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Designing Hybrid Solar Photovoltaic–Battery Systems for Firm Block Supply: A Techno-Economic Analysis#

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ABSTRACT

The techno-economics of firm block power supply from hybrid solar photovoltaic–battery energy storage systems (BESSs) are central to achieving reliable and dispatchable renewable energy. This study evaluates grid-connected solar–BESS hybrid systems designed to deliver firm 250 MW power blocks over 4-hour, 6-hour, and 8-hour durations during daily morning and evening peaks. Multiple combinations of solar and BESS capacities were analyzed to identify system configurations that minimize the levelized cost of energy (LCOE) while maintaining supply reliability. The BESS was assumed to be charged solely by solar generation, with any surplus solar photovoltaic output curtailed after storage saturation. Results demonstrate that LCOE and reliability are strongly influenced by the solar-to-storage ratio and dispatch duration. Moderate solar oversizing enhances reliability and reduces unmet demand, whereas excessive scaling leads to diminishing economic returns due to higher capital costs and energy curtailment. The study underscores the importance of optimally balancing solar photovoltaic capacity and storage sizing to design cost-efficient, firm renewable-plus-storage systems capable of meeting peak-period demand reliably.

Keywords: photovoltaic, battery energy storage system, techno-economic performance, firm block supply, levelized cost of energy, grid-integrated RE plus storage systems

NOMENCLATURE

Abbreviations	
SOC	State of Charge
BESS	Battery Energy Storage System
ES	Energy Storage
LCOE	Levelized Cost of Energy
NPV	Net Present Value
CAPEX	Capital Expenditure
BOP	Balance of Plant
O&M	Operation and Maintenance
CEA	Central Electricity Authority
NEP	National Electricity Plan
RE	Renewable Energy
NREL	National Renewable Energy Laboratory
Symbols	
t	Year
r	Discount rate
$NPV_{energy\ delivered}$	Net present value of energy delivered
NPV_b	Net present value of BESS
$Present\ Value_{b,t}$	Present value of BESS
NPV_s	Net present value of solar
$Present\ Value_{s,t}$	Present value of solar costs
NPV_{costs}	Net present value of system costs
NPV_unmet	Net present value of total unmet demand

1. INTRODUCTION

The United Nations' Sustainable Development Goal on affordable and clean energy emphasizes the need to accelerate renewable energy (RE) integration [1] and reduce dependence on fossil fuels, which remain the primary contributors to global greenhouse gas (GHG) emissions [2]. Across the world, RE systems are rapidly expanding, supported by declining costs and policy commitments toward net-zero emissions. With continued reductions in battery prices and levelized cost of energy (LCOE), recent analyses such as the National Renewable Energy Laboratory's (NREL) 2023 cost projections highlight the growing viability of co-locating battery energy storage systems (BESSs) with renewable generation to enhance grid flexibility, improve project economics, and reduce curtailment [3].

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In emerging renewable markets such as India, where RE accounts for approximately half of the total installed power capacity of 484 GW as of August 2025 [4], integrating energy storage (ES) has become essential for addressing intermittency and maintaining grid stability. This is achieved by storing surplus generation during low-demand hours and discharging during peak periods.

Recent policy and market developments in India have shown competitive tariff discoveries of ₹3.1–₹3.5 per kWh for co-located solar–BESS projects with 2- to 4-hour storage durations, representing a 50%–60% cost reduction between late 2023 and early 2025 [5]. Similar large-scale hybrid projects worldwide are targeting dispatchable RE to meet rising evening peak demand cost-effectively. Long-term projections, such as those from India's National Electricity Plan (NEP) 2023 [6], estimate that national BESS requirements could increase from 35 GWh in 2026–27 to 236 GWh by 2031–32 and over 1,800 GWh by 2047, aligning with global net-zero trajectories [7].

These trends highlight the need for robust frameworks to determine the optimal sizing and dispatch of solar–BESS hybrid systems capable of supplying firm, dispatchable renewable power. The objective of this study was to develop and apply a techno-economic framework to identify the optimal configuration of grid-connected solar photovoltaic and BESS for firm block delivery during the daily morning and evening peak periods. The analysis focused on determining the most cost-effective combination of solar and storage capacities that can ensure a reliable supply at the lowest LCOE while maintaining operational flexibility. By evaluating multiple capacity ratios, dispatch durations, and operating strategies, the study established design guidelines that balance system economics, reliability, and energy utilization efficiency. Although the proposed framework is generic and applicable across different geographies and policy contexts, it is demonstrated here through a case study representing high solar potential conditions in South India.

2. METHODOLOGY

2.1 Overview

Here, the optimal sizing of solar and co-located BESS required to deliver a firm 250 MW block supply during the morning and evening peak hours was determined. Multiple scenarios were analyzed to identify the most optimal combination of solar and BESS capacities capable of meeting the target demand.

