discharge Capacity	150 cum/sec
Power Transformer			
Type		3-Phase, Dy11, Oil immersed, Forced Oil Forced Water cooled with on-load tap changer	
Number of Unit		Four (4) sets	
Rated capacity		280 MVA	
Rated voltage		400/16.5 kV	

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Table 2. Pump Turbine and Generator/Motor specifications of PPSP

Pump Turbine		**Generator/Motor**	
Type	Francis, Vertical Shaft Reversible	Type	3-Phase, Vertical Shaft Synchronous Generator–Motor, Semi-umbrella
Number of Unit	Four (4) sets	Number of Unit	Four (4) sets
Net head	214.5/177.0/149.4 m	Rated capacity	Generator- 250 MVA
Total dynamic head	218.8 /159.0 m		Motor - 255 MW
Maximum turbine output at normal head	225 MW	Rated voltage	16.5 kV
Maximum pump input	250 MW	Rated current	Generator- 8748 A
Maximum turbine/pump discharge	150/142 m^3/s		Motor- 9546 A
Rated Revolving speed	250 rpm	Rated Revolving speed	250 rpm

crystalline modules with DC capacities ranging between 10.4–10.9 MW and uniform cumulative AC inverter capacities of 10 MW. The PV arrays cover areas from 61,727 m^2 to 64,370 m^2, with a consistent temperature coefficient of -0.43%/°C, and system losses varying from 21.56% to 25.1%. Tilt angle differs across sites between 5°–20°. The detailed overview of all the five plants is given below in Table 3.

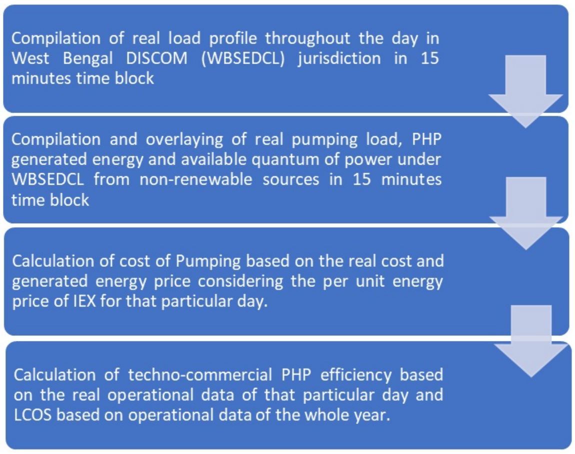
2.3 Methods of the Case Study

To evaluate the role of the PPSP in balancing the demand-supply scenario of the West Bengal State Electricity Distribution Company Limited (WBSEDCL), the real operational data of the Load Dispatch Center (LDC) of WBSEDCL, responsible for real-time grid management in terms of Power Availability (MW) from long-term power purchase agreements, Pumping Power (MW) required to store water in the upper reservoir from the lower reservoir, and Generated Power (MW) by releasing water from the upper reservoir to lower reservoir during high demand and the Actual Demand (MW) i.e., real-time electricity requirement that must be met have been collected from the SCADA system of the LDC. To conduct the study, six representative days in the year 2023 viz, 6th Feb., 26th April, 8th June., 24th Aug., 4th Oct., and 30th Dec. are chosen to capture seasonal variations in solar generation, electricity demand and grid conditions across West Bengal. These days encompass diverse scenarios like winter and summer peaks, monsoon cloud cover and transitional seasons, allowing a comprehensive evaluation of the Purulia Pumped Storage Plant's performance under real-world operational constraints.

The primary focus of the study is to examine how the pumping and generation of PPSP durations and quantities align with demand variation, ensuring grid stability and evaluate techno-commercial feasibility of a hypothetical scenario where the pumping of the PPSP will be done primarily using solar power and the balance required power from the grid. This approach ensures robust techno-economic analysis of solar-powered pumping, highlighting fluctuations in daily efficiency, cost savings, and grid dependency reduction, thereby providing validated insights for renewable integration policy and hybrid system scalability.

The analysis has been broadly divided into two scenarios, one is real operational scenario and the other is hypothetically simulated scenario based extrapolated real data as shown in the Figure 3 (a) and (b) schematic block diagrams respectively and furnished below.

a) In the first scenario, as shown in the Figure 3 (a) schematic block diagram, calculation of techno-commercial PHP efficiency and LCOS, as it has already been operated on the considered days for which this study is being conducted, have been calculated as furnished in the following flowchart.



Compilation of real load profile throughout the day in West Bengal DISCOM (WBSEDCL) jurisdiction in 15 minutes time block

Compilation and overlaying of real pumping load, PHP generated energy and available quantum of power under WBSEDCL from non-renewable sources in 15 minutes time block

Calculation of cost of Pumping based on the real cost and generated energy price considering the per unit energy price of IEX for that particular day.

Calculation of techno-commercial PHP efficiency based on the real operational data of that particular day and LCOS based on operational data of the whole year.

b) In the second scenario, as shown in the Figure 3 (b) schematic block diagram and Figure 4 schematic diagram, the peaking operation is analysed based on the load profile within the WBSEDCL jurisdiction of West Bengal state, in conjunction with solar generation profiles. Solar plants distributed in 5 different regions of the state as shown in Figure 3 are cumulatively considered for the analysis and generation data for the year 2023 has been considered by hypothetically introducing 1500 MW cumulative capacity of solar PV plant so that all the four pumps of the PPSP can be operated simultaneously. Pumping operation has been considered

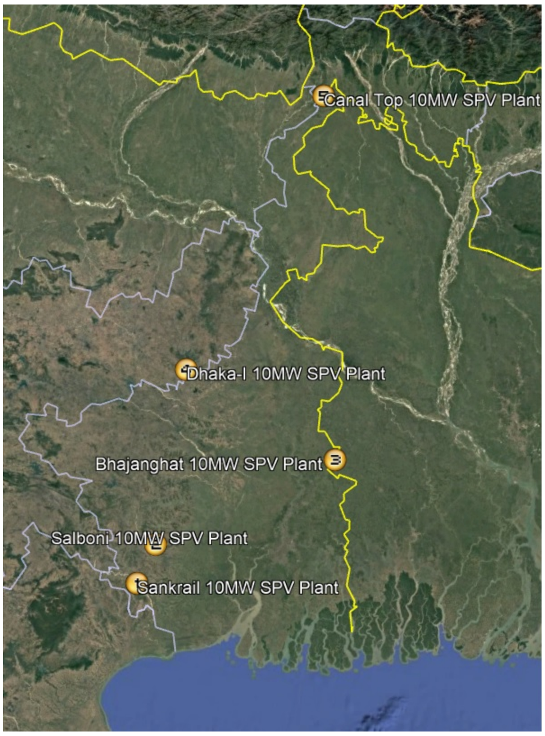


Figure 2. Geo-location of all the five Solar PV Plants

Table 3. Overview of the Solar PV Plants

Sl. No.	Location of the SPV Plant	Latitude and Longitude	DC Plant Capacity at STC	PV Array Area and Temp. Coefficient of Power	AC Inverter Capacity	Tilt Angle and Pitch
1	Teesta Canal Top, Uttar Dinajpur	26.482° N and 88.315° E	10.4 MW, Poly-crystalline Module	63089 m^2 and -0.43 %/°C	10 MW	5° and 10 m
2	Dhaka-I, Birbhum	24.02° N and 87.30° E	10.5 MW, Poly-crystalline Module	62100 m^2 and -0.43 %/°C	10 MW	16° and 7m
3	Bhajanghat, Nadia	23.38° N and 88.76° E	10.9 MW, Poly-crystalline Module	64370 m^2 and -0.43 %/°C	10 MW	20° and 7.5 m
4	Salboni, West Midnapore	22.35° N and 85.18° E	10.48 MW, Poly-crystalline Module	63275 m^2 and -0.43 %/°C	10 MW	18° and 7m
5	Sankrail, Jhargram	22.16° N and 87.06° E	10.5 MW, Poly-crystalline Module	61727 m^2 and -0.43 %/°C	10 MW	16° and 7m

