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Techno-Economics of Grid-Tied Battery Energy Storage System Through Repowering of Utility-Scale Solar PV Projects in India

Ashish Kumar Sharma [1], Ishan Purohit [2], Saurabh Motiwala [3], Sudarshan Kumar [3] and Pallav Purohit [4,*]

[1] Energy, Economics and Sustainability Cluster, University of Petroleum and Energy Studies (UPES), Dehradun 248007, India; ashishk.sharma@ddn.upes.ac.in
[2] Solar Technology Application and Resource Center (STAR-C), International Solar Alliance (ISA), Gurgaon 122003, India; ipurohit@isa.int
[3] Department of Aerospace Engineering, Indian Institute of Technology (IIT) Bombay, Mumbai 400076, India; saurabhmotiwala01@gmail.com (S.M.); sudar@aero.iitb.ac.in (S.K.)
[4] Energy, Climate and Environment (ECE) Program, International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria
* Correspondence: purohit@iiasa.ac.at; Tel.: +43-2236-807-336

Abstract

India's rapid expansion of utility-scale solar photovoltaic (PV) capacity is increasingly constrained by aging assets and the temporal mismatch between generation and peak demand. This study develops a techno-economic framework integrating battery energy storage systems (BESSs) with repowered solar PV projects, using repowered electricity as a low-cost charging source. A capacity-based assessment estimates national repowering potential of 7.2 GWp under power purchase agreement constraints and 10.9 GWp under technical limits. The levelized cost of repowered electricity is ₹1.40/kWh, significantly lower than prevailing utility-scale solar tariffs under stated assumptions. Levelized storage costs range from ₹5.08 to ₹4.12/kWh for 2–6 h durations, declining with improved inverter and balance-of-system utilization. Financial analysis under a ₹10 per kWh peak tariff arbitrage scenario yields internal rates of return between 17.5% and 24.2%, with positive project viability across configurations. Sensitivity analysis identifies capital cost as the dominant economic driver. Environmental benefits include annual greenhouse gas reductions of 13.8–17.2 $MtCO_2$, accumulating to 411–514 $MtCO_2$ over the project lifetime. These findings demonstrate that repowering-integrated battery storage offers a cost-effective, scalable pathway to enhance renewable integration, displace fossil fuel peak generation, and support India's low-carbon transition, highlighting a viable framework for improving system flexibility and overall system performance.

Keywords: energy transition; utility-scale solar PV; solar repowering; grid-tied battery energy storage systems (BESSs); energy arbitrage; levelized cost of electricity; India

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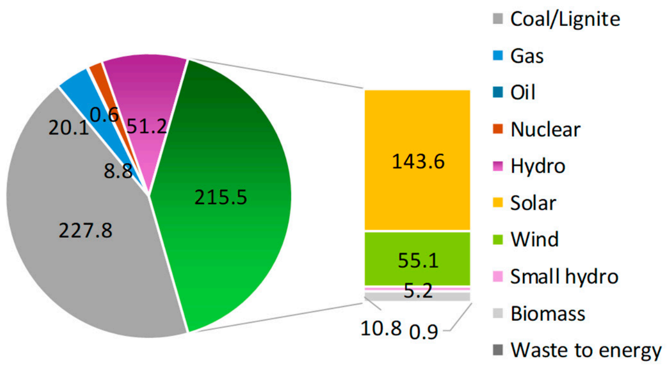
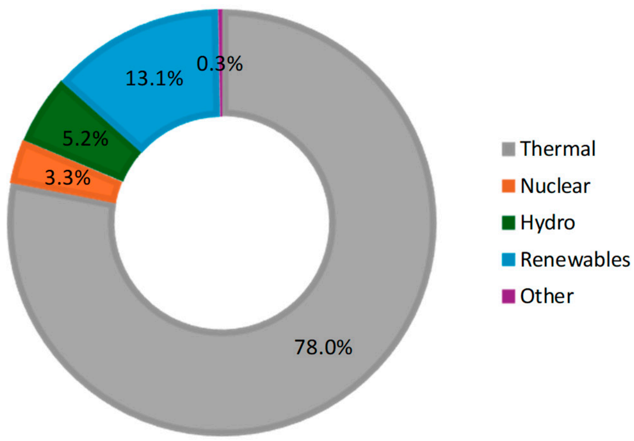
1. Introduction

India's demand for clean energy is accelerating, driven by its COP26 commitment to achieve net zero greenhouse gas (GHG) emissions by 2070 and its strategic goal of attaining energy independence by 2047, a target that coincides with the centenary of its independence [1,2]. At least 50% of India's electricity requirements are projected to come from renewable sources by 2030 [3–5]. To achieve these goals, the Government of India has set an ambitious target of 500 GW of non-fossil fuel installed capacity by 2030 [5,6], reflecting a transition from a coal-dominated system toward a diversified and sustainable energy mix [7,8]. Rapid economic growth, urbanization, industrial expansion, and rising per-capita electricity consumption are driving a surge in electricity demand, while energy security concerns, fossil fuel price volatility, and climate change reinforce the imperative for renewable energy deployment [9–12].

India's electricity generation fleet continues to diversify, yet fossil fuels still hold the largest share. As of February 2026, coal and lignite together contribute 227.8 GW, ensuring dependable baseload supply despite their environmental footprint (Figure 1a). Other non-renewable sources comprise natural gas (20.1 GW), oil (0.6 GW), nuclear (8.8 GW), and large hydropower (51.2 GW), all of which support grid stability and energy storage functions [13]. Renewables have grown quickly, reaching 215.5 GW, or about 40% of total installed capacity. Solar dominates this segment with 143.6 GW, followed by wind at 55.1 GW, while biomass, small hydro, and waste-to-energy make smaller contributions (Figure 1a). Renewable capacity is now approaching coal's level, indicating a fundamental shift toward lower-carbon energy.



(a)



(b)

Figure 1. Overview of India's power sector (as of February 2026): (**a**) installed power generation capacity by source; and (**b**) share of electricity generation by source [13,14].

Actual electricity generation, however, tells a different story. Thermal power plants supply nearly 78% of total generation (156.12 TWh), whereas renewables provide only about 13%, underscoring the challenges posed by intermittency (Figure 1b). Hydropower and nuclear account for roughly 5% and 3%, respectively, with a minor amount of electricity imported from Bhutan [14]. This gap between capacity and generation underscores the urgent need for greater energy storage capacity, more flexible grid operation, and demand-side management to enable a dependable low-carbon transition.

Among renewable sources, solar energy has emerged as the primary driver of India's renewable expansion [15]. With solar irradiance ranging from 4 to 7 kWh per square meter per day across most regions and nearly 300 sunny days annually [16,17], large tracts of semi-arid land in Rajasthan, Gujarat, and Andhra Pradesh are ideal for utility-scale deployment [18,19]. As of February 2026, India has installed approximately 143.6 GW of solar capacity [14,20], including utility-scale parks, rooftop systems, floating solar, and hybrid solar–wind projects (Figure 2). Solar has driven new renewable capacity additions over the past decade, supported by declining module costs, competitive reverse auctions, production-linked incentive schemes, and programs such as Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan (PM-KUSUM) [21–23]. Between 2015 and 2026, cumulative solar capacity grew from 1.6 GW to 143.6 GW, representing a compound annual growth rate of 45.5% [20,24,25]. Despite rapid deployment, solar and wind generation are constrained by intermittency, lower capacity utilization factors, and temporal misalignment with peak electricity demand, particularly during early morning and evening hours. This increases challenges for grid stability and frequency management, highlighting the urgent need for energy storage solutions [26–30].

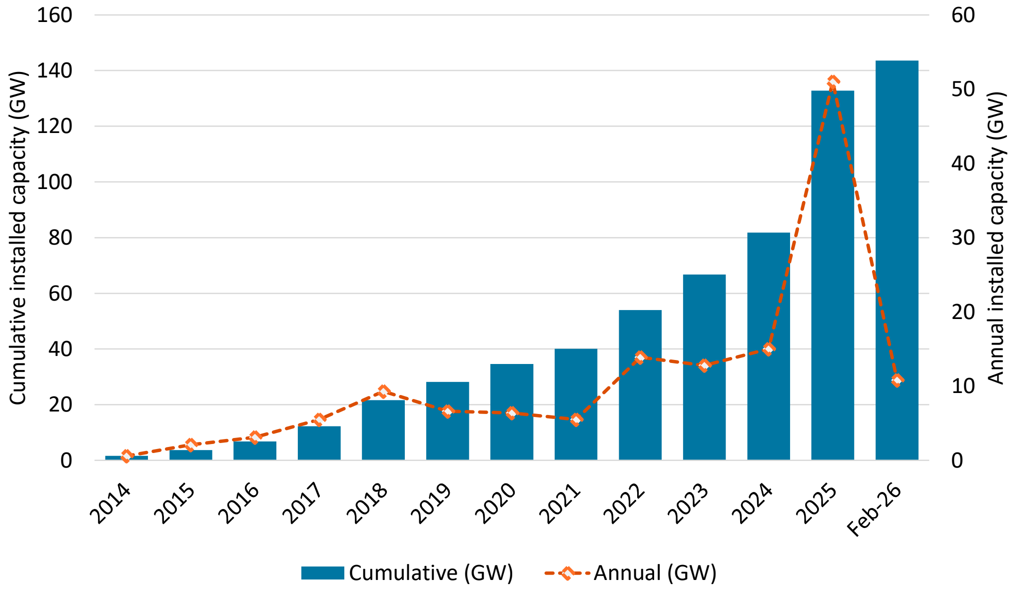


Figure 2. Cumulative solar power installed capacity in India (2015–January 2026) [13,14].

In response, the Government of India has launched a dedicated energy storage mission, targeting 47–50 GW (236–260 GWh) of battery energy storage systems (BESSs) and pumped storage hydropower (PSH) by 2031–32 [31–33]. Battery energy storage provides multifunctional benefits across generation, transmission, and distribution, including renewable firming [34], peak shifting, frequency regulation [35–37], congestion relief, voltage support, black start capability, and EV load management (Table S1) [36–40]. The trend in tendered energy storage capacity in India from 2023 to 2025 shows a significant increase from 41 GWh to 102 GWh (Figure S1), reflecting accelerated policy support and growing market momentum toward large-scale storage deployment [36,37,41].

The rapid scale-up and improving cost competitiveness of solar-plus-battery projects between 2023 and 2025 is summarized in Table S2 [42]. Awarded tenders indicate a shift from small pilot projects to utility-scale systems [43], with capacities reaching up to 2000 MW of renewable energy paired with 4000 MWh of storage [15,16]. Most projects follow the build–own–operate model, reflecting growing investor confidence, while a few adopt the EPC model [30,41]. Peak power management is the primary use case across nearly all tenders [44,45]. Discovered tariffs have declined from approximately ₹2.70 to ₹4.31 per kWh, with recent large-scale tenders achieving ₹2.70 to ₹3.13 per kWh, signaling improving cost competitiveness [29,40,46].

However, integrating storage at scale increases electricity costs due to additional capital expenditure, round-trip efficiency losses, and degradation costs [47–50]. While renewable-plus-storage systems improve dispatchability and peak management, high levelized costs remain a barrier. One promising approach to reducing costs is repowering existing solar plants [51], which involves replacing older modules with higher-efficiency panels, upgrading inverters, and optimizing system configurations [52–54].

1.1. Solar PV Repowering: Global Evidence and Frameworks

As mentioned above, repowering refers to the systematic upgrading of aging photovoltaic assets by replacing modules, inverters, or other DC-side components [54]. Lifecycle assessments of both rooftop and ground-mounted silicon PV systems have also shown that the optimal environmental window for repowering occurs when a plant is between 15 and 21 years old [54]. Beyond this range, accumulated efficiency losses and missed generation make continued operation both ecologically and economically inferior to repowering. The U.S. Department of Energy and the National Renewable Energy Laboratory have quantified project-level economic benefits, reporting improvements in the internal rate of return, reductions in the levelized cost of energy (LCOE), extended asset lifetimes, and enhanced equity outcomes for host communities [55]. A consistent finding across these global studies is that repowering makes use of existing land leases, grid interconnections, and civil infrastructure, assets that account for 30 to 50% of the original capital investment [56,57], to achieve substantially higher energy output with relatively modest additional spending. Several investigations have also noted that early projects were built with lower efficiencies and higher capital costs [55,58]; retrofitting these plants with modern technology can significantly raise energy production while using the same land and transmission infrastructure [53–55].

Although these international studies offer strong methodological foundations, their direct translation to India is limited by the country's distinctive power purchase agreement (PPA) frameworks, quickly evolving solar tariffs, and a large stock of early-generation utility-scale assets with highly variable degradation behavior. Within India, the literature on solar PV repowering is still emerging. The International Energy Agency has pointed to aging plant performance as a structural hurdle for India's renewable integration efforts, but it did not quantify integrated repowering combined with storage pathways [59]. The most detailed study to date is by Motiwala et al. [58], who analyzed over 2000 utility-scale solar PV projects commissioned between 2010 and 2022. They estimated India's repowering potential at roughly 9 GWp under both regulated (PPA-constrained) and unregulated (technical limit) scenarios [58]. Their work shows that repowering can restore or even exceed contracted capacity utilization factors without needing extra land or transmission upgrades, offering a capital-efficient alternative to greenfield solar development. That study, however, concentrates on repowering potential and the techno-economic features of PV upgrades; it does not explore the downstream uses of the additional energy generated.