In this study, the LCOE, expressed in ₹/kWh, represents the per-unit cost of electricity delivered by solar–BESS hybrid systems over its lifetime. The calculation of LCOE incorporated both capital and operating expenditures, including investment in solar photovoltaic modules, balance-of-system components, battery packs, maintenance, insurance, monitoring, and periodic battery replacements. Financial parameters such as the discount rate (r), project lifetime, and technology-specific degradation rates were applied to determine the LCOE.

By integrating these technical and financial elements, the framework enabled a comparative assessment of alternative solar–BESS configurations to identify the least-cost and most reliable solution for firm power supply.

2.2 Dispatch strategy of grid-connected solar and BESS

The dispatch model prioritizes instantaneous grid demand while coordinating the operation of solar and BESS to ensure firm power delivery. The BESS operates in a load-following configuration, charging during periods of excess solar generation and discharging during evening hours to meet the target supply. Table 1 and Fig. 1 provide the dispatch strategy of grid-connected solar and BESS.

Table 1: Dispatch strategy of grid-connected solar and BESS

Solar hours	• *Prioritize demand supply*: Solar output is first directed to meet the instantaneous grid demand. • *Surplus for BESS charging:* Once the demand is met, the remaining generation is supplied for charging the BESS until the state of charge (SOC) reaches unity. • *Curtailment:* Any energy left after meeting the demand and charging the BESS is curtailed.
Non-solar hours	• *BESS discharge:* The BESS discharges to supply the firm block demand during non-solar hours. • *Unmet demand:* If the BESS runs out of stored energy (SOC falls below the required level), the remaining demand is considered unmet, and a penalty is applied.

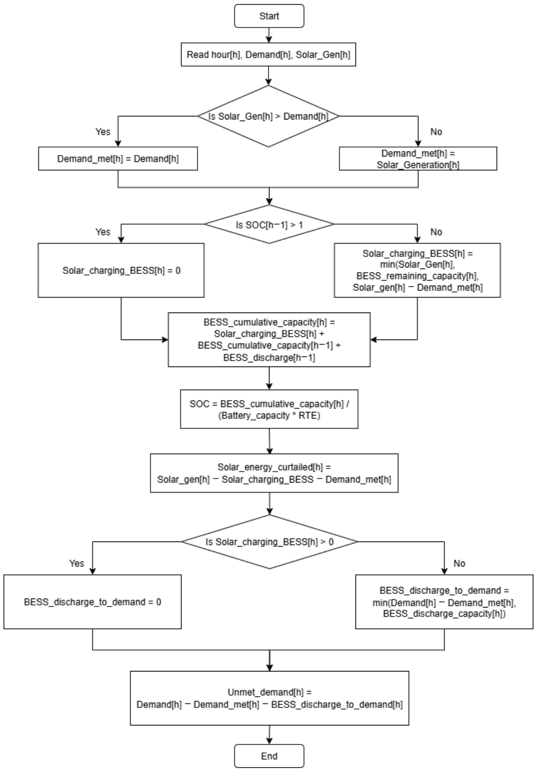

Fig. 1 Flowchart for dispatch strategy

2.3 *Techno-economics of firm block supply from solar and BESS*

The LCOE was computed by determining the net present value (NPV) of both total system costs and the energy delivered over the project lifetime, discounted at a rate *r*. The present value of energy delivered in year *t* was calculated by discounting the total energy supplied with the load at the given discount rate. The NPV of total energy delivered is expressed as:

$$\mathrm{NPV}_{\text{energy delivered}} = \sum_{t=0}^{24} \text{Preset value of energy delivered}_{t}. \quad (1)$$

2.3.1 BESS cost components

The total BESS cost in the first year comprised the balance of plant (BOP) cost, initial capital cost, and operation and maintenance (O&M) cost. The BOP and capital costs were determined by multiplying their respective unit costs (₹/kWh) by the total installed battery capacity (MW). The O&M cost in year t was obtained by escalating the first-year O&M cost at the specified annual rate, while replacement costs were included in the relevant years. The present value of the BESS cost in year t was calculated by discounting the total annual cost at the rate r. The NPV of BESS over the lifetime is given by:

$$\mathrm{NPV}_{\mathrm{b}} = \sum_{t=0}^{t=24} \text{Present value}_{\mathrm{b,t}}. \quad (2)$$

2.3.2 Solar cost components

The total solar cost in the first year included the initial capital expenditure (CAPEX) and O&M cost, with subsequent years (*t ≥ 1*) accounting only for annual O&M expenses. The present value of solar cost in year *t* was obtained by discounting the total annual cost at the rate *r*. The NPV of solar is expressed as:

$$\mathrm{NPV}_{\mathrm{s}} = \sum_{t=0}^{t=24} \text{Present value}_{\mathrm{s,t}}. \quad (3)$$