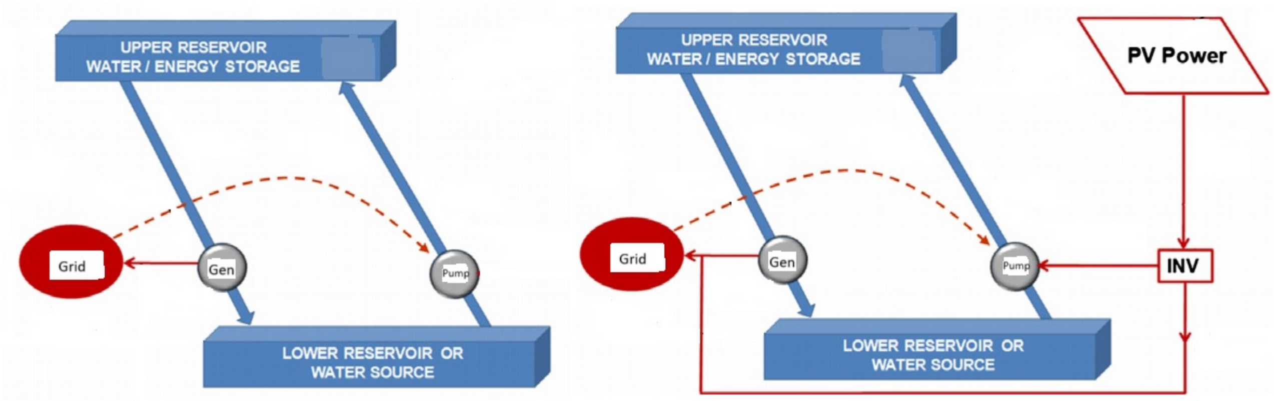
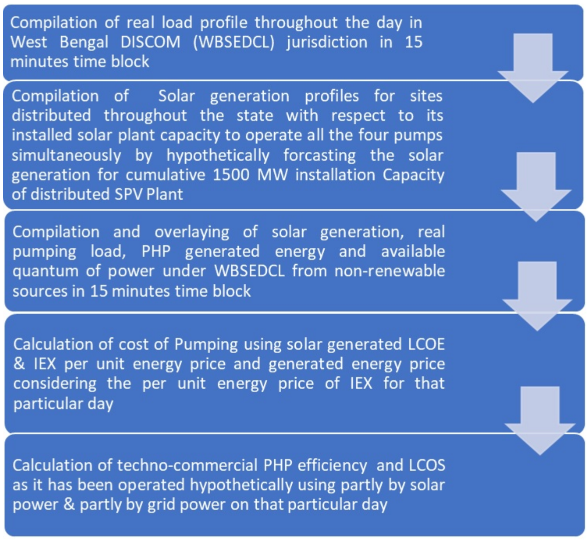


Figure 3. Schematic Block diagram of **(a)** the PHP power plant; **(b)** the PHP-Solar PV hybrid power plant

using excess solar generation during daylight hours only.



Based on the above, cost of pumping is calculated partially considering solar LCOE for the portion of water level pumped using solar power and partially considering the per unit energy price of IEX platform [37] of that particular day for the portion of water level pumped using grid power.

Both the above scenarios are evaluated using the quantitative parameters viz., PH, LCOE, LCOS, DE and CPR. Definition and calculation method of the parameters are furnished below.

2.3.1 Pumping Head (PH)

The pumps were operated during the actual operation of PPSP pumping and during the calculation of pumping head i.e., the water head level that could have been pumped using the hypothetically introduced solar plant capacity, as per the following pumping principle.

- One pump if synchronised for pumping must continue for at least two power blocks i.e., 30 minutes.
- Pumping can be done if the solar power is available in the multiple of 240MW as the pumps are of fixed speed type.
- If one pump operates for duration of 1hr it can raise 0.57m of water head level of the upper reservoir.
- Command to start any pump shall be given 12 minutes prior to the time of synchronisation for pumping operation.
- A gap of minimum 30 minutes shall be maintained between the starting of pumping operation of two pumps as shown in Figure 5 below.

a) In the actual operational scenario, in the Figure 3 (a) schematic block diagram, the pumping head is calculated by first summing the total pumping load in megawatts (MW) over all the 15-minute time blocks and then converted into the Pumping energy (MWH). The formula can be summarised as:

$$H_{\text{pumping}} = \text{Total Pumping Energy}(MWh)/(240MW \times PHF) \tag{1}$$

Where, PHF is pumping head factor =0.576 m/hour.

This method ensures the head is derived from the aggregate energy used for pumping, scaled appropriately for practical application.

b) In the hypothetical scenario, as shown in the Figure 3 (b) schematic block diagram and Figure 4 schematic diagram, the pumping head is calculated as per the flowchart shown in Figure 6 by first determining the operational duration of each pump that can be hypothetically operated using the available solar power from 1500MW solar plant capacity and the required balance power from the grid in line with the pumping criteria and to replicate the actually head pumped in the real operation scenario on that day, which is the difference between its stop time and start time. This duration, converted into hours, is then multiplied by PHF considering a linear relationship between pump runtime and the resulting head, based on the pumping flow rate and system characteristics to compute the individual pumping head in meters. The total pumping head is obtained by summing the contributions from all active pumps. This method assumes, the calculations are repeated for each pump, and the cumulative effect provides the overall pumping head for the given time period.

2.3.2 Daily Efficiency (DE)

It may be defined as the ratio of energy generated for meeting the daily load to the energy required for pumping the water from the lower reservoir to the upper reservoir for that particular day. PHP Daily Efficiency is computed by the formula [24] given as hereunder:

$$\eta_{daily} = \frac{E_g}{E_p} \tag{2}$$

Where; E_g= Energy generated for meeting the daily load, E_p = Pumping Energy for that particular day.

2.3.3 Actual Commercial Performance Ratio (ACPR)

It may be defined as the ratio of the generated energy price to the pumping energy cost using grid power as done in the actual operation for that particular day.

$$CPR_{act} = \frac{E_g x P_{IEX}}{E_p x Cagp} \tag{3}$$

2.3.4 Hypothetical Commercial Performance Ratio (HCPR)

It may be defined as the ratio of the generated energy price to the pumping energy cost using both grid power