1.2. Repowering Solar with Battery Energy Storage Systems

The integration of battery energy storage with utility-scale solar PV has been extensively studied in recent years, driven by rapid declines in lithium-ion battery costs and growing policy mandates for dispatchable renewables [40,47–52]. Migliari et al. [51] evaluated the levelized cost of storage (LCOS) for BESSs deployed specifically to mitigate PV curtailment, finding that configurations using low-cost energy charging could reduce the LCOS substantially compared to grid-charged alternatives. At the global level, the IRENA [40] established foundational cost and market trajectories for electricity storage through 2030, identifying storage duration, cycling frequency, and charging cost as the three primary LCOS drivers. More recently, the NREL reported continued cost reductions for 4 h utility-scale BESSs, with capital costs declining by 40–50% between 2018 and 2023 and further reductions projected through 2035 [50]. A techno-economic analysis of BESSs co-located with utility-scale PV in Sweden and Germany by Koubar et al. [52] found that energy arbitrage combined with ancillary service participation can yield payback periods of 2–7 years depending on market structure, highlighting the sensitivity of BESS economics to the price differential between off-peak charging and on-peak discharge.

Several studies have examined the techno-economic viability of BESSs in India, providing benchmarks critical for contextualizing this work. Jindal and Shrimali [60] established that renewable energy paired with battery storage became cost competitive with new coal power in India starting in 2022. Purohit et al. [54] analyzed BESS economics from a distribution company perspective, quantifying value streams and reporting an LCOS of approximately ₹2.44 per kWh. Similarly, Deshwal and Sangwan [53] conducted a state-level techno-economic assessment of solar-plus-storage systems. However, none of these foundational studies considered the unique advantage of using low-cost repowered solar energy as a dedicated charging source for BESSs. Across the global and Indian literature, a clear pattern emerges: the economic viability of BESSs is highly sensitive to the levelized cost of charging energy. Yet, the possibility that low-cost electricity from repowering underperforming solar assets could serve as a structurally advantaged charging source has remained unexamined.

This review identifies two significant gaps. First, no study has systematically quantified the synergistic economics of using repowered solar energy, produced at a fraction of the cost of new-built capacity, as a dedicated low-cost charging source for grid-connected BESSs. Second, the environmental co-benefits of this integrated approach, particularly avoiding greenhouse gas emissions from displaced coal-based peak generation, have not been assessed at the national scale. Consequently, the potential of repowering to reduce the LCOS and enhance both the financial and environmental performance of BESSs remains unexplored in the context of India's energy transition.

While the repowering potential estimation framework builds on the prior work of Motiwala et al. [58], this study extends their analysis along three key dimensions: (i) quantification of the system-level economic value of repowered solar as a dedicated BESS charging source; (ii) a national-scale environmental assessment of this integrated pathway; and (iii) methodological refinement through validation of capacity-based estimates against project-level generation data (Appendix B). Together, these contributions establish an integrated techno-economic and environmental assessment framework for repowering-enabled storage systems in India.

This study addresses these gaps by presenting an integrated approach that estimates the national repowering potential of utility-scale solar PV assets in India and assesses the techno-economic feasibility of integrating this repowered energy with grid-connected BESSs. The analysis evaluates repowering potential under existing power purchase agreements and technical limits, quantifies levelized cost metrics including the LCOE of repowered energy and the LCOS of stored energy, examines financial viability through the net present value (NPV), internal rate of return (IRR), and payback period under an energy arbitrage framework, and assesses environmental benefits in terms of GHG emission reductions achieved by displacing coal-based generation during peak periods. By considering the combined effects of repowering and energy storage at scale, this study provides actionable insights for policymakers, utilities, and investors, highlighting cost-effective pathways to enhance grid flexibility, maximize renewable energy utilization, and accelerate India's transition toward a low-carbon power system.

2. Materials and Methods

The following sections present the conceptual framework for solar PV repowering, including pathways and estimation approaches, as well as the techno-economic and environmental assessment framework for repowered solar PV–BESSs.

2.1. Conceptual Framework for Solar PV Repowering

As introduced earlier, repowering is defined as the enhancement in generation capability at relatively older solar projects through technological upgrades, installation of higher-efficiency modules, or expansion of DC capacity without significant modification to land footprint or transmission infrastructure [55,58]. To reflect real-world deployment scenarios, repowering can be conceptualized along two pathways: repowering up to the PPA limit and repowering up to the technical limit. Both approaches are detailed in the following subsections.

2.1.1. Repowering up to PPA Limit

In India, utility-scale solar PV projects typically operate under PPAs at a fixed tariff for 25 years [59,61]. These tariffs are determined through competitive bidding by off-takers such as the Solar Energy Corporation of India (SECI), NTPC Vidyut Vyapar Nigam (NVVN), and Discoms, and the PPAs specify upper and lower energy supply limits expressed as the equivalent capacity utilization factor (CUF). Energy delivered within this range qualifies for the contracted tariff; energy generation beyond these limits generally lacks regulatory provisions for compensation or banking [62].

During early operation, most utility-scale solar PV projects meet or slightly exceed the contracted PPA limits. However, over time, module degradation and other performance losses lead to gradual underperformance relative to contractual benchmarks [55,58]. Repowering under the PPA limit focuses on restoring the plant's energy output by augmenting DC capacity behind existing inverters, thereby achieving the target CUF without substantial modifications to the balance-of-system infrastructure or grid interconnection. This approach improves asset utilization while remaining compliant with contractual frameworks.

2.1.2. Repowering up to Technical Limit

Modern inverters can typically handle DC overloading up to approximately 70% [63–65], enabling the addition of modules and increased energy output without inverter replacement [64,65]. Repowering to this technical limit allows generation beyond the capacity utilization factor specified in the PPA while continuing to use existing balance-of-system components. The optimal overloading level is site-specific, influenced by available land, solar irradiance, ambient temperature, and inverter clipping losses [58,65–67]. Simulation studies using PVsyst for a representative 10 MW utility-scale plant in Jodhpur indicate that inverter clipping becomes significant beyond 50% overloading [58], particularly under high irradiation and desert temperature conditions. The AC-based capacity utilization factor rises with overloading up to approximately 50% but further increases lead to diminishing returns in the DC-based capacity utilization factor due to clipping losses. For both repowering pathways, the repowering potential can be estimated using either a generation-based or a capacity-based approach, as described in the following sections.

2.1.3. Generation-Based Approach

The generation-based method quantifies repowering potential by comparing the contracted energy under the PPA with the actual energy generated over a defined period. The resulting difference represents the energy performance gap arising from module degradation, system losses, curtailment, and other operational constraints. This approach focuses on deviations in energy yield rather than changes in installed capacity. Figure 3a illustrates a stepwise procedure to estimate the additional solar capacity required by comparing actual generation with PPA-based energy expectations and accounting for site-specific performance conditions. The contracted annual energy (E_PPA,max) is derived from the agreed CUF and installed AC capacity over annual operating hours. The energy gap (ΔE = E_PPA, max − E_actual) is then computed, and the additional DC capacity (ΔP_DC) required to close this gap is estimated using site-specific performance parameters such as the CUF, performance ratio, or specific yield, depending on data availability.

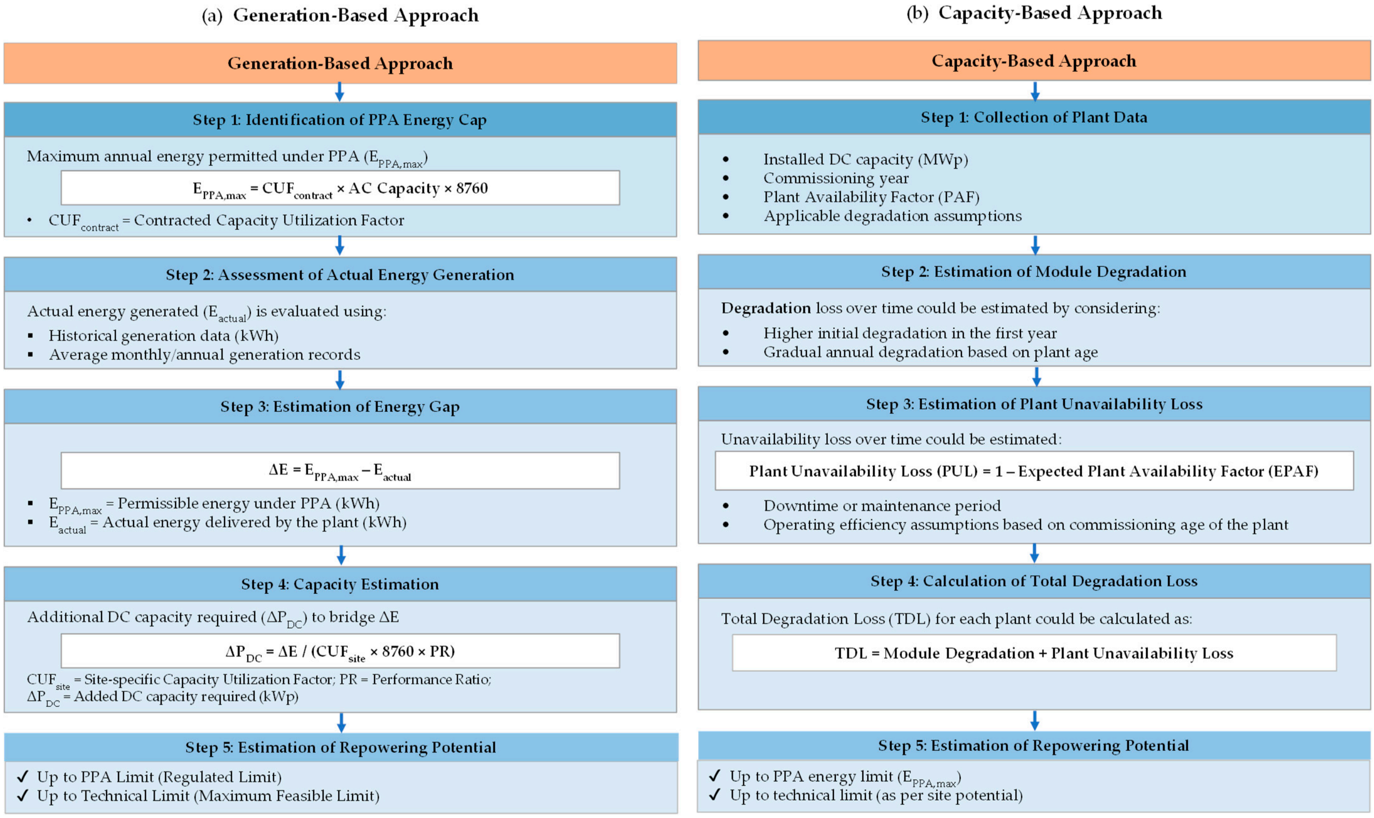


Figure 3. Conceptual framework for solar PV repowering: (**a**) generation-based and (**b**) capacity-based approach.

2.1.4. Capacity-Based Approach

The capacity-based method estimates repowering potential by analyzing the installed DC capacity of operational photovoltaic plants and quantifying the effective loss of usable capacity due to module degradation and plant unavailability. This approach relies primarily on technical performance parameters and standardized degradation assumptions rather than historical generation data, enabling a scalable and consistent framework suitable for large-scale aggregation studies. Figure 3b presents a stepwise procedure in which plant-level data, including installed DC capacity, commissioning year, and availability metrics, are first compiled. Module degradation is then estimated using standard degradation rates, followed by plant unavailability losses derived from the plant availability factor (PUL = 1 − EPAF). These components are combined into a defined aggregate loss index representing total effective capacity loss, from which repowering potential is evaluated with respect to both contractual PPA constraints and maximum technical feasibility limits.

This approach does not require actual energy shortfalls but remains sensitive to operational variability. Thus, estimating repowering potential through a generation-based approach has limitations regarding the availability and quality of project-wise continuous energy generation data, as well as specific project design details. Furthermore, generation data for Indian utility-scale solar projects are often treated as commercially sensitive and rarely disclosed publicly, making the capacity-based approach more feasible for national-scale assessments. On the other hand, the capacity-based method provides a more stable and conservative estimate of recoverable capacity loss (Table 1). In view of the above, this study adopts the capacity-based approach due to its methodological consistency, reduced dependence on short-term operational fluctuations, and suitability for national-scale assessment of solar repowering potential. To empirically validate this methodological choice, the capacity-based approach was cross-verified against a generation-based method using actual metered performance data from four representative utility-scale solar projects commissioned under India's National Solar Mission (Phase I, Batch II). As detailed in Appendix B, this validation exercise confirms that the capacity-based method yields conservative yet structurally consistent estimates relative to generation-based assessments, thereby supporting its robustness for national-scale aggregation.

Table 1. Comparative assessment of the generation-based and capacity-based approaches.

Aspect	Generation-Based Approach	Capacity-Based Approach
Primary basis	Energy gap between PPA-permitted energy and actual generation	Installed DC capacity adjusted for degradation and availability losses
Data requirement	Detailed historical generation data	Installed capacity, commissioning year, degradation rates, availability factors
Dependence on operational conditions	High (affected by curtailment, dispatch, grid outages)	Low (based on technical aging and contractual availability norms)
Sensitivity to market and/or regulatory factors	Influenced by scheduling and grid restrictions	Largely independent of market-driven variability
Data availability in India	Low—relies on confidential plant-level generation data often inaccessible	High—uses publicly available data on capacity, age, and standard parameters
Scalability	Limited where project-level data are unavailable	Highly scalable for regional or national aggregation
Strength	Reflects actual performance gap	Technically consistent, uniform, conservative
Limitation	Data-intensive, sensitive to external factors	Relies on assumed degradation rates and standard parameters

2.2. Techno-Economic Assessment Framework for Repowered Solar PV–BESS

A techno-economic assessment is conducted to evaluate the financial viability of augmenting existing utility-scale solar photovoltaic projects through incremental DC-side capacity additions, with particular emphasis on integration with the grid-tied BESS. The framework assesses cost-effectiveness, revenue potential, and environmental benefits of repowered solar assets, providing insights relevant to investors, utilities, and policymakers. Key techno-economic indicators, including the levelized cost of electricity for repowered systems (LCOE_R) and the levelized cost of storage (LCOS), are used to quantify overall system performance. In addition to levelized cost metrics, the financial viability of repowered solar integrated with the BESS is evaluated under an energy arbitrage configuration, where excess solar generation during periods of high irradiance is used to charge the storage system, which is subsequently discharged during peak demand periods.

Financial performance is further assessed using discounted cash flow-based indicators, including the NPV, IRR, and discounted payback period. These metrics incorporate capital expenditure, operating costs, energy yield, storage efficiency losses, and revenue streams based on peak and off-peak tariff differentials. In addition, the environmental benefits of repowered solar coupled with the BESS are estimated in terms of avoided emissions resulting from the displacement of marginal coal-based generation during peak demand periods, using grid emission factors and marginal generation assumptions. A schematic representation of the stepwise methodology is presented in Figure 4, while the mathematical formulations used for the economic and environmental indicators are provided in Appendix A.

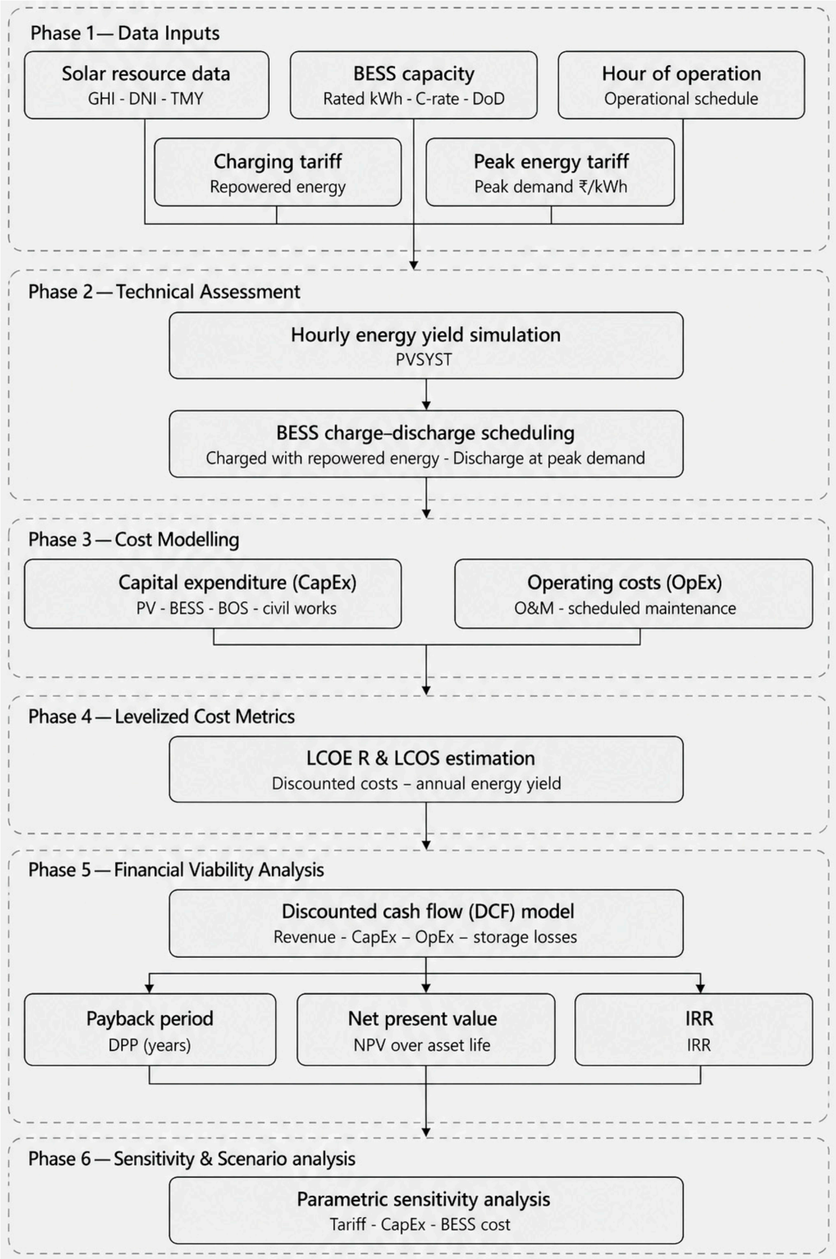


Figure 4. A schematic of methodological framework adopted for techno-economic assessment of solar PV–BESS.

It is worth mentioning that, in the present study, the BESS is designed to operate exclusively with surplus energy generated from the repowered solar PV plant. The battery is charged during daytime hours using repowered solar generation and discharged during morning and evening peak demand periods to maximize energy arbitrage benefits. Consequently, the operation of the BESS is constrained by the availability and temporal profile of repowered solar energy. This constraint is central to the analysis, distinguishing it from studies where the BESS may be charged from grid electricity [68–70]. The present analysis focuses on energy arbitrage using surplus repowered solar generation, as this represents the most immediate and policy-relevant application under current Indian market conditions. Ancillary services and capacity market participation, which would require distinct operational strategies and regulatory frameworks, are not considered in this analysis. Thus, ancillary services, capacity markets, and other grid support functions have not been considered in this study, as these applications typically require operational flexibility, rapid response capability, and charging from multiple energy sources, including the grid, to maintain the required state of charge.

3. Results

This section presents the results of the multi-dimensional assessment of solar repowering, structured into three main components: (i) the national repowering potential of utility-scale solar PV projects, (ii) operational and financial performance of repowered solar energy integrated with a BESS, and (iii) greenhouse gas emission reduction potential. All results are derived using the frameworks and methodologies described in Section 2, integrating technical, financial, and environmental parameters to provide a comprehensive evaluation of the feasibility and long-term implications of solar repowering in India.

3.1. Potential of Repowering of Utility-Scale Solar Projects in India

The repowering potential of India's operational utility-scale solar capacity was estimated using the methodologies outlined in Section 2. Table 2 summarizes the annual and cumulative repowering potential. The results indicate that the total repowering potential under existing PPA conditions is approximately 7.2 GWp, whereas the technical feasibility assessment suggests a higher potential of 10.9 GWp. These national estimates are derived using the validated capacity-based framework. As demonstrated in Appendix B, a project-level comparison against actual generation data confirms that these figures represent robust, conservative lower-bound estimates of India's repowering potential. The divergence between contractual and technical potentials highlights substantial latent capacity within existing solar assets. Repowering up to PPA limits enables continued energy export under existing agreements, while incremental generation beyond these limits can be directed to BESS charging, thereby improving asset utilization without requiring additional land or major transmission upgrades.

Table 2. Installed capacity-wise annual repowering potential in India.

Year	Annual AC Capacity (MW)	Cumulative AC Capacity (MW)	Repowering Potential (MWp)—PPA Limit	Repowering Potential (MWp)—Technical Limit
2010–2011	185	185	30	102
2011–2012	919	1105	149	460
2012–2013	1110	2215	180	500
2013–2014	864	3079	139	346
2014–2015	1719	4798	264	602
2015–2016	4604	9402	692	1381
2016–2017	8452	17,854	1080	2536
2017–2018	6481	24,335	825	1296
2018–2019	7191	31,526	817	1079
2019–2020	2741	34,266	291	274
2020–2021	7535	41,802	680	377
2021–2022	11,849	53,651	836	592
2022–2023	5286	58,937	310	264
2023–2024	12,730	71,667	592	637
2024–2025	9344	81,011	319	467
Total			7.2 GWp	10.9 GWp

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Table 3 presents the state-wise assessment of utility-scale solar PV repowering potential in India up to FY 2024–2025. The results reveal that Karnataka and Rajasthan possess the highest repowering potential, jointly accounting for a significant share of the national opportunity due to their large installed solar capacity bases. Other major contributors include Andhra Pradesh, Tamil Nadu, Telangana, and Gujarat, reflecting the concentration of utility-scale solar deployment in these states.

Table 3. State-wise repowering potential of utility-scale solar PV installations in India up to FY 2024–2025.

S. No.	State/UT	Installed AC Capacity (MW) Up to FY 2024–2025	DC Capacity (MWp)	Eligible for Repowering (DC, MWp)	Repowering Potential—PPA Limit (MWp)	Repowering Potential—Tech. Limit (MWp)
1	Karnataka	7377.22	10,328.108	10,328.108	1401.48	2121.68
2	Rajasthan	6557.055	9179.877	9179.877	1245.67	1885.80
3	Andhra Pradesh	4178.21	5849.494	5849.494	793.75	1201.65
4	Tamil Nadu	4002.63	5603.682	5603.682	760.39	1151.15
5	Telangana	3615.98	5062.372	5062.372	686.94	1039.95
6	Gujarat	3429.008	4800.611	4800.611	651.42	986.18
7	Madhya Pradesh	2500.995	3501.393	3501.393	475.12	719.28
8	Maharashtra	1938.847	2714.386	2714.386	368.33	557.61
9	Uttar Pradesh	1794.60	2512.44	2512.44	340.93	516.13
10	Punjab	929.827	1301.758	1301.758	176.64	267.42
11	Odisha	486.50	681.10	681.10	92.42	139.92
12	Chhattisgarh	250.65	350.91	350.91	47.62	72.09
13	Uttarakhand	225.394	315.552	315.552	42.82	64.82
14	Haryana	139.807	195.73	195.73	26.56	40.21
15	Kerala	132.20	185.08	185.08	25.11	38.02
16	West Bengal	125.25	175.35	175.35	23.79	36.02
17	Bihar	106.00	148.40	148.40	20.14	30.49
18	Assam	37.00	51.80	51.80	7.03	10.64
19	Jharkhand	24.00	33.60	33.60	4.56	6.90
20	Himachal Pradesh	14.00	19.60	19.60	2.66	4.03
21	Daman & Diu	12.135	16.989	16.989	2.31	3.49
22	Delhi	8.50	11.90	11.90	1.61	2.44
23	Andaman & Nicobar	5.00	7.00	7.00	0.95	1.44
24	Tripura	5.00	7.00	7.00	0.95	1.44
25	Dadar & Nagar Haveli	3.15	4.41	4.41	0.60	0.91
26	Goa	1.00	1.40	1.40	0.19	0.29
	Total	37,899.958	53,059.941	53,059.941	7200.00	10,900.00

3.2. LCOE Estimation for Repowered Energy and BESS

Table 4 summarizes the key assumptions used to calculate the LCOE for a 100 MW repowered plant. It assumes a capital cost of ₹17.5 million /MW, with annual operating costs set at 1.5% of CAPEX [58]. The plant is expected to operate for 25 years with a CUF of 22%, reflecting moderate usage levels. Further details are provided in Table 4.

Table 5 presents the key technical and financial assumptions used for the LCOS and economic assessment of a grid-scale battery energy storage system (BESS). The system is assumed to have an energy capacity of 1 GWh with a selected storage duration (2–6 h), a round-trip efficiency of 90%, and a depth of discharge of 90% [68–70]. The system is designed for a cycle life of up to 12,000 cycles, although this constraint is not binding within the assumed project lifetime.

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Table 4. Input parameters used in the LCOE of repowered energy [58].

Parameter	Unit	Value
Capacity of Plant	MW	100
CAPEX	Million ₹/MW	17.5
Total CAPEX	Million ₹	1750
OPEX	% of CAPEX	1.5
Annual OPEX	Million ₹	26.25
Debt	% of CAPEX	70
Equity	% of CAPEX	30
Years of Operation	Years	25
Interest on Debt	%	8
Return on Equity	%	14
WACC	%	9.8
CUF of Plant	%	22

Table 5. Input parameters used in the LCOS and financial assessment of the BESS [40,68–71].