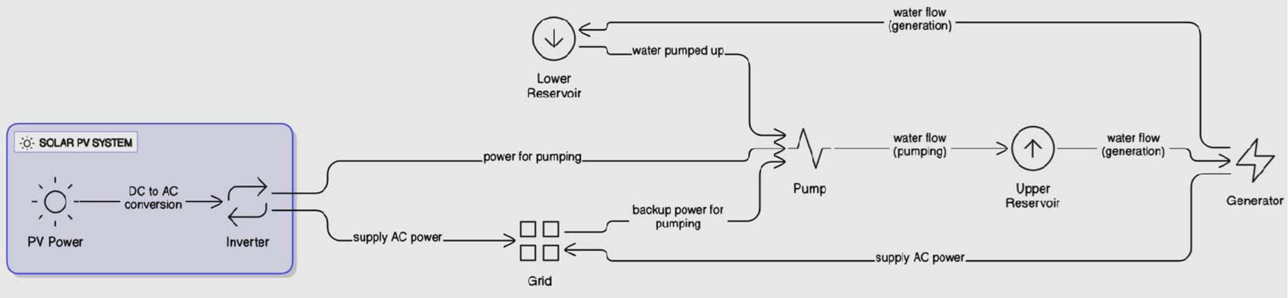


Figure 4. Schematic diagram of the PHP-Solar PV hybrid power plant

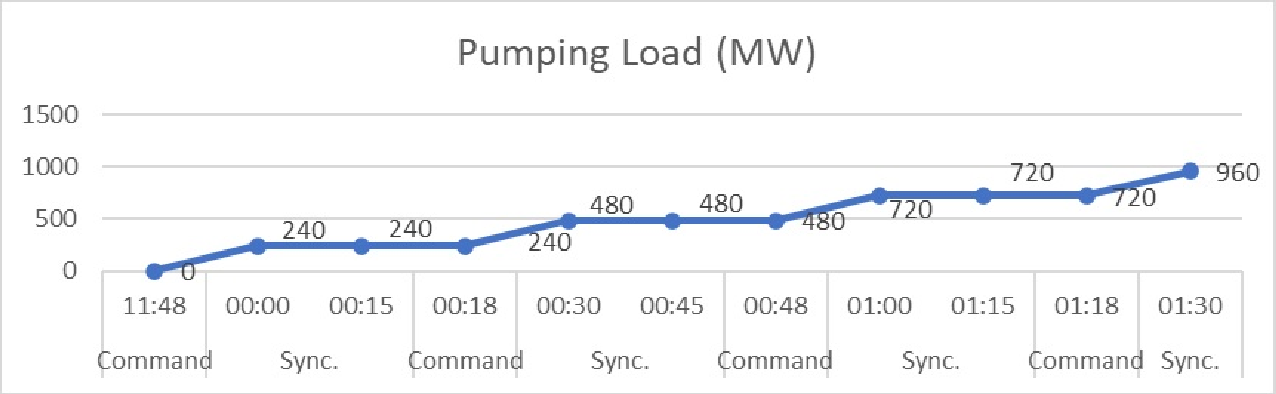


Figure 5. Pumping operation principle of PPSP

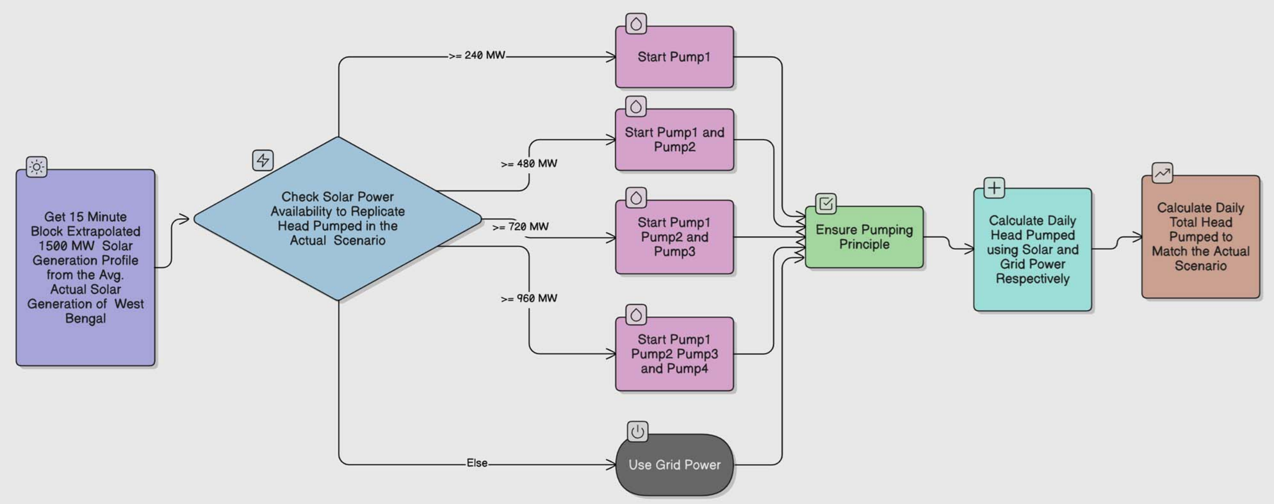


Figure 6. Flow Chart of the PHP-Solar PV hybrid power plant pumping head calculation methodology

and solar power as done in the actual operation for that particular day.

$$CPR_{hyp} = \frac{E_g x P_{IEX}}{E_{pq} x C_{agp} + E_{ps} x LCOE} \tag{4}$$

Where; E_g = Generated Energy, P_{IEX} = Block Price per unit as per IEX for that particular day, E_{pg} = Pumping Energy from grid, C_{agp} = Actual per unit pumping grid power average cost for that particular day, E_{ps} = Pumping Energy from solar power plant, LCOE = Average Solar energy cost per unit for the West Bengal state.

The study of the actual scenario of the PPSP operation and the hypothetical integration scenario with solar PV provides valuable real-world insights into the techno-economic feasibility of a solar-PHP hybrid system. However, it's based on several data limitations that may affect the completeness of the analysis to some extent and has an impact on key performance indicators viz., DE and Cumulative Pumped Ratio CPR. The limitations can be described as (a) Lack of evaporation and precipitation data which can result in overestimation of usable water volume, (b) Unaccounted residual water from previous pumping days which can lead to less pumping and higher generation on the days studied here, (c) Consideration of 0.576 m/hr linear pumping head factor for the ease of calculation, assuming pumping of water from minimum level to the maximum level of the upper reservoir in spite of the conical shape of the upper reservoir and thus it's inverse relation with the pumping duration having a value range of 0.45 - 0.576 m/hr and (d) Limited temporal scope of only 6 days which will lead to missing record of extreme weather events. Impact of these limitations on DE and CPR are furnished in the Table 4 below.

2.3.5 Levelized Cost of Storage (LCOS)

It denotes the total cost of storage with respect to cumulative electricity generation discounted over its lifetime. LCOS involves initial investment cost, pumping cost, generation cost, and operation and maintenance cost. In specific, this comprises initial capital cost (ICC), charging and discharging costs, operation and maintenance (O& M) costs, and effects of PHES technology's degradation over time, i.e. decreased output [31].

LCOS is computed by the formula [38] given below:

$$LCOS = \frac{ICC + \sum_n^N \frac{O\&M}{(1+r)^n} + \sum_n^N \frac{ChargingCost}{(1+r)^n} - \frac{end-of-lifecost}{(1+r)^{N+1}}}{\sum_n^N \frac{Elec_{discharged}(1-d)^n}{(1+r)^n}} \tag{5}$$

Where; ICC = Initial capital cost, $O\&M$ = Operation and maintenance cost, r = Discount rate (%), N: Project life (years), d = Degradation rate (%).

The calculation of LCOS is done based on some assumptions which are, real-world pumping and generation data from 2023 is representative of typical annual performance, use of Indian Energy Exchange (IEX) spot market prices as the selling tariff, use of constant West Bengal's average LCOE even if addition of more distributed solar plants in case of hypothetical scenario, no consideration of government taxes, subsidies or policy incentives, discount rate of 10%, plant life of 40 years, linear annual performance degradation rate of 0.25% and end of life residual value of the plant as 20% of the ICC.

2.3.6 Levelized Cost of Electricity (LCOE)

The equation [39, 40] for calculating the LCOE for a PV system is given in Eq. (4) below:

$$LCOE = \frac{1 + \sum_{t=1}^{n} \frac{(OM_t + F_t - SV_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t(1-d)^t}{(1+r)^t}} \tag{6}$$

Where; I = initial capital cost (INR/MW), OM_t = yearly Operational and Maintenance cost (INR/MW), F_t = yearly interest expenditure cost (INR/MW), SV_t = scrap value at the end of the project (INR/MW), E_t = rated energy output per year (kWh/MW), d = degradation rate, r = discount rate, and n = project lifetime.

The parameter considered for calculation as per CERC RE regulation has been shown in the Table 5 below.

3. Result and Discussion

3.1 Actual Scenario

In the first scenario, compilation of real load profile throughout the day in West Bengal DISCOM jurisdiction in 15 minutes time block and the real pumping load, PPSP generated energy and available quantum of power under WBSEDCL from non-renewable sources in the same time block on 6th Feb., 26th April, 8th June, 24th Aug., 4th Oct., and 30th Dec. of the year 2023 have been shown below in Figure 7.

(a) From the load demand and supply curve, it can be seen that on 6th February, morning peak load duration was from 07:00 Hr to 11:00 Hr, evening peak load duration was from 18:00 Hr to 22:00 Hr and the pumping operation of PPSP was done twice during 00:00 Hr to 06:00 Hr & 12:00 Hr to 17:00 Hr. Both the morning and evening peak demands were served by generating from PPSP during from 07:00 Hr to 11:00 Hr & 17:00 Hr to 22:00 Hr. The quantum of grid energy used to pump the total head of 22m throughout the day was 9170MWh to generate 6947 MWh energy from the PPSP.

(b) On 26th April, midnight peak load duration above the power availability was from 00:00 Hr -05:00 Hr, evening peak load duration was 18:00 Hr to 23:59 Hr and the pumping operation of PPSP was done during 03:00 Hr to 12:00 Hr. Both the midnight and evening peak demands were served by generating from PPSP during 00:00 Hr – 02:30 Hr & 18:00 Hr to 23:59 Hr. The quantum of grid energy used for pumping of the total head of 10.57m throughout

Table 4. Impact of data limitations on DE and CPR

Sl. No.	Data Limitations	Impact on DE and CPR
1	No evaporation/precipitation data	May be overestimated
2	Unaccounted residual water	May be overestimated
3	Linear Pumping Head Factor	May be overestimated
4	Limited temporal scope	May not reflect annual average

Table 5. Parameters considered for calculation of LCOE

Parameter	Value	Parameter	Value
Plant Capacity at STC (MW)	10.5	Project Cost Share	100% Loan
Plant CUF	17%	O&M Charges (Rs. In Cr.)	1.40%
Design Energy Generation in MU	15.64	Escalation of O&M Charges	5.72%
Auxiliary Consumption	0.25%	25 Years Loan Tenure Interest Rate	4.00%
Repayment period in years	10.00	Spare Cost of O&M Charges	15.00%
Discounting Rate	9.98%	Insurance Cost of Net Asset Value	0.35%
Depreciation/year	3.80%	CEA Emission Factor	0.716 tCO$_2$/MWh
Electricity tariff inflation per annum	3%	Carbon Credit Value (VCS)	0.3 USD
Plant Life	25 Years	End of Life/Scrap Value	5% of Project Cost

(a) (b) (c) (d) (e) (f)

Figure 7. Actual load demand profile and actual PPSP pumping using grid power and generation operation on (a) 6^{th} February; (b) 6th Feb., 26th April, 8th June, 24th Aug., 4th Oct., and 30th Dec. of the year 2023.

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the day was 4403 MWh to generate 4575 MWh energy from the PPSP, which means water pumped on 25th April was not fully used on that day and used on 26th April for generating more energy than the pumped energy on that day.

(c) On 8th June, the power demand throughout the day was above the available power quantum. Midnight peak load duration was from 00:00 Hr to 06:00 Hr, afternoon peak was from 13:00 Hr to 17:00 Hr and evening peak load duration was from 19:00 Hr to 23:59 Hr. The pumping operation of PPSP was done during 06:00 Hr to 15:00 Hr and all the three peak demands were served by generating from PPSP during 00:00 Hr – 02:00 Hr & 15:30 Hr to 23:59 Hr. The quantum of grid energy used for pumping the total head of 14.63m throughout the day was 6097 MWh to generate 4078 MWh energy from the PPSP.

(d) On 24th Aug, the power demand throughout the day was above the available power quantum except for a very small duration. Midnight peak load duration was from 00:00 Hr to 06:00 Hr, afternoon peak was from 12:00 Hr to 16:00 Hr and evening peak load duration was from 18:00 Hr to 23:59 Hr. The pumping operation of PPSP was done during 09:00 Hr to 14:45 Hr. The midnight peak and evening peak demand were served by generating from PPSP during 00:00 Hr to 02:45 Hr & 05:45 Hr to 07:15 Hr and during 17:30 Hr to 20:45 Hr. The quantum of grid energy used for pumping the total head of 9.33m throughout the day was 3888 MWh to generate 1494 MWh energy from the PPSP.

(e) On 4thOct, midnight peak load duration above the power availability was from 00:00 Hr -02:00 Hr, evening peak load duration was 17:00 Hr to 23:59 Hr and the pumping operation of PPSP was done during 05:00 Hr to 14:30 Hr. The evening peak demand was served by generating from PPSP during 04:30 Hr to 23:59 Hr. The quantum of grid energy used for pumping of the total head of 11.44m throughout the day was 4767 MWh to generate 4011 MWh energy from the PPSP.

(f) On 30th Dec, one morning to midday peak load was formed during 07:00 Hr to 12:30 Hr and another evening peak was formed during 17:00 Hr to 19:30 Hr. The pumping operation of PPSP was done thrice during 00:00 Hr to 06:15 Hr, 13:45 to 16:00 Hr & 21:00 Hr to 23:59 Hr. Both the morning and evening peak demands were served by generating from PPSP during from 06:45 Hr to 13:15 Hr and 16:30 Hr to 20:45 Hr respectively and the excess generated energy was evacuated to the grid. The quantum of grid energy used to pump the total head of 12.3m throughout the day was 5127 MWh to generate 3829 MWh energy from the PPSP.

Calculated results of techno-commercial PHP efficiency based on the real operational data of that particular day for which this study has been conducted and LCOS based on operational data of the whole year of 2023 has been shown in the Table 6 and Table 7 below. Calculation of cost of Pumping and generated energy price have been done based on the real average cost per unit grid energy and per unit energy price of IEX respectively for that particular day.

The Commercial Performance Ratio in the actual scenario i.e., CPR_{act} results reveal a critical interplay between pumping energy, generated energy, and energy demand, with performance variations driven by operational strategies and grid conditions across six representative days in 2023. The daily efficiency fluctuated significantly from 38.43% to 103.89%, reflecting its dependency on grid power availability and demand patterns.

On 6th February, a very low pumping cost of 3.29/kWh for 9170 MWh and high generation of 6947 MWh yielded an excellent CPR of 159.50, while on 26th April, a high efficiency of 103.9% was achieved, with 4575 MWh generated from 4404 MWh pumped was negated by a moderate 4.64/kWh pumping cost, resulting in a break-even CPR of 98.36. The 8th June saw a profitable CPR of 102.20 despite a high 5.63/kWh cost for 6097 MWh pumping and mediocre efficiency of 66.88% with 4078 MWh generated, due to high peak summer selling prices. In stark contrast, the 24th August was disastrous with a CPR of 40.23 and lowest efficiency of 38.43% due to the highest pumping cost of 6.01/kWh for 3888 MWh and catastrophically low generation requirement of only 1494 MWh, which denotes suboptimal pumping during off-peak hours. While on 4th October a CPR of 137.37 with good efficiency of 80.43% was achieved by generating 4011 MWh from 4767 MWh pumped energy overcoming a high 5.46/kWh pumping cost, and on 30th December a CPR of 152.18 was achieved for securing a strong profit margin due to the low pumping cost of 4.51/kWh for 5127 MWh and solid generation of 3829 MWh.

The findings are reinforcing that lower pumping cost can enhance profitability even when generation lags behind pumping and highlighting the critical impact of energy input costs and demand timing on the performance of PPSP. When generation exceeds pumping (e.g., 26th April), efficiency peaks, but reliance on expensive grid power (e.g., 24th August) erodes viability.