Category	Particulars	Unit	Value
Technical	Battery Energy Capacity	GWh	1
	Storage Duration	h	2, 4, 6
	Efficiency	%	90%
	Depth of Discharge (DOD)	%	90%
	Maximum No. of Cycles before Replacement	No's	12,000
	BESS Year-on-Year Energy Degradation	%	1.00%
	BESS Degradation Start Year	Year	07
	BESS Annual Availability	%	100%
Financial	BESS Cost for 2 h Battery	₹ * Million/MWh	10
	Cost Factor ± (2 h, 4 h, 6 h)		1.00, 0.85, 0.73
	1st Year OPEX	%	1.0%
	YoY OPEX Escalation	%	0.82%
	Debt	%	70.0%
	Debt Interest Rate	%	8%
	Debt Tenure †	Years	12
	Equity	%	30.0%
	Return on Equity	%	14.0%
	Life of BESS (years)	No's	33
	Y-o-Y RE Charging Cost Increase	%	0.0%
	Avg. Growth of Electricity Market Prices	%	0.0%
	Working Capital Duration	Months	12
	Weighted Average Cost of Capital (WACC)	%	9.8%
	Tariff in Peak Load Time	₹ *	10

* 1 USD = ₹89.96 as on 1 January 2026. † The 12-year period denotes the debt tenure used in the project financing structure. The techno-economic analysis (including LCOE, LCOS, NPV, and IRR) is conducted over a full 33-year project lifetime, which is consistent with the BESS operational lifespan assumed for the environmental assessment in Section 3.4. ± Cost factors represent the reduction in power-related component costs (inverters, transformers, BOS) as storage duration increases, reflecting lower power capacity requirements for the same energy capacity.

An annual degradation rate of 1% is considered from mid-life onwards, with full system availability assumed for modeling simplicity. On the financial side, the analysis assumes a capital cost of ₹10 Million/MWh (for 2 h storage), with an initial OPEX at 1% of CAPEX and an annual escalation of 0.82%. The project is financed with a 70% debt and 30% equity structure, an 8% cost of debt, and a 14% return on equity, resulting in a weighted average cost of capital (WACC) of 9.8%. The BESS cost was assumed to decrease with increasing storage duration due to economies of scale, inverter capacity and BoS change w.r.t. storage duration hours. Thus, a cost factor of 1.00, 0.85, and 0.73 has been considered for 2 h, 4 h, and 6 h storage systems.

The project is evaluated over a 33-year operational lifetime, consistent with the BESS degradation and emission reduction framework described in Section 3.4. The financial analysis assumes a 70:30 debt-to-equity financing structure with a 12-year debt tenure [54], reflecting prevailing financing practices for utility-scale energy storage projects in India. The weighted average cost of capital (WACC) is estimated at 9.8% [68], based on an 8% return on debt and a 14% return on equity [68]. A peak electricity tariff of ₹10/kWh, corresponding to the price ceiling established by the Central Electricity Regulatory Commission (CERC) for the Green Day-Ahead Market (GDAM) [71], is adopted for revenue estimation. The BESS is assumed to operate with one full charge–discharge cycle per day, constrained by the daily availability of repowered solar generation. To provide a conservative financial assessment, annual escalation rates for both charging costs and electricity market prices are assumed to be zero. The complete set of financial assumptions is summarized in Table 5.

Considering the parameter values mentioned in the above table, repowered LCOE has been estimated at ₹1.40/kWh for a 25-year operation, reflecting the economic advantage of extending the operational life of repowered assets. Compared to current utility-scale solar tariffs in India (₹2.50–3.50/kWh; Figure S2), repowering demonstrates strong economic viability. The levelized cost of delivered energy from a 1 GWh BESS, charged with repowered solar energy (₹1.40/kWh), was estimated for storage durations of 2, 4, and 6 h (Table 5).

Longer-duration BESS configurations exhibit lower delivered LCOS due to the reduced inverter and balance-of-system (BOS) requirements per unit of stored energy. This trend is consistent with observed BESS tender tariffs in India, although many tenders reflect combined renewable energy and BESS operations rather than dedicated integration with solar repowering. The analysis presented here assumes a single daily cycle, with charging during peak solar generation hours and discharging during the evening or next-day morning peak demand period. Table 6 summarizes the levelized cost of storage (LCOS) for the evaluated BESS configurations.

Table 6. Levelized cost of storage (LCOS).

Storage Duration (h)	Total CAPEX (₹Crore)	Power Capacity (MW)	LCOS (₹/kWh)
2	1000	500	5.08
4	850	250	4.60
6	730	167	4.12

3.3. Financial Assessment of BESS Using Repowered Energy

Longer-duration storage systems demonstrate higher NPV and IRR, along with shorter payback periods, confirming the financial viability of repowering-based BESSs under an assumed peak electricity price of ₹10/kWh. As an example, the positive project NPV of ₹642 Cr at a discount rate (WACC) of 9.80% indicates that the project is expected to generate returns significantly higher than its overall cost of capital over the project lifetime. Positive NPV implies that, after recovering the total project investment of ₹1000 Cr and meeting the required return expectations of lenders and investors, the project is still capable of creating an additional economic value of ₹642 Cr. This reflects the strong long-term profitability and financial sustainability of the project.

Furthermore, longer-duration systems enhance flexibility in energy dispatch, allowing better alignment with peak demand and renewable energy availability, which not only improves financial returns but also maximizes the decarbonization potential of the power system. It is important to note that the comparative performance of different storage durations is conditional on the assumption of a single daily cycle and on the specific

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application of energy arbitrage under a ₹10/kWh peak tariff environment; these results should not be interpreted as universally applicable across all market designs or use cases. Table 7 summarizes the key financial indicators for BESS configurations with varying storage durations.

Table 7. Financial performance indicators for repowered BESSs.

Storage Duration (h)	CAPEX (₹Cr)	NPV (₹Cr)	Internal Rate of Return (IRR, %)	Discounted Payback (Years)
2	1000	642	17.49%	8.3
4	850	785	20.70%	6.6
6	730	900	24.18%	5.4

3.4. GHG Emission Reduction Potential

The greenhouse gas (GHG) mitigation potential of the repowering-based BESS was assessed based on the displacement of coal-fired generation. For an installed repowering capacity of approximately 11 GWp and a CUF of 22%, the annual energy available for BESS charging is estimated at 21.2 TWh. After accounting for round-trip efficiency losses (90% efficiency), the effective usable energy is about 19.1 TWh per year. Assuming a coal emission factor of 0.9 tCO_2/MWh [72], the corresponding avoided emissions are approximately 17.2 $MtCO_2$ annually, which is equivalent to 47 $ktCO_2$ per day. Using the national grid emission factor of 0.724 tCO_2/MWh (as per CEA's CO_2 Baseline Database for the Indian Power Sector [73]) yields a more conservative estimate of 13.8 $MtCO_2$ annually.

The coal displacement scenario (0.9 tCO_2/MWh) represents the high-end estimate, applicable when stored renewable energy displaces coal-based generation during peak demand periods. The grid-average scenario (0.724 tCO_2/MWh) provides a more conservative estimate based on the national generation mix. Actual emission reductions depend on the marginal generation source displaced in each region and hour. India's Western and Eastern regions, where coal comprises a larger share of generation during peak hours, would approach the coal displacement scenario more closely, while Southern and Northern regions with greater renewable penetration would be nearer the grid-average estimate.

The BESS considered in this study has an operational lifetime of 33 years. During the first seven years of operation, the system is assumed to operate without performance degradation, contributing annual reductions of approximately 17.2 $MtCO_2$ (or 13.8 $MtCO_2$ under the grid-average factor).

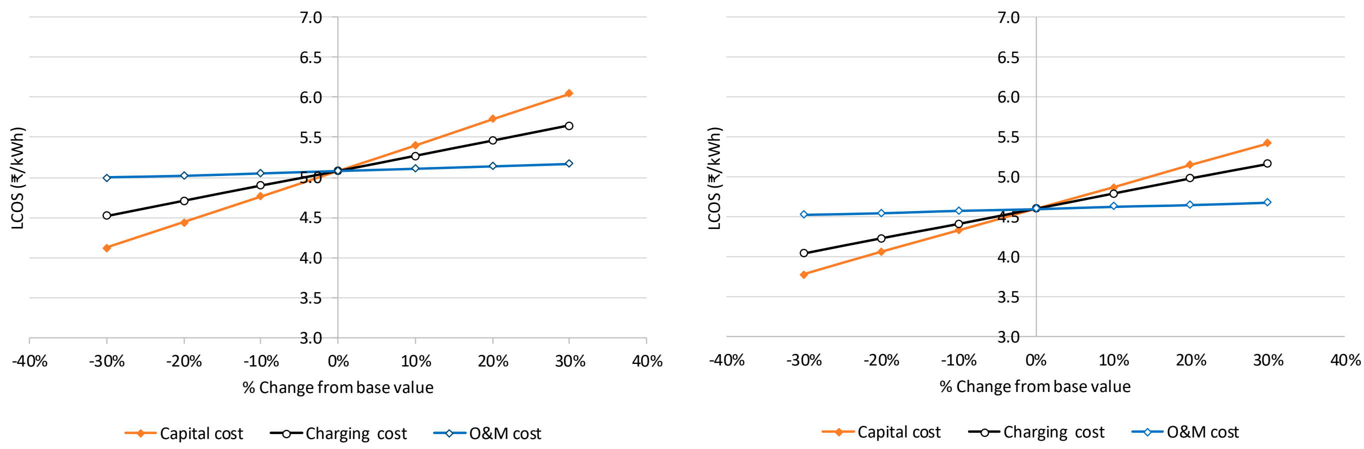
From the eighth year onward, the BESS is assumed to degrade at a rate of 1% per year. Consequently, the annual CO_2 emission reduction capability also decreases by 1% each year relative to the previous year. For example, the emission reduction in the eighth year becomes 99% of the annual value, and this degradation continues progressively until the 33rd year of operation. Considering this degradation profile, the cumulative CO_2 emission reduction achieved over the entire 33-year operational lifetime of the BESS is estimated to be approximately 512 $MtCO_2$ for the coal displacement scenario and approximately 411 $MtCO_2$ for the grid-average scenario. Actual emission reductions will depend on the marginal generation displaced across different regions and operating conditions.

These results indicate that the large-scale deployment of a repowering-based BESS can significantly mitigate emissions from peak coal generation while enabling more effective utilization of renewable energy during periods of high demand. By aligning energy storage operation with renewable availability and peak load, BESS deployment provides both decarbonization and system flexibility benefits.

3.5. Sensitivity Analysis

To assess the robustness of the techno-economic results, a sensitivity analysis was conducted on the key parameters driving the LCOS and overall financial performance of the BESS. The analysis focuses on the 2 h and 4 h configurations, as these are the most widely adopted for peak shaving and energy arbitrage applications. Although the base case techno-economic assessment includes 2 h, 4 h, and 6 h storage configurations, the 6 h system is excluded from the sensitivity analysis due to its limited deployment in the specific application context considered in this study. Longer-duration systems are typically associated with use cases beyond short-duration peak arbitrage and are therefore less representative of the operational focus of this work. Nevertheless, the qualitative sensitivity results derived from the 2 h and 4 h cases are expected to remain valid for the 6 h configuration, as the relative influence of capital expenditure, charging cost, and O&M expenses is governed by consistent underlying cost structures and scaling relationships. In particular, capital cost remains the dominant driver of the LCOS, followed by charging energy cost and O&M expenses across all durations.

Figure 5 illustrates the sensitivity of the LCOS for 2 h and 4 h storage systems to variations in capital cost, charging cost, and O&M cost, with each parameter varied within a ±30% range relative to the base case. This range is selected to reflect typical uncertainty bounds reported in recent utility-scale battery storage cost projections by the National Renewable Energy Laboratory (NREL) and the International Renewable Energy Agency (IRENA) [40,49]. The analysis highlights the relative influence of key cost components on lifecycle storage economics and provides insights into the primary drivers of project viability.



(**a**) 2 h of storage (**b**) 4 h of storage

Figure 5. Sensitivity of LCOS to capital cost, charging cost, and O&M cost for (**a**) 2 h and (**b**) 4 h BESS configurations.

The baseline LCOS for the 2 h system is ₹5.08/kWh, while the 4 h system has a lower baseline of ₹4.60/kWh, indicating that longer-duration storage achieves higher economic performance due to improved utilization of inverter and balance-of-system components. Across both configurations, capital cost emerges as the dominant sensitivity driver. For the 2 h system (Figure 5a), a ±30% variation in capital cost changes the LCOS from ₹4.12 to ₹6.05/kWh. For the 4 h system (Figure 5b), the same variation shifts the LCOS from ₹3.78 to ₹5.42/kWh. The pronounced slope of the capital cost response highlights that upfront investment including battery pack prices, inverter costs, balance-of-system components, installation, and financing terms governs lifecycle economics. Accordingly, reductions in capital expenditure translate directly into lower delivered cost of storage.

Charging costs represent the second most important factor. For the 2 h configuration, a ±30% variation in charging cost moves the LCOS between ₹4.52 and ₹5.82/kWh; similar behavior is observed for the 4 h system. Higher charging cost increases the operational expense of energy procurement, raising the delivered cost of storage. This result highlights the critical role of electricity tariff design and access to low-cost renewable energy. In particular, charging from repowered solar generation (LCOER = ₹1.40/kWh) significantly improves storage economics relative to scenarios relying on grid electricity or higher-cost generation sources.

In contrast, O&M costs have a negligible impact on the LCOS for both configurations. Even a ±30% variation results in changes of less than ₹0.05/kWh, confirming that O&M expenses constitute a minor share of the total lifecycle costs relative to capital and charging expenditures. The near-flat sensitivity curve further indicates that routine operational costs do not materially affect the economic feasibility of the storage system.

Figure S3 in the SI presents the sensitivity of the IRR to variations in the charging cost and selling price (i.e., discharge tariff) for both storage configurations under the energy arbitrage application. For the 2 h system, as the charging cost varies from −30% to +30%, the IRR decreases from 18.6% to 16.3%, showing that higher charging cost moderately reduces profitability. Conversely, over the same variation range in the selling price, the IRR increases sharply from 10.5% to 24.0%. This demonstrates that project returns are far more sensitive to the discharge electricity price than to the charging cost. For the 4 h system, a ±30% change in the charging cost moves the IRR from 22.0% to 19.4%, while a ±30% variation in the selling price shifts the IRR from 12.8% to 28.3%. The higher absolute IRR values for the 4 h system reflect improved revenue generation from better alignment with peak price differentials and enhanced energy-shifting capability.

Overall, the sensitivity analysis confirms that the selling price is the dominant driver of the IRR for BESS projects, while the charging cost has a comparatively moderate impact. The 4 h configuration consistently outperforms the 2 h system, exhibiting higher returns and greater resilience to market variability. These findings underline the importance of peak tariff levels and storage duration in determining the financial attractiveness of repowering-based BESS projects.

4. Discussion

The integration of a BESS with repowered utility-scale solar PV projects presents a technically feasible and economically attractive pathway for enhancing renewable energy utilization in India. Unlike conventional solar-plus-storage configurations that rely on newly developed PV capacity, the framework proposed in this study leverages low-cost electricity generated through repowering existing solar assets. This creates a unique synergy by simultaneously improving asset productivity, reducing charging energy costs, and maximizing the utilization of existing land and transmission infrastructure. The findings thereby extend the existing literature, which has generally evaluated repowering and energy storage independently, by establishing a direct techno-economic linkage between these two strategies [53–58].

4.1. National Repowering Opportunity

A key outcome of the analysis is the identification of a substantial national repowering opportunity. The estimated potential of approximately 7.2 GWp under existing PPA constraints and 10.9 GWp under technical limits suggests that significant additional renewable generation can be unlocked without requiring new land acquisition or major transmission expansion. These findings are consistent with international assessments that identify repowering as an effective strategy for extending asset life, improving energy yield, and maximizing the utilization of existing grid infrastructure [53–58]. Recent studies from Europe and the United States similarly indicate that repowering aging solar facilities can increase generation capacity by 20–80% while reducing development timelines and environmental impacts relative to greenfield projects [73,74]. Such findings reinforce the importance of repowering as a resource efficiency strategy within rapidly expanding renewable energy systems.

4.2. Economic Performance and Cost Competitiveness

The economic significance of this integration is reflected in the estimated LCOE of repowered energy at approximately ₹1.40/kWh. While this value depends on assumptions regarding capital costs, module performance, and financing conditions, the result indicates that repowered electricity can be supplied at a cost substantially lower than many recent utility-scale solar procurement prices in India (₹2.50–3.50/kWh, Figure S2). This cost advantage is primarily attributable to the reuse of existing land, evacuation infrastructure, permitting approvals, and balance-of-system components, thereby reducing the overall capital requirements [55–58]. Similar conclusions have been reported by the NREL [75] and Fraunhofer ISE [76], which found that infrastructure reuse is one of the principal economic drivers supporting solar repowering projects. The low charging cost achieved through repowering directly benefits storage economics, as charging energy represents a significant component of the LCOS [40,49–51].

The LCOS values obtained in this study, ranging from ₹5.08/kWh for 2 h storage systems to ₹4.12/kWh for 6 h systems, indicate that longer-duration storage configurations provide superior economic performance under the assumed operating conditions. This trend is consistent with findings reported by the IRENA [40], NREL [49], Migliari et al. [50], and the latest Lazard Levelized Cost of Storage analysis [77], all of which identify asset utilization and charging cost as key determinants of storage competitiveness. Longer-duration systems distribute capital expenditures over greater energy throughput, thereby reducing unit storage costs and increasing operational flexibility. The results further suggest that low-cost charging energy obtained from repowered solar assets can partially offset the cost penalties traditionally associated with longer-duration storage technologies, thereby improving their competitiveness in renewable-dominated power systems.

4.3. Financial Viability and Sensitivity Analysis

The financial analysis demonstrates that repowering-based BESS configurations can generate attractive investment returns under an energy arbitrage business model. Internal rates of return ranging from approximately 17.5% to 24.2% and positive NPV across all evaluated storage durations indicate that the proposed configuration can be commercially viable under favorable peak–off-peak price differentials. These findings are broadly consistent with previous studies showing that storage profitability is strongly influenced by electricity price spreads and utilization rates [40,52,60]. The superior performance of the 4 h and 6 h storage systems reflect their greater ability to shift renewable generation from periods of surplus production to periods of peak demand, thereby maximizing arbitrage opportunities.

The sensitivity analysis provides further insight into the factors governing project performance. Capital expenditure was identified as the dominant determinant of the LCOS, followed by charging energy cost, whereas operation and maintenance expenditures exhibited comparatively limited influence. These findings align closely with previous storage cost studies that identify battery capital costs as the largest contributor to lifecycle storage economics [40,49–51]. Similar conclusions are reported in the latest NREL Annual Technology Baseline [73], which projects that future reductions in battery capital costs will remain the most important driver of declining storage costs. The results also demonstrate that project profitability is considerably more sensitive to electricity selling prices than to charging cost (Figure S3), highlighting the growing importance of electricity market design and tariff structures in determining storage investment attractiveness. As India expands real-time markets, ancillary service mechanisms, and time-of-day pricing frameworks, storage revenues are likely to become increasingly dependent on dynamic market signals rather than fixed contractual tariffs [42,44]. Although the 6 h configuration is not included in the sensitivity analysis, the qualitative relationships between the capital cost, charging cost, and LCOS are expected to remain consistent, as the underlying cost structure scales with the duration-dependent cost factors described in Section 3.2.

4.4. Power System and Environmental Implications

From a power system perspective, the proposed approach offers advantages beyond direct economic returns. Increasing shares of variable renewable energy create growing requirements for flexibility resources capable of balancing fluctuations in generation and demand [44–46]. According to the IEA Electricity 2025 report [74], battery storage is expected to become one of the fastest-growing flexibility resources globally due to its ability to provide energy-shifting, frequency regulation, and reserve services. Repowered solar assets coupled with storage can contribute to these objectives by reducing renewable curtailment, improving the utilization of existing infrastructure, and shifting energy delivery toward peak demand periods. Such functionality is particularly relevant in India, where renewable energy capacity additions are accelerating rapidly while electricity demand continues to grow. The integration of repowering and storage therefore supports both renewable expansion and power system reliability objectives.

The environmental implications are also significant. The analysis indicates that approximately 17.2 MtCO_2 of annual emissions could potentially be avoided through the displacement of coal-based electricity generation under a coal displacement scenario (0.9 tCO_2/MWh), with a more conservative estimate of 13.8 MtCO_2 under the national grid-average emission factor (0.724 tCO_2/MWh). Cumulative lifetime reductions exceed 500 MtCO_2 and 400 MtCO_2, respectively, under the assumed battery degradation trajectory. These results are consistent with broader evidence indicating that energy storage can facilitate deeper decarbonization by increasing renewable energy utilization and reducing dependence on fossil fuel-based peaking generation [44,46]. The IRENA World Energy Transitions Outlook [78] identifies storage deployment as a critical enabler of high-renewable electricity systems and long-term decarbonization pathways. Although actual emission reductions will depend on the marginal generation source displaced across different regions and operating conditions, the estimated reductions demonstrate the potential contribution of repowering-based storage systems toward India's climate mitigation commitments and net zero transition objectives [1–8].

4.5. Policy Implications and Implementation Framework

The policy implications of this study are particularly important. Existing regulatory frameworks in India were largely designed around standalone renewable generation and may not adequately accommodate integrated repowering-plus-storage projects. Realizing the full potential identified in this study may therefore require regulatory reforms that facilitate repowering within existing PPAs, allow flexible utilization of surplus generation, and appropriately compensate storage for the multiple grid services it provides. Similar recommendations have been highlighted in recent IEA [74,78] and IRENA [79] policy assessments, which emphasize the need for market structures that recognize the system value of storage and flexibility resources.

A specific policy instrument that could operationalize these findings is a hybrid power purchase agreement (PPA) framework. Under this structure, the existing contracted capacity would continue to receive the fixed feed-in tariff stipulated in the original PPA, while incremental generation from repowering beyond the contracted entitlement would be remunerated through a separate, flexible mechanism. This surplus energy could be directed to charge co-located BESSs for peak-time discharge, sold in the Green Day-Ahead Market, or used to provide ancillary services where feasible. Implementation would require a phased regulatory approach: near-term enabling guidelines and accounting standards (1–2 years), medium-term standardized hybrid PPA templates with time-of-day tariff structures (3–5 years), and long-term evolution toward full market integration (>5 years). A regulatory sandbox to pilot hybrid PPA designs under controlled conditions would accelerate learning and support evidence-based policy development.

In addition to regulatory reforms, concessional financing, viability gap funding mechanisms, and domestic battery manufacturing support could further improve project economics and accelerate deployment. Such measures would not only improve renewable energy integration but also enhance energy security, reduce transmission expansion requirements, and contribute to broader sustainability objectives. While hybrid power purchase agreements are identified as a necessary policy enabler, their detailed contractual design—including tariff segmentation, risk allocation, and settlement protocols—falls outside the techno-economic scope of this study and would require state-specific operational frameworks to translate this economic potential into deployable policy.

4.6. Limitations and Future Research Directions

Despite these encouraging findings, several limitations should be acknowledged. First, the analysis employs a simplified energy arbitrage framework based on representative charging and discharging tariffs. Participation in ancillary service markets and capacity remuneration mechanisms is not considered, as these applications involve distinct operational requirements and market participation structures. Participation in ancillary service markets could generate additional revenues but would require different operational strategies (e.g., maintaining state of charge for rapid response) that are not compatible with the solar-charging constraint assumed here. Preliminary estimates from international markets suggest revenue stacking could improve IRRs by 2–5 percentage points, a finding that warrants investigation as Indian markets evolve. As India's ancillary services market matures, future research should evaluate revenue stacking models that could further improve project economics.

Second, the dispatch modeling assumes a simplified operating strategy of one full charge–discharge cycle per day. While this provides a consistent basis for comparing storage configurations, it does not capture the operational flexibility enabled by optimized dispatch strategies informed by hourly load variations. Future studies should incorporate chronological, hourly dispatch optimization using representative Indian load profiles to assess how alternative charging and discharging strategies influence storage economics and to more rigorously determine the optimal storage duration under realistic grid conditions.

Third, the analysis assumes fixed battery performance parameters, including cycle life, round-trip efficiency, and degradation rates, which may vary significantly across technologies and operational regimes. Fourth, the environmental assessment assumes the displacement of coal-dominated marginal generation; actual emissions reductions will depend on the marginal generation mix displaced, which varies across regions, time periods, and system operating conditions. Finally, the national repowering estimates are derived using a capacity-based approach that relies on generalized assumptions regarding degradation and plant availability, rather than plant-level operational data. Future research should incorporate plant-specific performance datasets, stochastic electricity price modeling, battery augmentation strategies, and probabilistic uncertainty analysis to enhance the robustness and realism of techno-economic assessments.

Overall, the findings indicate that solar PV repowering and battery energy storage should not be viewed as independent interventions but rather as complementary strategies for maximizing the value of existing renewable energy assets. By combining low-cost repowered generation with flexible energy storage, the proposed approach offers a scalable pathway for improving renewable energy utilization, enhancing grid flexibility, reducing greenhouse gas emissions, and supporting India's transition toward a more resilient, cost-effective, and low-carbon electricity system.

5. Conclusions

This study presents an integrated techno-economic and environmental assessment of integrating a BESS with repowered utility-scale solar PV projects in India. By establishing a direct linkage between solar repowering and battery storage economics, the analysis demonstrates that repowering existing solar assets can unlock substantial additional generation capacity while simultaneously providing a structurally low-cost charging source for a grid-tied BESS. This integrated approach enhances asset utilization without requiring additional land or major transmission expansion, enabling more effective use of existing grid infrastructure.

The analysis yields four principal findings. First, the national repowering potential is estimated at approximately 7.2 GWp under existing PPA constraints and 10.9 GWp under technical limits, representing a significant opportunity to enhance renewable generation capacity without greenfield development. Second, repowered solar energy offers a substantial cost advantage, with a levelized cost of ₹1.40/kWh, considerably lower than recent solar auction tariffs (₹2.50–3.50/kWh). When used to charge the BESS, the levelized cost of storage ranges from ₹4.12/kWh to ₹5.08/kWh, with longer storage durations showing lower costs due to improved capital utilization. Third, financial indicators, including the NPV and IRR (17.5–24.2%), highlight the robust economic viability of repowering-based BESS configurations under an assumed peak electricity price of ₹10/kWh. Fourth, the environmental analysis demonstrates substantial greenhouse gas reductions, with annual savings of 13.8–17.2 $MtCO_2$ and cumulative reductions of 411–514 $MtCO_2$ over the project lifetime, depending on the emission factor scenario.