The LCOS result of the PPSP in the actual operational scenario, which relies solely on grid power for pumping, ranges from 0.38 to 2.32 INR/kWh i.e., approx. 0.05 to 0.30 USD/kWh, reflecting significant variability due to dependence on volatile grid electricity prices. This aligns with global benchmarks for Pumped Hydro Storage, which typically report LCOS values between 0.10–0.50 USD/kWh i.e., approx. 8–40 INR/kWh depending on regional economics, project scale, regional energy markets and operational regimes [41, 42, 43]. The lower end of PPSP's LCOS is notably economical and competitive with international values, while the upper end, driven by high grid power costs highlights the economic vulnerability of conventional

Table 6. Techno-commercial analysis of PPSP for the actual operation

Day of Operation	E_p (MWh)	$H_{pumping}$(m)	C_{agp} (INR/kWh)	E_g(MWh)	η_{daily}	CPR_{act}
6th FEB	9170	22	3.29	6947	75.76	159.50
26th APR	4403.75	10.57	4.64	4575	103.89	98.36
8th JUN	6097.25	14.63	5.63	4078	66.88	102.20
24th AUG	3888.25	9.33	6.01	1494.25	38.43	40.23
4th OCT	4767	11.44	5.46	4011.25	84.15	137.37
30th DEC	5127	12.30	4.51	3829	74.68	152.18

Table 7. LCOS of PPSP for the actual operation in 2023

Parameter	Variable	Value
Initial capital cost (Crore)	ICC	2475
Discount rate	r	10%
Plant life	N	40 years
Annual degradation	d	0.25%
Annual generation (MWh)	Ei	1366936.2
Annual pumping (MWh)	Pi	1758346.2
Average Pumping tariff using Grid power (INR/kWh)	Tp	3.29 - 6.01
IEX Selling tariff (INR/kWh)	Ts	3.5 - 12.0
Charging cost (Crore)	Pi*Tp	578.49 - 1056.77
Discharged Electricity Selling Price (Crore)	Ei*Ts	478.43 - 1640.32
Annual Operation & Maintenance Cost (Crore)	O&M	2
Residual value	End of Life	20% of ICC
Storage Cost for PPSP (INR/kWh)	LCOS	0.38 - 2.32

grid-powered pumping without renewable integration.

3.2 Hypothetical Scenario

The graphs shown in Figure 8 below illustrate the solar generation profiles of Teesta Canal Top, Dhaka-I, Bhajanghat, Salboni, and Sankrail 10 MW solar PV plants distributed across West Bengal, along with their average generation for the six days of 2023 considered for the study to get the scenario of each season throughout the study year. Each plant exhibits a bell-shaped generation curve peaking around midday, with variations due to location-specific solar irradiance, tilt angles, and regional weather variation. For instance, Bhajanghat and Dhaka-I show higher peaks in some graphs, while Teesta Canal Top and Sankrail display slightly lower or fluctuating outputs. The average generation profile smooths out these variations, providing a consolidated trend. Seasonal differences are evident, with broader curves in summer (June) due to longer daylight and narrower profiles in winter (December). These variations highlight the complementary nature of distributed solar plants, ensuring more stable aggregate generation for Pumped Hydro Storage integration.

In order to get sufficient solar generated power to pump the PPSP having cumulative pump capacity of 1000MW, the real average generation/10MW for the six days of 2023 considered for the study are hypothetically extrapolated to solar generation profiles of cumulative 1500 MW installation capacity of SPV Plant distributed throughout the state have been shown in the Figure 9 below.

The water head pumping potential from the PPSP Lower Reservoir to the Upper Reservoir using the solar generation received from the hypothetical cumulative 1500MW solar PV plant capacity as shown in Figure 10 below have been calculated for the particular days considered for the study as per the pumping principle. The derived results are furnished in the Table 8 below.

The results shows that on 6th February, Pump 1 can be operated for 8.5 hours, raising the water head by 4.896 m, while Pump 2, 3, and 4 can contribute 3.744 m, 2.736 m, and 1.152 m, respectively, totaling 12.528 m of pumping potential if pumped using the solar power only. Similarly, on 26th April, pumping potential of 15.984 m, on 8th June, pumping potential of 14.976m, on 24th August, pumping potential of 11.22 m and on 4th October, pumping potential of 13.39 m have been found. On $30th$ December, Pump 1, 2 and 3 can contribute to a total pumping potential of 9.648 m, while Pump 4 remained idle as the solar generation is not sufficient to operate all the four pumps simultaneously. The results demonstrate how solar-powered pumping varies seasonally, with higher head contributions in spring (April) and lower in monsoon (August) and winter (December).

Figure 11 below illustrates the same load demand profile of actual operation of the studied six days keeping every parameter same as it was in Figure 7 and by only simulating the PPSP pumping operation using solar power primarily from the hypothetical 1500 MW distributed PV capacity and supplemented by grid

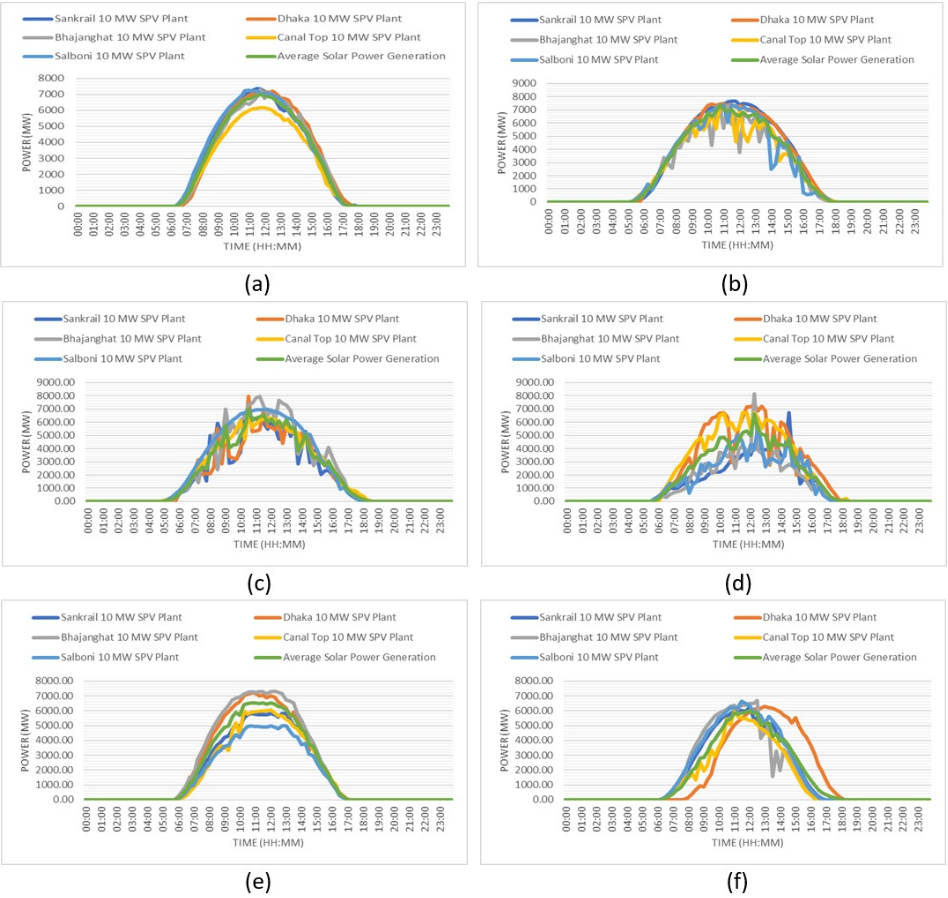

Figure 8. Solar generation profile of various 10MW solar PV plants of West Bengal and their average generation profile on (a) 6th February; (b) 26th April; (c) 8th June; (d) 24th August; (e) 4th October; (f) 30th December of the year 2023

Table 8. PPSP Upper Reservoir Head Pumping Potential Using 1500 MW Solar Generation