The economic advantage of longer-duration BESS configurations arises primarily from lower power-related costs per unit of stored energy. However, this does not imply that 4 h or 6 h systems are universally optimal. The preferred storage duration depends on the specific application, grid conditions, and operational requirements. While 4 h systems provide the best economic performance for the peak shaving and energy arbitrage scenarios considered in this study, longer-duration systems (e.g., 6 h) may be more suitable for applications requiring extended energy supply, such as renewable firming, weak grid, or remote and power-deficient areas. Further research using chronological hourly dispatch optimization and representative Indian load profiles would provide additional insights into the optimal storage duration under real-world grid and market conditions.

From a policy perspective, these findings highlight the need for a regulatory framework that explicitly recognizes and incentivizes solar repowering alongside integrated storage deployment. India's extension of transmission charge waivers for energy storage projects until 2028 already aligns with this objective by reducing cost barriers and improving project bankability [80]. However, realizing the full investment potential of these technologies will require more comprehensive policy action.

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In particular, regulatory provisions are needed to enable repowering within existing PPAs, provide clear rules governing the use of surplus energy, and support the development of hybrid contracting models. A hybrid PPA framework, comprising a dual-component tariff structure where existing contracted capacity receives the fixed feed-in tariff while incremental generation is remunerated through a flexible mechanism, offers a practical pathway. Implementation would require phased regulatory pilots: near-term (1–2 years) enabling guidelines and accounting standards; medium-term (3–5 years) standardized hybrid PPA templates with time-of-day tariff structures; and long-term (>5 years) full market integration. These reforms could be advanced through phased regulatory pilots, followed by progressive standardization of hybrid tariff structures, and supported by viability gap funding mechanisms and streamlined approval processes. Recent policy developments, including emerging regulatory guidelines for battery energy storage systems, further indicate growing momentum toward strengthening grid stability and facilitating deeper renewable energy integration.

Coupled with tariff reforms that value flexibility, viability gap funding, and streamlined approval processes, these measures would support India's transition to a resilient, low-carbon power system. As India's ancillary services market and capacity mechanisms mature, future studies should evaluate revenue stacking models that incorporate frequency regulation, reserve provision, and capacity payments alongside energy arbitrage. Regulatory frameworks that enable access to multiple revenue streams while maintaining appropriate safeguards against market manipulation would further enhance the bankability of repowering-based storage projects.

The findings demonstrate that solar PV repowering and battery energy storage should not be viewed as independent interventions but rather as complementary strategies for maximizing the value of existing renewable energy assets. By combining low-cost repowered generation with flexible energy storage, the proposed approach offers a scalable pathway for improving renewable energy utilization, enhancing grid flexibility, reducing greenhouse gas emissions, and supporting India's transition toward a more resilient, cost-effective, and low-carbon electricity system. While further research is needed to refine dispatch optimization, incorporate revenue stacking models, and validate performance assumptions with plant-level data, the present study provides a robust foundation for policy development and investment decisions in India's evolving power sector.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18147455/s1, Figure S1: Trend in tendered energy storage capacity in India; Figure S2: Trend of average utility-scale solar PV tariffs in India (2010–2025); Figure S3. Sensitivity of IRR to charging cost and selling price for (a) 2-h and (b) 4-h BESS configurations; Table S1: Applications of Energy Storage Across Power System Segments; Table S2. Major Solar and BESS awarded tenders in India (2023–2025).

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Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery Energy Storage Systems
BOO	Build–Own–Operate
CAPEX	Capital Expenditure
CUF	Capacity Utilization Factor
DOD	Depth of Discharge
EPC	Engineering, Procurement, and Construction
GDAM	Green Day-Ahead Market
GHG	Greenhouse Gas
GWp	Gigawatt Peak
INR (₹)	Indian Rupee
IRR	Internal Rate of Return
KREDL	Karnataka Renewable Energy Development Limited
LCOE	Levelized Cost of Electricity
LCOE_R	Levelized Cost of Repowered Energy
LCOS	Levelized Cost of Storage
NHPC	National Hydroelectric Power Corporation
NPV	Net Present Value
NTPC	National Thermal Power Corporation
NVVN	NTPC Vidyut Vyapar Nigam
NSM	National Solar Mission
OPEX	Operating Expenditure
PPA	Power Purchase Agreement
PSH	Pumped Storage Hydropower
RUMSL	Rewa Ultra Mega Solar Limited
SECI	Solar Energy Corporation of India Limited
SJVN	Satluj Jal Vidyut Nigam Limited
WACC	Weighted Average Cost of Capital

Appendix A. Techno-Economic Framework

The levelized cost of repowered energy, $\mathrm{LCOE_R}$, is defined as the ratio of the discounted stream of incremental lifecycle costs to the discounted stream of annual energy output obtained from simulation over the residual project lifetime. The incremental lifecycle cost of repowered energy, $\mathrm{ILC_R}$, can be estimated as

$$ILC_R = \sum_{t=1}^{T} \frac{I_0 + \Omega_t}{(1+\kappa)^t} \quad \text{(A1)}$$

where I_0 represents the incremental capital investment required for DC-side repowering, κ denotes the discount rate (corresponding to the weighted average cost of capital, WACC), t is the year index over the residual project lifetime, and Ω_t represents the operation and maintenance (O&M) expenditure incurred in year t.

The annual energy output, AEO, can be estimated by using the following equation

$$AEO = \sum_{t=1}^{T} \frac{E_t}{(1+\kappa)^t} \quad \text{(A2)}$$

where E_t represents the annual net energy output in year t.

Therefore, the levelized cost of repowered energy, $LCOE_R$, is estimated as

$$LCOE_R = \sum_{t=1}^{T} \frac{I_0+\Omega_t}{(1+\kappa)^t} \Big/ \sum_{t=1}^{T} \frac{E_t}{(1+\kappa)^t} \quad \text{(A3)}$$

It is worth mentioning that the annual energy output has been derived from detailed technical modeling using PVSYST. This ensures that degradation losses, inverter clipping, temperature effects, and system losses are explicitly captured in the economic evaluation. Consequently, the estimated LCOER reflects both financial discounting and the site-specific technical performance of the repowered system. Financial parameters (CAPEX) were selected by taking cost break-up for a range of solar PV projects under implementation.

In the present analysis, the BESS is assumed to be charged using incremental energy generated from the repowered solar capacity during peak solar hours. The stored energy is subsequently discharged during peak demand periods to support peak power management. Therefore, to evaluate the economic feasibility of utilizing repowered solar electricity for peak shifting applications, the levelized cost of storage (LCOS) can be estimated as

$$LCOS = \sum_{t=1}^{N} \frac{C_0+O_t+\left(E_{ch,t}\times LCOE_R\right)}{(1+\mu)^t} \Big/ \sum_{t=1}^{N} \frac{E_{ch,t}\times\eta_{rt}}{(1+\mu)^t} \quad \text{(A4)}$$

where C_0 denotes the initial capital investment of the BESS, μ represents the discount rate corresponding to the weighted average cost of capital (WACC), and N indicates the operational lifetime of the storage system in years. The term O_t refers to the annual operation and maintenance expenditure incurred in year t, while $E_{ch,t}$ represents the quantity of electrical energy charged into the BESS during year t. The parameter $LCOE_R$ corresponds to the levelized cost of repowered solar electricity used as the charging source. The round-trip efficiency of the storage system is denoted by η_{rt}, which accounts for conversion losses during charging and discharging processes. Accordingly, the net discharged energy in year t is represented as $E_{ch,t} \times \eta_{rt}$, thereby explicitly incorporating storage efficiency losses into the economic assessment.

The discounted payback period (DPP) is defined as the time required for the cumulative discounted net cash flows to recover the initial capital investment.

$$\sum_{i=1}^{t} \frac{CF_i}{(1+\kappa)^i} = I_o \quad \text{(A5)}$$

where I_0 represents the total initial capital investment, κ denotes the discount rate corresponding to the weighted average cost of capital (WACC), and CF_i represents the net cash flow in year i. The net cash flow includes revenues from energy arbitrage, savings from peak power management, and operation and maintenance expenditures. The parameter "t" indicates the year in which the cumulative discounted cash flows become equal to the initial investment.

The net present value (NPV) is defined as the difference between the discounted stream of net cash flows and the initial capital investment over the project life.

$$\sum_{i=1}^{N} \frac{CF_t}{(1+\kappa)^t} - I_o \quad \text{(A6)}$$

where N denotes the project life in years, and CF_t represents the net cash flow in year t, incorporating revenues from peak tariff realization, energy arbitrage benefits, and associated operational costs. All other parameters retain their previously defined meanings.

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The internal rate of return (IRR) is defined as the discount rate at which the discounted stream of net cash flows becomes equal to the initial investment.

$$\sum_{i=1}^{N} \frac{CF_t}{(1+\kappa)^t} = I_o \quad \text{(A7)}$$

where κ represents the discount rate that satisfies the above condition, and CF_t denotes the net cash flow in year t. The IRR reflects the effective rate of return generated by the investment in repowered solar capacity integrated with the BESS.

The environmental benefits of repowered *Solar* + *BESS* are evaluated based on the displacement of marginal coal-based generation during peak demand periods. The cumulative GHG emission reduction over the project lifetime has been estimated as

$$GHG_{avoided} = \sum_{i=1}^{N} E_{dis,t} \times EF_{coal} \quad \text{(A8)}$$

where $E_{dis,t}$ represents the quantity of electricity discharged from the BESS during peak demand hours in year t. This discharged energy corresponds to the portion of stored repowered solar generation that is assumed to substitute marginal fossil-based electricity during high-demand intervals. The parameter EF_{coal} denotes the grid emission factor associated with coal-based electricity generation, expressed in terms of tons of CO_2 equivalent per megawatt hour (tCO_{2e}/MWh). This factor reflects the average carbon intensity of coal-dominated marginal generation within the grid and serves as the basis for estimating avoided emissions. N represents the operational lifetime of the project.

Appendix B. Validation of Capacity-Based Repowering Methodology

The manuscript estimates India's solar PV repowering potential using a capacity-based methodology that quantifies recoverable capacity losses arising from long-term module degradation and representative plant unavailability. This approach is adopted due to the absence of publicly accessible, plant-level metered generation data for the majority of India's utility-scale PV fleet, which are commercially confidential and therefore unavailable for national-scale analysis. An alternative generation-based methodology estimates repowering potential from the deviation between the contractual upper capacity utilization factor (CUF) specified in the power purchase agreement (PPA) and the observed plant CUF. This approach implicitly aggregates the effects of module degradation, soiling losses, grid curtailment, interannual irradiance variability, O&M downtime, and other operational constraints. Consequently, it typically yields higher repowering estimates, particularly for underperforming assets. However, its application at scale is limited by the availability of long-term, plant-level generation records.

To evaluate the robustness of the capacity-based formulation adopted in this study, both methodologies are applied to four representative utility-scale solar PV plants commissioned under Phase I (Batch II) of India's National Solar Mission (NSM). The comparison assesses whether the capacity-based approach provides conservative and internally consistent estimates of repowering potential relative to the generation-based method, and whether it is suitable for national-scale application. The validation dataset is drawn from a commercially procured proprietary database containing commissioning records, monthly generation profiles, and operational performance indicators. Due to confidentiality constraints, all projects are anonymized. The key characteristics of the dataset, along with observed annual CUFs for the financial years 2013–14 and 2014–15, are summarized in Table A1.

Table A1. Characteristics of validation projects and observed annual CUFs.

Project	State	AC Capacity (MW)	Commercial Operation Date (CoD)	PPA Upper CUF (%)	Average CUF FY 13–14 (%)	Average CUF FY 14–15 (%)
Plant A	Rajasthan	20	February 2012	24.5	21.25	21.60
Plant B	Rajasthan	20	February 2013	24.5	19.36	22.02
Plant C	Andhra Pradesh	20	April 2013	24.5	21.52	21.32
Plant D	Rajasthan	15	January 2013	24.5	23.71	23.48

The observed CUFs are consistently below the contractual ceiling (24.5%), reflecting a combination of structural and non-structural losses, including module degradation, soiling, grid curtailment, interannual resource variability, and O&M-related downtime. As shown in Figure A1, Plants A–C operate approximately 3–4 percentage points below the contractual limit, whereas Plant D operates close to the ceiling, within approximately one percentage point.

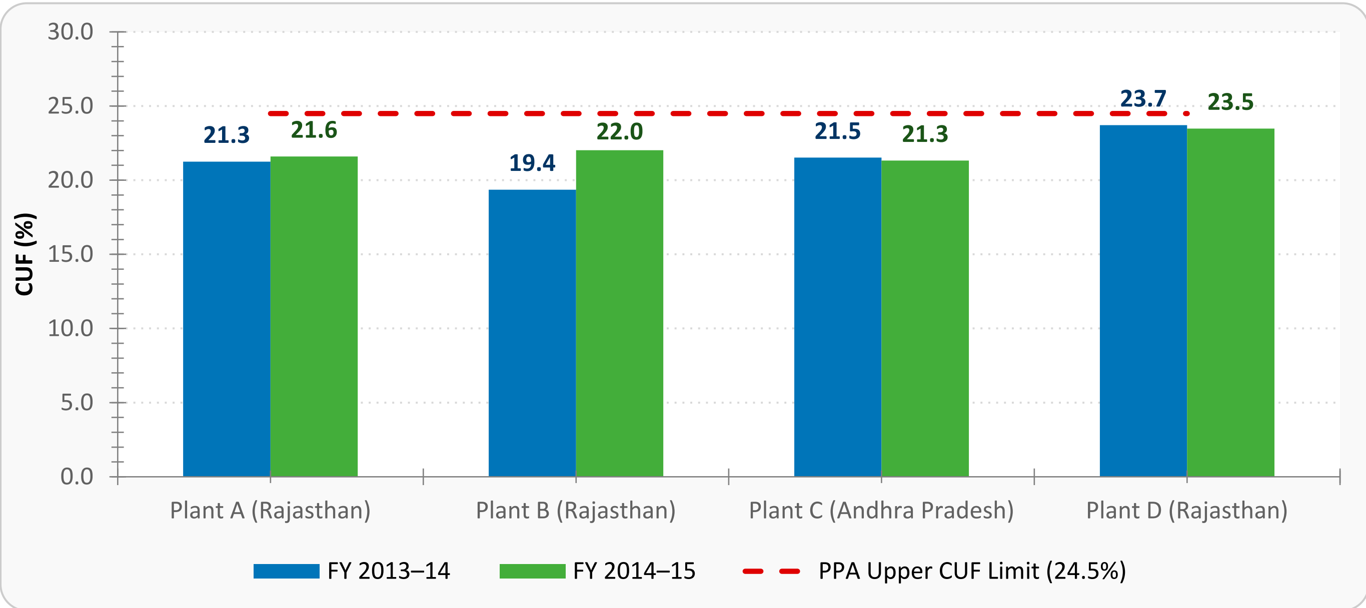

Figure A1. Observed annual CUF versus PPA upper limit (24.5%). Plants A–C exhibit persistent underperformance relative to the contractual ceiling, while Plant D operates near the upper bound. Data derived from a proprietary anonymized database.

Interannual variability is evident in Plant B, where the CUF increases from 19.36% in FY 2013–14 to 22.02% in FY 2014–15, indicating that short-term performance fluctuations are driven by site- and year-specific factors rather than structural degradation alone. The generation-based approach cannot disentangle these components, as it aggregates all loss mechanisms into a single performance gap. In contrast, the capacity-based methodology isolates structural degradation and representative unavailability, enabling more consistent cross-plant comparison.

Table A2 compares the repowering potential estimates derived from both methodologies. The generation-based estimates are computed from the CUF gap relative to the 24.5% PPA ceiling, using a performance ratio of 0.78 and an incremental CUF of 22%, representative of climatic conditions in Rajasthan and Andhra Pradesh. The capacity-based estimates follow the methodology outlined in Section 2.1.4 of the manuscript, incorporating a DC:AC ratio of 1.05, cumulative degradation (2.5% in Year 1 and 0.8–0.9% annually thereafter), and plant unavailability of 3.0–3.5%.

Table A2. Generation-based vs. capacity-based repowering potential. A positive difference means the generation method gives the higher estimate.

Project	CUF Gap (pp *)	Generation Method (MWp)	Capacity Method (MWp)	Difference (MWp)	Capacity Relative to Generation	Interpretation
Plant A (Rajasthan)	3.08	2.80	1.60	+1.20	57%	Generation method higher; operational losses not in capacity model
Plant B (Rajasthan)	3.81	3.46	1.41	+2.05	41%	Generation method higher; operational losses not in capacity model
Plant C (Andhra Pradesh)	3.10	2.82	1.41	+1.41	50%	Generation method higher; operational losses not in capacity model
Plant D (Rajasthan)	0.90	0.62	1.06	−0.44	171%	Capacity method higher; degradation is binding constraint near PPA ceiling
Plants A–C range	3.1–3.8	2.80–3.46	1.41–1.60	+1.20–+2.05	41–57%	Capacity method consistently lower for underperforming plants

* Percentage points (difference in percentage of CUF).

For Plants A–C, the generation-based method yields estimates 75% to 145% higher than the capacity-based approach, with the largest divergence observed for Plant B due to anomalously low performance in FY 2013–14. This reflects short-term operational or resource variability rather than persistent degradation. Plant D represents a distinct regime, where performance is already close to the contractual ceiling; here, cumulative degradation becomes the binding constraint, and the capacity-based approach yields a higher estimate.

The results indicate that the capacity-based methodology provides conservative estimates of repowering potential for the majority of assets in the dataset. This is particularly relevant for a national-scale assessment, where the fleet is structurally similar to Plants A–C. Under a generation-based formulation applied to the full portfolio, the aggregate repowering potential would likely exceed the manuscript's estimates of 7.2 GWp (PPA-constrained scenario) and 10.9 GWp (technical potential), implying that these values should be interpreted as lower bounds rather than central estimates.

Two considerations support the use of the capacity-based approach for national-scale assessment. First, plant-level generation data are commercially restricted and not available for most of India's >2100 utility-scale solar projects. The validation dataset used in this Appendix is derived from a proprietary database and is not publicly reproducible, limiting the scalability of the generation-based approach. In contrast, the capacity-based method requires only the commissioning year and installed capacity, both of which are publicly available, enabling full-fleet coverage.

Second, the generation-based approach conflates structural degradation with exogenous, time-specific factors such as interannual irradiance variability and curtailment. These effects may not be permanently mitigated through repowering and therefore introduce upward bias in estimated recoverable capacity. The capacity-based approach, by modeling cumulative physical degradation and representative unavailability, yields a structurally consistent and comparable estimate across heterogeneous assets.

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Finally, applying uncertainty multipliers from prior work (P90 = 1.091; P99 = 1.162) to the manuscript's P50 baseline yields the probabilistic estimates presented in Table A3. These factors reflect irradiance dataset uncertainty, approximately 8.75% for pre-2016 projects (Meteonorm 7.x) and approximately 6.35% for post-2016 datasets (SolarGIS).

Table A3. National repowering potential at P90 and P99 confidence levels.

Scenario	P50 Baseline (GWp)	P90 Estimate (GWp)	P99 Estimate (GWp)
PPA Limit Scenario	7.20	~7.85	~8.37
Technical Limit Scenario	10.90	~11.89	~12.67

Relative to the 2021 baseline (7.6% of installed AC capacity), the repowering intensity increases to 8.9% in the present dataset. This increase is primarily driven by the aging of the 2010–2016 commissioning cohort, which was originally deployed with DC:AC oversizing ratios of 5–30%, compared with current design norms of 50–60%. These assets now exhibit 9–15 years of cumulative degradation, materially increasing economically recoverable repowering potential.

References

1. IEA. *India's Clean Energy Transition Is Rapidly Underway, Benefiting the Entire World*; International Energy Agency (IEA): Paris, France, 2022.
2. MoEFCC. *Commitments Made Under CoP26: Updated Nationally Determined Contributions and Renewable Energy Initiatives in India*; Press Information Bureau, Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India: New Delhi, India, 2026. Available online: https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1882840&reg=3&lang=2 (accessed on 22 March 2026).
3. Dubey, B.; Agrawal, S.; Sharma, A.K. India's Renewable Energy Portfolio: An Investigation of the Untapped Potential of RE, Policies, and Incentives Favoring Energy Security in the Country. *Energies* **2023**, *16*, 5491. [CrossRef]
4. Kumar, J.C.R.; Majid, M.A. Renewable Energy for Sustainable Development in India: Current Status, Future Prospects, Challenges, Employment, and Investment Opportunities. *Energy Sustain. Soc.* **2020**, *10*, 2. [CrossRef]
5. CEA. *Transmission System for Integration of over 500 GW RE Capacity by 2030*; Central Electricity Authority (CEA), Ministry of Power: New Delhi, India, 2022.
6. MoP. *500 GW Non-Fossil Fuel Target*; Ministry of Power (MoP), Government of India: New Delhi, India, 2026. Available online: https://www.powermin.gov.in/static/uploads/2026/05/df68bc7bf21a7e46d1b01529930c137d.pdf (accessed on 24 March 2026).
7. Gulagi, A.; Ram, M.; Bogdanov, D.; Sarin, S.; Mensah, T.N.O.; Breyer, C. The Role of Renewables for Rapid Transitioning of the Power Sector across States in India. *Nat. Commun.* **2022**, *13*, 5499. [CrossRef] [PubMed]
8. Khan, K.A.; Anjum, A.; Subhan, M.; Khairuddin, N.A.B. Evaluating the disaggregated impact of renewable and non-renewable electricity generation on economic welfare in India. *Sci. Rep.* **2025**, *15*, 26725. [CrossRef] [PubMed]
9. Vijay, R.; Tongia, R. Renewable energy and India's demand growth: Benchmarking aggregate energy and time-of-day feasibility under technical and policy variability. *Electr. J.* **2025**, *38*, 107502. [CrossRef]
10. MoSPI. *Energy Statistics India 2025*; National Statistics Office, Ministry of Statistics and Programme Implementation (MoSPI), Government of India: New Delhi, India, 2025. Available online: https://mospi.gov.in/sites/default/files/publication_reports/Energy_Statistics_2025/Energy%20Statistics%20India%202025_27032025.pdf (accessed on 24 March 2026).
11. NITI Aayog. *Scenarios Towards Viksit Bharat and Net Zero: An Overview (India Energy Security Scenarios)*; NITI Aayog: New Delhi, India, 2026. Available online: https://www.niti.gov.in/sites/default/files/2026-02/Scenarios-Towards-Viksit-Bharat-and-Net-Zero-%20An-Overview-Vol1.pdf (accessed on 24 March 2026).
12. Purohit, I.; Purohit, P. Technical and Economic Potential of Concentrating Solar Thermal Power Generation in India. *Renew. Sustain. Energy Rev.* **2017**, *78*, 648–667. [CrossRef]
13. CEA. *All India Installed Capacity (in MW) of Power Stations (as on 28 February 2026)—Utilities*; Central Electricity Authority (CEA): New Delhi, India, 2026.
14. CEA. *Executive Summary on Power Sector (February 2026)*; Central Electricity Authority (CEA): New Delhi, India, 2026.

15. MNRE. *Solar PV Potential of India*; Ministry of New and Renewable Energy, GOI: New Delhi, India, 2025. Available online: https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2025/10/202510011411647635.pdf (accessed on 24 March 2026).
16. TERI. *Reassessment of Solar Potential in India: A Macro-Level Study*; The Energy and Resources Institute: New Delhi, India, 2025. Available online: https://teriin.org/policy-brief/reassessment-solar-potential-india-macro-level-study (accessed on 24 March 2026).
17. IRENA. *Remap Renewable Energy Prospects for India*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2017. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/May/IRENA_REmap_India_paper_2017.pdf (accessed on 24 March 2026).
18. Purohit, I.; Purohit, P.; Shekhar, S. Evaluating the Potential of Concentrating Solar Power Generation in Northwestern India. *Energy Policy* **2013**, *62*, 157–175. [CrossRef]
19. Harinarayana, T.; Kashyap, K. Solar Energy Generation Potential Estimation in India and Gujarat, Andhra, Telangana States. *Smart Grid Renew. Energy* **2014**, *5*, 275–289. [CrossRef]
20. CEA. *Installed Capacity Report*; Central Electricity Authority (CEA): New Delhi, India, 2026. Available online: https://cea.nic.in/installed-capacity-report/?lang=en (accessed on 22 March 2026).
21. MNRE. *Production Linked Incentive (PLI) Scheme: National Programme on High Efficiency Solar PV Modules*; Ministry of New and Renewable Energy (MNRE), Government of India: New Delhi, India, 2021. Available online: https://mnre.gov.in/en/production-linked-incentive-pli/ (accessed on 22 March 2026).
22. MNRE. *PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan) Scheme*; Ministry of New and Renewable Energy (MNRE), Government of India: New Delhi, India, 2019. Available online: https://mnreliveportal.hkapl.in/landing-about.html (accessed on 22 March 2026).
23. MNRE. *PM Surya Ghar: Muft Bijli Yojna*; Ministry of New and Renewable Energy (MNRE), Government of India: New Delhi, India, 2024. Available online: https://pmsuryagharyojana.in/ (accessed on 22 March 2026).
24. PIB. *The Solar Surge: India's Bold Leap Toward a Net Zero Future*; Press Information Bureau (PIB), Government of India: New Delhi, India, 2025. Available online: https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/aug/doc2025819616301.pdf (accessed on 22 March 2026).
25. CEA. *Annual Generation Report*; Central Electricity Authority (CEA): New Delhi, India, 2026. Available online: https://cea.nic.in/annual-generation-report/?lang=en (accessed on 22 March 2026).
26. IEEFA. *Meeting India's Peak Power Demand with Clean Energy*; Institute of Energy Economics and Financial Analysis (IEEFA): New Delhi, India, 2025. Available online: https://ieefa.org/sites/default/files/2025-07/Meeting%20India%E2%80%99s%20Peak%20Power%20Demand%20with%20Clean%20Energy_0.pdf (accessed on 22 March 2026).
27. Rodrigues, N.; Das, D.; Ewen, M. *Coal's Diminishing Role in India's Electricity Transition*; Ember: London, UK, 2025. Available online: https://ember-energy.org/app/uploads/2025/10/Coals-diminishing-role-in-Indias-electricity-transition.pdf (accessed on 22 March 2026).
28. Teferi, T.G.; Tella, T.G.; Hampannavar, S. Impact of Large-Scale Renewable Energy Integration on the Grid Voltage Stability. *Results Eng.* **2024**, *23*, 102398. [CrossRef]
29. Mlilo, N.; Brown, J.; Ahfock, T. Impact of Intermittent Renewable Energy Generation Penetration on the Power System Networks—A Review. *Technol. Econ. Smart Grids Sustain. Energy* **2021**, *6*, 25. [CrossRef]
30. CEC. *Unlocking India's Energy Transition Addressing Grid Flexibility Challenges and Solutions*; Center for Energy and Climate (CEC): New Delhi, India, 2025. Available online: https://www.ifri.org/sites/default/files/2025-02/ifri_raizada_unlocking_india_energy_transition_2025_0.pdf (accessed on 24 March 2026).
31. NITI Aayog. *India's Energy Storage Mission: NITI Aayog and Rocky Mountain Institute*; NITI Aayog & Rocky Mountain Institute: New Delhi, India, 2017.
32. MOP. *National Framework for Promoting Energy Storage Systems*; Ministry of Power (MoP), Government of India: New Delhi, India, 2023. Available online: https://powermin.gov.in/sites/default/files/National_Framework_for_promoting_Energy_Storage_Systems_August_2023.pdf (accessed on 24 March 2026).
33. CEA. *Roadmap to 100 GW of Hydro Pumped Storage Projects (PSPs) by 2035–36*; Central Electricity Authority, Ministry of Power, Government of India: New Delhi, India, 2026. Available online: https://cea.nic.in/wp-content/uploads/notification/2026/01/Roadmap_to_100_GW_of_Hydro_Pumped_Storage_Projects-2.pdf (accessed on 24 March 2026).
34. Li, X.; Yao, L.; Hui, D. Optimal Control and Management of a Large-Scale Battery Energy Storage System to Mitigate Fluctuation and Intermittence of Renewable Generations. *J. Mod. Power Syst. Clean Energy* **2016**, *4*, 593–603. [CrossRef]
35. Garttan, G.; Alahakoon, S.; Emami, K.; Jayasinghe, S.G. Battery Energy Storage Systems: Energy Market Review, Challenges, and Opportunities in Frequency Control Ancillary Services. *Energies* **2025**, *18*, 4174. [CrossRef]
36. Huang, J.; Yang, D. Improved System Frequency Regulation Capability of a Battery Energy Storage System. *Front. Energy Res.* **2022**, *10*, 904430. [CrossRef]