		06.02.2023					**26.04.2023**		
Pumping Unit	**Sync**	**De-sync**	**Duration (Hr)**	**Head (m)**	**Pumping Unit**	**Sync**	**De-sync**	**Duration (Hr)**	**Head (m)**
Pump 1	07:30	16:00	8.5	4.896	Pump 1	06:45	16:15	9.5	5.472
Pump 2	08:30	15:00	6.5	3.744	Pump 2	07:30	15:45	8.25	4.752
Pump 3	09:30	14:15	4.75	2.736	Pump 3	08:00	14:15	6.25	3.6
Pump 4	11:00	13:00	2	1.152	Pump 4	09:30	13:15	3.75	2.16
Total Head Pumping Potential				**12.528**	**Total Head Pumping Potential**				**15.984**
		08.06.2023					**24.08.2023**		
Pumping Unit	**Sync**	**De-sync**	**Duration (Hr)**	**Head (m)**	**Pumping Unit**	**Sync**	**De-sync**	**Duration (Hr)**	**Head (m)**
Pump 1	06:45	16:30	9.75	5.616	Pump 1	07:00	16:30	9.5	5.472
Pump 2	08:00	15:45	7.75	4.464	Pump 2	08:30	15:00	6.5	3.744
Pump 3	08:30	14:30	6	3.456	Pump 3	10:00	14:30	4.5	1.8
Pump 4	10:30	13:00	2.5	1.44	Pump 4	12:15	12:45	0.5	0.2
Total Head Pumping Potential				**14.976**	**Total Head Pumping Potential**				**11.22**
		04.10.2023					**30.12.2023**		
Pumping Unit	**Sync**	**De-sync**	**Duration (Hr)**	**Head (m)**	**Pumping Unit**	**Sync**	**De-sync**	**Duration (Hr)**	**Head (m)**
Pump 1	07:00	15:45	8.75	5.04	Pump 1	08:00	15:45	7.75	4.464
Pump 2	08:00	15:00	7	4.032	Pump 2	09:15	14:45	5.5	3.168
Pump 3	09:00	14:00	5	2.88	Pump 3	10:15	13:45	3.5	2.016
Pump 4	10:15	12:45	2.5	1.44	Pump 4	00:00	00:00	0	0
Total Head Pumping Potential				**13.39**	**Total Head Pumping Potential**				**9.648**

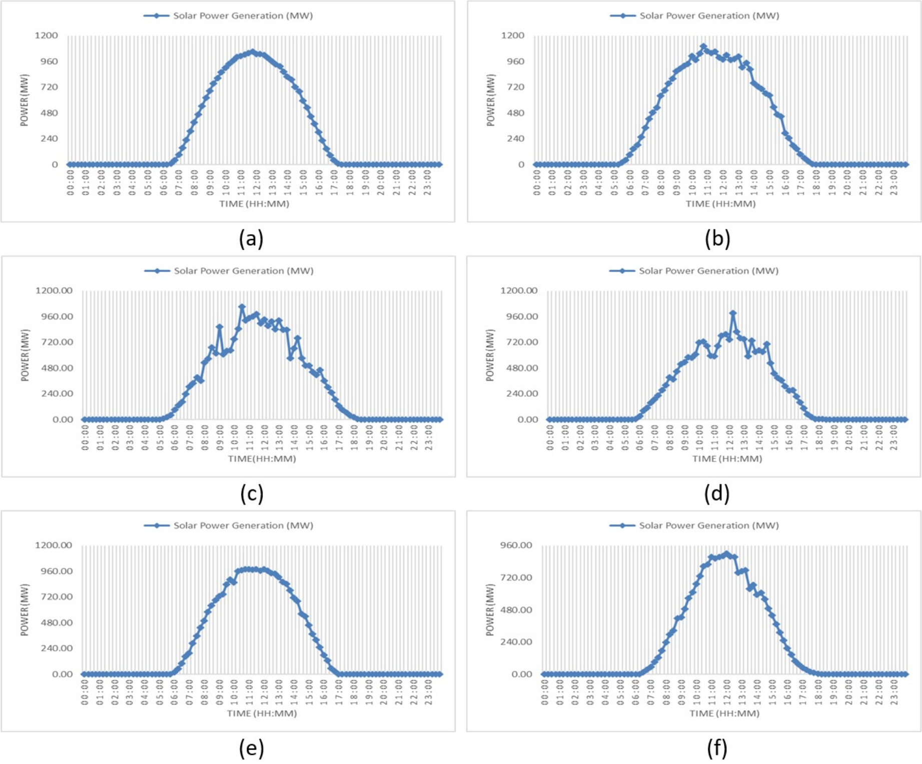

Figure 9. Extrapolated solar generation profile of cumulative 1500 MW distributed solar PV plants across West Bengal state on (a) 6th February; (b) 26th April; (c) 8th June; (d) 24th August; (e) 4th October; (f) 30th December of the year 2023

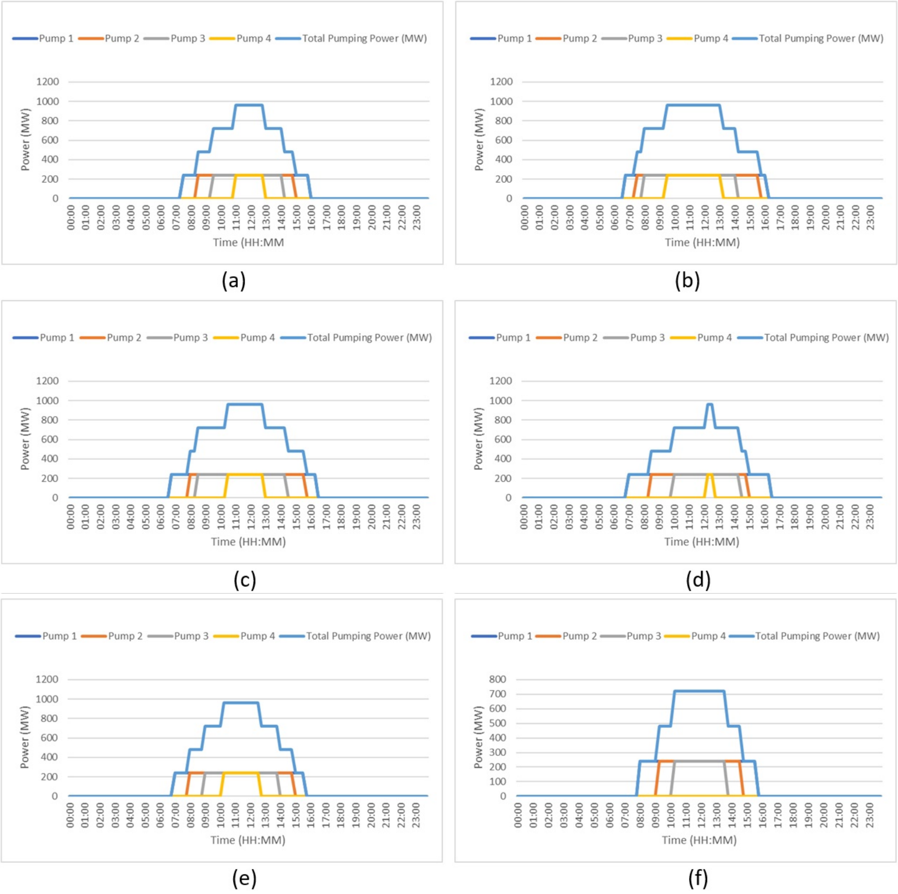

Figure 10. Pumping pattern in the hypothetical scenario using the extrapolated solar generation of cumulative 1500 MW distributed solar PV plants across West Bengal state on (a) 6th February; (b) 26th April; (c) 8th June; (d) 24th August; (e) 4th October; (f) 30th December of the year 2023

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Figure 11. Actual load demand profile and hypothetical PPSP pumping using solar power and generation operation on (a) 6th February; (b) 26th April; (c) 8th June; (d) 24th August; (e) 4th October; (f) 30th December in the year 2023

power. Each graph presents the actual load demand (MW), available grid power (MW), PPSP generation (MW), hypothetical solar generation (MW), solar power pumping load (MW) and grid power pumping load (MW) in 15-minute blocks. The simulated pumping scenario for the studied six days is discussed hereunder.

(a) 6th February 2023: 12.53 m of pumping head out of the total 22 m of the actual operation, is pumped using solar power from 07:30 to 16:00 Hr and the balance 9.47 m is supplemented by grid power.

(b) 26th April 2023: The total 10.57 m pumping head of the actual operation is pumped from 06:45 to 16:15 Hr using solar power only without any grid assistance.

(c) 8th June 2023: Demand exceeded supply throughout the day. The total 14.63 m pumping head of the actual operation is pumped from 06:45 to 16:30 Hr using solar power only, eliminating grid dependency.

(d) 24th August 2023: Despite persistent high demand, the total 9.33 m pumping head of the actual operation is pumped from 07:00 to 16:30 Hr using solar power only, eliminating grid dependency.

(e) 4th October 2023: The total 11.44 m pumping head of the actual operation is pumped from 07:00 to 15:45 Hr using solar power only, reducing grid reliance.

(f) 30th December 2023: 9.65 m of pumping head out of the total 12.30 m of the actual operation, is pumped using solar power from 08:00 to 15:45 Hr and remaining 2.65 m is supplemented by grid power.

The western regional plants of the West Bengal state viz., Dhaka-I and Salboni demonstrate superior performance with LCOE of 2.16-2.43/kWh. The eastern regional plant i.e., Bhajanghat shows moderate result of LCOE 2.28/kWh, while the northern regional Teesta Canal-top installation resulting in the highest LCOE (3.02/kWh). The southern region plant i.e., Sankrail maintains stable performance with LCOE of 2.86/kWh. The calculated LCOE as per CERC RE regulation [44] for all the five plants are shown in the Table 9 below.

Calculated results of CPR based on the hypothetical pumping scenario of the studied six days and LCOS based on the actual generation data of the whole year of 2023 and hypothetical pumping data using solar power primarily with grid power as supplementary source has been shown in the Table 10 and Table 11 below. Calculation of the cost of Pumping and generated energy price have been done using combination of solar LCOE and real average cost per unit grid energy and per unit energy price of IEX respectively for that particular day. Calculation of DE has not been done in this case as all the actual operational quantities have been kept same.

In the hypothetical scenario, the CPR improved dramatically across all six days due to the displacement of costly grid power for pumping with cheaper solar energy i.e., LCOE of 2.55/kWh. The most significant gains were

Table 9. LCOE of the Solar PV Plants in West Bengal

Sl. No.	SPV Plant	Plant Cost (INR in Cr.)	LCOE (INR/kWh)	Average LCOE (INR/kWh)
1	Bhajanghat	41	2.28	2.55
2	Teesta Canal Top	54	3.02	
3	Dhaka-I	39	2.16	
4	Salboni	44	2.43	
5	Sankrail	51.19	2.86	

Table 10. Techno-commercial Analysis of PPSP in the Hypothetical Scenario

Day of Operation	Average Solar Generation/10 MW (MWh)	1.5GW Cumulative Plant Solar Generation (MWh)	PPSP Head Pumped using Solar and Grid Power(m)	PPSP Pumping Cost using Hybrid Power (INR)	PPSP Generation Price (INR)	CPRhyp
6th FEB	45789.36	6868404.64	12.53 and 9.47	26306500.00	48119190.20	182.92
26th APR	51747.32	7762097.77	10.57	11229562.50	20098518.15	178.98
8th JUN	45296.90	6794535.55	14.63	15547987.50	35081951.48	225.64
24th AUG	37012.53	5551879.98	9.33	9915037.50	9401408.14	94.82
4th OCT	44027.98	6604196.95	11.44	12155850.00	35753593.95	294.13
30th DEC	34881.46	5232218.35	9.65 and 2.65	15243570.00	35187453.46	230.83

observed on days with previously high grid power costs. For instance, on 24th August, the CPR improved from 40.23 to 94.82 as the exorbitant 6.01/kWh grid power cost was eliminated, though the plant's underlying low generation of 1494 MWh from 3888 MWh pumped energy. Similarly, on 4th October and 30th December, CPRs soared to 294.13 and 230.83 respectively, as solar power covered all or most of the pumping head of 11.44m and 9.65m respectively, slashing input costs while generated high revenue from generation of 4011 MWh and 3829 MWh sold at peak prices. This consistent enhancement presented in the Figure 12 underscores that while solar hybridization fundamentally improves economics by securing a cheap pumping power source, the final CPR remains a function of both this low-cost power and the plant's operational efficiency in converting stored energy into valuable peak power.

In the hypothetical solar integrated scenario, the LCOS for PPSP decreases significantly to a range of 0.31 to 1.05 INR/kWh, compared to 0.38–2.32 INR/kWh in the actual grid-powered scenario, which is influenced by the lower LCOE of solar power of 2.55 INR/kWh and the variability in electricity selling price as high as 12.0 INR/kWh. This improved LCOS range aligns more consistently with the global benchmarks for modern Pumped Hydro Storage systems, which typically fall between 0.10–0.20 USD/kWh i.e., approximately 8–16 INR/kWh [42, 43]. In comparison, lithium-ion battery storage being the dominant short-duration technology has an LCOS range of 0.17–0.296 USD/kWh for 4-hour systems [43], making PHS more economical for large-scale and long-duration applications. However, the PPSP's actual LCOS is notably lower than many international PHS projects due to possibly India's lower labor and construction costs. The LCOS remains low, particularly when solar generation aligns with peak pumping needs, minimizing grid dependency. The results highlight the operational flexibility and economic benefits of solar-PPSP hybridization, where cost stability of solar energy mitigates price volatility in grid power, enhancing financial viability. However, seasonal variations in solar output necessitate supplementary grid power, as seen on 6th February and 30th December, where partial grid pumping were required. This underlines the importance of optimizing solar capacity and storage scheduling to maximize cost savings and energy reliability.

The integrated solar-PPSP hybrid system demonstrates significant seasonal performance disparities, during monsoon i.e., on 24th August, the underperformance of the system can be seen as it yields a critically low Hypothetical CPR of 94.82 and DE of 38.43% despite full solar-powered pumping of a 9.33 m head. This is primarily driven by the high grid power cost of 6.01 INR/kWh, suboptimal demand-generation alignment and lowest solar yield of 37,012.53 MWh/10MW. In stark contrast, spring/winter i.e., on 26th April and 30th December the system achieves over 100% DE and CPR as high as 230.83, facilitated by favourable solar conditions 51,747.32 MWh/10MW and strong peak demand alignment. This type of underperformance as occurred during monsoon can be mitigated by using strategies like optimized procurement of supplementary grid power during cheaper IEX price windows, advanced scheduling for pumping [45, 46] to build reservoir reserves and potential hybridization with wind power [47] to stabilize renewable energy input to ensure year-round level LCOS viability within the range of 0.31-1.05 INR/kWh.

Table 12 below concisely summarizes the techno-economic advantages of integrating solar power with Pumped Hydro Storage, as demonstrated in the case

Table 11. LCOS of PPSP for the Year 2023 in Hypothetical Scenario

Parameter	**Variable**	**Value**
Initial capital cost (Crore)	ICC	2475
Discount rate	r	10%
Project life	N	40 years
Annual degradation	d	0.25%
Annual generation (MWh)	Ei	1366936.2
Annual pumping (MWh)	Pi	1758346.2
Average Pumping tariff using Solar power (INR/kWh)	Tp	2.55
IEX Selling tariff (INR/kWh)	Ts	3.5 - 12.0
Charging cost (Crore)	Pi*Tp	448.378
Discharged Electricity Selling Price (Crore)	Ei*Ts	478.43 - 1640.32
Annual Operation & Maintenance Cost (Crore)	O&M	2
Residual value	End of Life	20% of ICC
Storage Cost for PPSP (INR/kWh)	LCOS	0.31 - 1.05