37. Akram, U.; Nadarajah, M.; Shah, R.; Milano, F. A Review on Rapid Responsive Energy Storage Technologies for Frequency Regulation in Modern Power Systems. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109626. [CrossRef]
38. Randhawa, K. Development of Stationary Battery Storage Systems in India—Progress and Prospects in 2025. *Next Res.* **2026**, *4*, 101213. [CrossRef]
39. Gupta, L. Strategic Deployment of Energy Storage Systems in the Indian Power Grid. *J. Adv. Manag. Res.* **2025**, *22*, 440–470. [CrossRef]
40. IRENA. *Electricity Storage and Renewables: Costs and Markets to 2030*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2017. Available online: https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets (accessed on 24 March 2026).
41. IRENA. *Utility-Scale Batteries Innovation Landscape Brief*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Utility-scale-batteries_2019.pdf (accessed on 24 March 2026).
42. CEA. *Draft Central Electricity Regulatory Commission (Ancillary Services)*; Central Electricity Regulatory Commission: New Delhi, India, 2021. Available online: https://cercind.gov.in/2021/draft_reg/EM-Ancillary-Services-Regulations.pdf (accessed on 24 March 2026).
43. Tender Detail. Battery Energy Storage Tenders in India. 2026. Available online: https://www.tenderdetail.com/Indian-tender/battery-energy-storage-tenders (accessed on 24 March 2026).
44. IEA. *Electricity Grids and Secure Energy Transitions*; International Energy Agency: Paris, France, 2023. Available online: https://iea.blob.core.windows.net/assets/ea2ff609-8180-4312-8de9-494bcf21696d/ElectricityGridsandSecureEnergyTransitions.pdf (accessed on 24 March 2026).
45. Zichella, C. DOE Advisory Committee's Grid Modernization Recommendations: Evolving to an Integrated Grid. *Electr. J.* **2014**, *27*, 64–71. [CrossRef]
46. MERC. *Order in Case No. 155 of 2024: Interlocutory Application (IA) No. 48 of 2024 in Case No. 155 of 2024*; Maharashtra Electricity Regulatory Commission (MERC): Mumbai, India, 2024. Available online: https://merc.gov.in/wp-content/uploads/2024/09/Order-in-Case-No.155-of-2024.pdf (accessed on 27 May 2026).
47. Lomardi, P.; Schwabe, F. Sharing Economy as a New Business Model for Energy Storage Systems. *Appl. Energy* **2017**, *118*, 485–495. [CrossRef]
48. CEIA. *Techno-Economic Analysis of Solar Photovoltaics and Battery Energy Storage at a Vietnam Industrial Park*; Clean Energy Investment Accelerator: Washington, DC, USA, 2023. Available online: https://docs.nrel.gov/docs/fy23osti/84352.pdf (accessed on 24 March 2026).
49. NREL. *Cost Projections for Utility-Scale Battery Storage: 2025 Update*; National Renewable Energy Laboratory: Golden, CO, USA, 2025. Available online: https://docs.nrel.gov/docs/fy25osti/93281.pdf (accessed on 24 March 2026).
50. Migliari, L.; Cocco, D.; Petrollese, M. Levelized Cost of Storage (LCOS) of Battery Energy Storage Systems (BESS) Deployed for Photovoltaic Curtailment Mitigation. *Energies* **2025**, *18*, 3602. [CrossRef]
51. IEA. *World Energy Outlook 2025*; International Energy Agency (IEA): Paris, France, 2025. Available online: https://pure.iiasa.ac.at/id/eprint/20996/ (accessed on 2 April 2026).
52. Koubar, M.; Oskar, L.; Lingfors, D.; Huang, P.; Berg, M.; Munkhammar, J. Techno-economical assessment of battery storage combined with large-scale Photovoltaic power plants operating on energy and Ancillary Service Markets. *Appl. Energy* **2025**, *382*, 1025200. [CrossRef]
53. Deshwal, D.; Sangwan, P. Enhancing Solar Energy Integration: A Techno-Economic Viability Assessment in India. *Wirel. Pers. Commun.* **2023**, *132*, 1933–1960. [CrossRef]
54. Herceg, S.; Fischer, M.; Weiß, K.-A.; Schebek, L. Life Cycle Assessment of PV Module Repowering. *Energy Strategy Rev.* **2022**, *43*, 100928. [CrossRef]
55. DOE. *Quantifying the Impact of PV System Repowering and Module Reuse on PV Project Economics, Sustainability, & Equity*; National Renewable Energy Laboratory, U.S. Department of Energy: Golden, CO, USA, 2024. Available online: https://docs.nrel.gov/docs/fy25osti/91745.pdf (accessed on 24 March 2026).
56. Lantz, E.; Leventhal, M.; Baring-Gould, I. *Wind Power Project Repowering: Financial Feasibility, Decision Drivers, and Supply Chain Effects*; Technical Report NREL/TP-6A20-60535; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2013.
57. Mühlbauer, A.; Fan, Y.F.; Sambor, D.J.; Jacobson, M.Z. The Potential for Onshore Wind Repowering to Hasten the Energy Transition in the United States. *Proc. Natl. Acad. Sci. USA* **2026**, *123*, e2521050123. [CrossRef] [PubMed]
58. Motiwala, S.; Kumar, S.; Sharma, A.K.; Purohit, I. Enhancing Performance of Operational Utility-Scale Solar PV Projects in India through Re-Powering: Potential and Techno-Economic Assessment. *Energy Sustain. Dev.* **2024**, *83*, 101574. [CrossRef]
59. IEA. *Renewables Integration in India*; International Energy Agency (IEA): Paris, France, 2021. Available online: https://iea.blob.core.windows.net/assets/7b6bf9e6-4d69-466c-8069-bdd26b3e9ed1/RenewablesIntegrationinIndia2021.pdf (accessed on 24 March 2026).

60. Jindal, A.; Shrimali, G. At scale adoption of battery storage technology in Indian power industry: Enablers, frameworks and policies. *Technol. Forecast. Soc. Change* **2022**, *176*, 121467. [CrossRef]
61. CERC. RE Tariff Order, Central Electricity Regulatory Commission, India, 2017–2018. Available online: https://www.cercind.gov.in/2017/orders/05.pdf (accessed on 24 March 2026).
62. Gupta, U. Power ministry proposes amendments to tariff-based competitive bidding for solar, wind and hybrid renewable energy projects. *pv Magazine India*, 29 October 2024. Available online: https://www.pv-magazine-india.com/2024/10/29/power-ministry-proposes-amendments-to-tariff-based-competitive-bidding-for-solar-wind-and-hybrid-renewable-energy-projects/ (accessed on 25 March 2026).
63. Balfour, J.; Hill, R.; Walker, A.; Robinson, G.; Gunda, T.; Desai, J. Masking of Photovoltaic System Performance Problems by Inverter Clipping and Other Design and Operational Practices. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111067. [CrossRef]
64. Bahloul, M.; Khadem, S. A refined method for optimising inverter loading ratio in utility-scale photovoltaic power plant. *Energy Rep.* **2024**, *12*, 5110–5115. [CrossRef]
65. Sofar Solar. *Sofar 1100TL–3300TL Single-Phase Inverter User Manual*; Sofar Solar Co., Ltd.: Shenzhen, China, 2026; pp. 14–16. Available online: https://www1.sofarsolar.com/ (accessed on 23 May 2026).
66. Aslam, A.; Ahmed, N.; Qureshi, S.A.; Assadi, M.; Ahmed, N. Advances in Solar PV Systems; A Comprehensive Review of PV Performance, Influencing Factors, and Mitigation Techniques. *Energies* **2022**, *15*, 7595. [CrossRef]
67. Sharma, G.S.; Mahela, O.P.; Hussien, M.G.; Khan, B.; Padmanaban, S.; Shafik, M.B.; Elbarbary, Z.M.S. Performance Evaluation of a MW-Size Grid-Connected Solar Photovoltaic Plant Considering the Impact of Tilt Angle. *Sustainability* **2022**, *14*, 1444. [CrossRef]
68. Purohit, I.; Bose, S.; Atla, C. Techno-economics of grid-connected Battery Energy Storage System (BESS) in power distribution: Case study of a distribution company in India. *Energy Sustain. Dev.* **2026**, *92*, 201934. [CrossRef]
69. IEA. *Batteries and Secure Energy Transitions*; International Energy Agency: Paris, France, 2024. Available online: https://www.iea.org/reports/batteries-and-secure-energy-transitions (accessed on 22 May 2026).
70. NREL. *Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems*; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2018. Available online: https://docs.nlr.gov/docs/fy19osti/73822.pdf (accessed on 25 March 2026).
71. CERC. *Upper Cap Tariff Order*; Central Electricity Regulatory Commission (CERC): New Delhi, India, 2023. Available online: https://cercind.gov.in/2023/orders/SM-Order-290323.pdf (accessed on 24 March 2026).
72. CEA. *CO_2 Baseline Database for the Indian Power Sector*; Central Electricity Authority (CEA): New Delhi, India, 2025. Available online: https://cea.nic.in/wp-content/uploads/baseline/2025/12/User_Guide_V_21.0.pdf (accessed on 1 April 2026).
73. National Renewable Energy Laboratory (NREL). *Annual Technology Baseline 2024*; National Renewable Energy Laboratory: Golden, CO, USA, 2024. Available online: https://atb.nrel.gov (accessed on 30 May 2026).
74. International Energy Agency (IEA). *Electricity 2025: Analysis and Forecast to 2027*; International Energy Agency: Paris, France, 2025. Available online: https://www.iea.org/reports/electricity-2025 (accessed on 30 April 2026).
75. National Renewable Energy Laboratory (NREL). *PV Repowering and Lifetime Extension Strategies for Utility-Scale Solar Plants*; National Renewable Energy Laboratory: Golden, CO, USA, 2024.
76. Fraunhofer Institute for Solar Energy Systems ISE. *Electricity Storage Factsheet 2024*; Fraunhofer Institute for Solar Energy Systems (ISE): Freiburg, Germany, 2024.
77. Lazard. *Levelized Cost of Storage Analysis—Version 10.0*; Lazard: New York, NY, USA, 2024. Available online: https://www.lazard.com (accessed on 30 April 2026).
78. International Energy Agency (IEA). *Renewables 2025: Analysis and forecasts to 2030*; International Energy Agency: Paris, France, 2025. Available online: https://www.iea.org/reports/renewables-2025 (accessed on 30 April 2026).
79. International Renewable Energy Agency (IRENA). *World Energy Transitions Outlook 2024: 1.5 °C Pathway*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2024.
80. Dey, M. 100 Percent ISTS Charge Waiver for Co-Located BESS Projects Commissioned Before 30 June 2028. *Energetica India*, 10 June 2025. Available online: https://energetica-india.net/news/100-percent-ists-charge-waiver-for-co-located-bess-projects-commissioned-before-june-30-2028 (accessed on 23 May 2026).

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