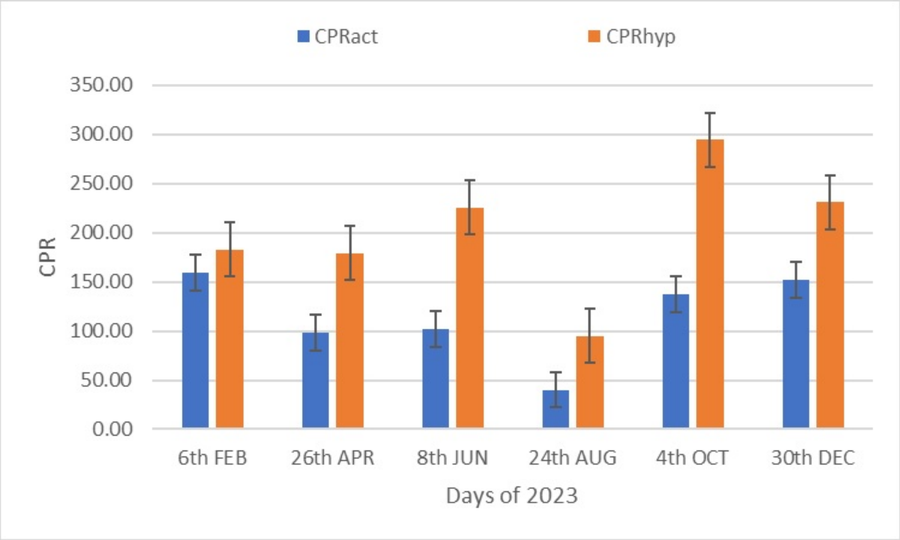

Figure 12. Comparative chart of CPR in the actual and hypothetical scenario

Table 12. Performance comparison between the two scenarios

Sl. No.	**Performance Metrics**	**Actual Scenario Performance**	**Hypothetical Scenario Performance**	**Outcome**
1	LCOS	0.38 – 2.32 INR/kWh	0.31 – 1.05 INR/kWh	Reduction of up to 55%
2	CPR	40.23 – 159.50	94.82 – 294.13	Increase of 14.7 to 135.7%
3	Pumping Energy Cost	3.29 – 6.01 INR/kWh	2.55 INR/kWh with minimal grid backup	Significant cost savings
4	Grid Dependency	100%	0–40% (seasonal variation)	Up to 100% reduction on most days
5	Economic Viability	Highly variable	Stable, cost-effective	Enhanced financial stability

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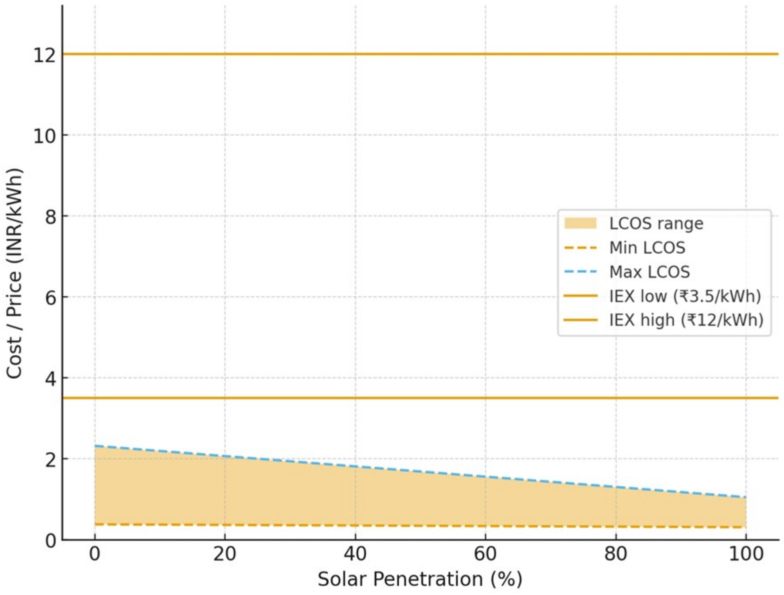

Figure 13. Impact of variation in solar penetration level on LCOS

study of the Purulia Pumped Storage Plant.

The plot of LCOS against varying levels of solar penetration as shown in the Figure 13 below reveals that, within the studied parameter range, the LCOS consistently remains below the minimum power price of 3.5/kWh. Specifically, the LCOS varies from 2.32/kWh under a 0% solar penetration scenario, where the plant is fully dependent on grid power pumping to as low as 0.31/kWh at 100% solar penetration, where pumping is entirely solar power driven. This outcome indicates that the Pumped Hydro Storage system remains economically viable across all penetration levels, with positive arbitrage potential even under conservative assumptions. Importantly, increasing solar penetration progressively enhances the cost advantage, thereby widening the margin between storage costs and market selling prices, and reinforcing the role of solar-integrated pumped storage as a competitive and resilient energy storage option in the evolving electricity market.

4. Conclusion

From the above comparative and feasibility analysis between the pumping operation of PPSP using grid power that has been done in actual scenario and the hypothetical pumping scenario created using solar power generated in the territory of the state for the year 2023, it is clearly visible that the CPR which were 159.50, 98.36, 102.20, 40.23, 137.37 and 152.18 on 6th Feb, 26th April, 8th June, 24th Aug, 4th Oct and 30th Dec of the year 2023 respectively in the actual operational scenario increased to 182.92, 178.98, 225.64, 94.82, 294.13 and 230.83 in the hypothetical scenario. On the other side the LCOS which was in the range of 0.38 - 2.32 INR per unit electricity in the actual operational scenario significantly reduced to the range 0.31 - 1.05 INR per unit in the hypothetical scenario due to the lower LCOE of 2.55 INR/kWh solar energy than the grid power price used for pumping of the water from lower reservoir to the upper reservoir of PPSP.

The study findings are underlining the economic viability of the hypothetical solar-PPSP hybrid model. Seasonal variations in solar generation and demand pattern may be effectively managed by serving most or all of the peak demand with solar-powered pumping, thereby reducing reliance on volatile grid power and enhancing grid stability. This integration not only can mitigate the intermittency of solar energy but also can optimise energy storage and dispatch, to achieve renewable energy goals of the West Bengal state. The findings highlight the transformative potential of solar-powered Pumped Hydro Storage in achieving cost-effective, reliable, and sustainable energy solutions for the state, offering policymakers a large-scale model for India's energy transition.

To overcome the limitations of this study, future research may be focused on precise data collection for evaporation, precipitation, and residual water levels of the upper reservoir by collecting full year data instead of a specific day which would further enhance the accuracy of energy storage efficiency metrices. Additionally, long-term case studies on hybrid floating solar PV-PHS [48, 49, 50, 51] system may be conducted as floating solar PV plant can reduce reservoir evaporation, improve solar efficiency through cooling effects, and maximize land-use synergy. Furthermore, extending the hybrid model to include wind energy by forming a wind-solar-PHS system [52, 53] may better address seasonal variability, ensuring more stable and reliable renewable energy integration for achieving high renewable penetration in diverse climatic and geographic scenarios. Case studies on BESS [54, 55, 56] may also be explored in scenarios where rapid response in milliseconds to seconds for frequency regulation and localized grid support is required as PHS faces trade-offs [3] like significant land/water use and long development time.

A key recommendation is the implementation of a dedicated feed-in tariff for stored renewable energy, extend viability gap funding for capital costs, and assign capacity credits for peak power assurance.

Nomenclature

PV	Photovoltaic
PHES	Pumped Hydroelectric Energy Storage
PPSP	Purulia Pumped Storage Plant
PHP	Pumped Hydroelectric Plant
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
IEX	Indian Energy Exchange
MNRE	Ministry of New and Renewable Energy
ACPR	Actual Commercial Performance Ratio scenario
HPCR	Hypothetical Commercial Performance Ratio
BESS	Battery Energy Storage System
SDG	Sustainable Development Goals
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
DISCOM	Distribution Company
RPO	Renewable Purchase Obligation
SCADA	Supervisory Control and Data Acquisition
NDC	Nationally Determined Contribution

Authors contributions
All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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