The total system cost was obtained by adding the NPVs of the solar, BESS, and unmet energy components.

$$\mathrm{NPV}_{\text{costs}} = \mathrm{NPV}_{\mathrm{s}} + \mathrm{NPV}_{\mathrm{b}} + \text{NPV\_unmet} \quad (4)$$

Finally, the LCOE of the firm block supply from solar–BESS hybrid systems was calculated as:

$$\text{LCOE (₹/kWh)} = \frac{\mathrm{NPV}_{\text{costs}}}{\mathrm{NPV}_{\text{Energy delivered}}}. \quad (5)$$

3. CASE STUDY

3.1 Case study framework and dispatch design

To determine the optimal generation pattern for the hybrid system, a detailed analysis was conducted for multiple combinations of solar photovoltaic and BESS capacities. Solar photovoltaic capacities of 250 MW, 350 MW, and 500 MW were evaluated for firm block supply durations of 4, 6, and 8 hours. Corresponding battery capacities of 1,100 MWh, 1,650 MWh, and 2,200 MWh were sized to deliver a constant 250 MW output during the specified dispatch periods, considering a round-trip efficiency of 95%. The generation profiles for all scenarios were derived from *Renewables Ninja* [8] data corresponding to Ryapte Village, Karnataka, located in South India [8].

For each solar–BESS hybrid system, a set of dispatch strategies reflecting different load-shifting conditions was implemented to assess operational performance. A constant 250 MW power block was scheduled during the morning (07:00–10:00) and evening (17:00–22:00) peak periods to replicate demand–supply alignment. Several combinations of morning and evening durations—2 + 2, 0 + 4, 4 + 0, 2 + 4, 4 + 2, 0 + 6, and 4 + 4 hours—were examined to evaluate the impact of shifting generation between peak windows. For example, the 2 + 2 case denotes 2 hours of morning operation (07:00–09:00) and 2 hours of evening operation (17:00–19:00), whereas the

4 + 0 case represents 4 hours of morning dispatch without evening operation.

3.2 Comparative results for various dispatch strategies

Each case was evaluated for the selected solar photovoltaic capacities and corresponding dispatch strategies to examine their impact on overall system performance. The analysis highlights how variations in morning and evening load-shifting patterns affect total demand served, the relative contribution of solar photovoltaic and BESS, energy curtailed, and the extent of unmet demand.

Fig. 2 presents the energy flow profile for a 350 MW photovoltaic plant with a 1,650 MWh BESS, supplying a flat 250 MW block during 4 hours of morning peak and 2 hours of evening peak operation.

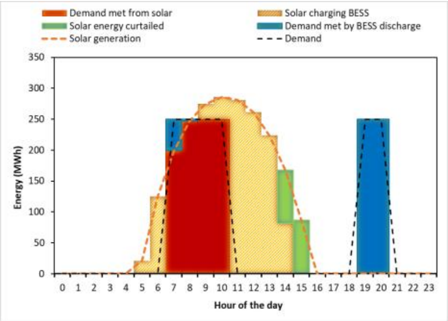

Fig. 2 Six-hour firm block supply from 350 MW solar and BESS

The three graphs shown in Fig. 3, 4, and 5 depict how solar capacity affects unmet electricity demand under different peak timing scenarios. A common trend can be observed, indicating a reduction in unmet demand with increased solar photovoltaic capacity. But this benefit must be weighed against escalating costs necessitating a cost–benefit analysis through LCOE.

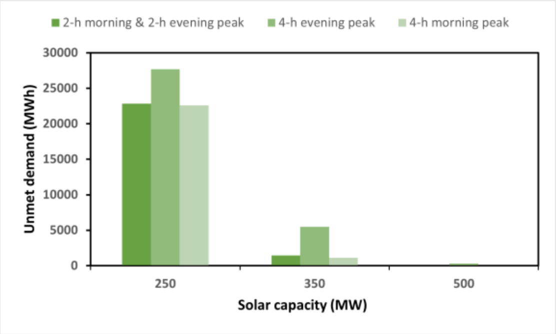

Fig. 3 Variation in unmet demand with different solar photovoltaic sizing for a 4-hour firm block supply

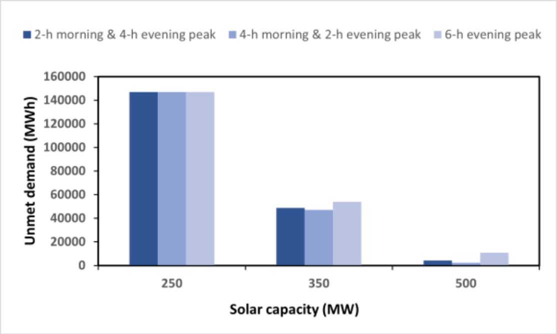

Fig. 4 Variation in unmet demand with different solar photovoltaic sizing for a 6-hour firm block supply

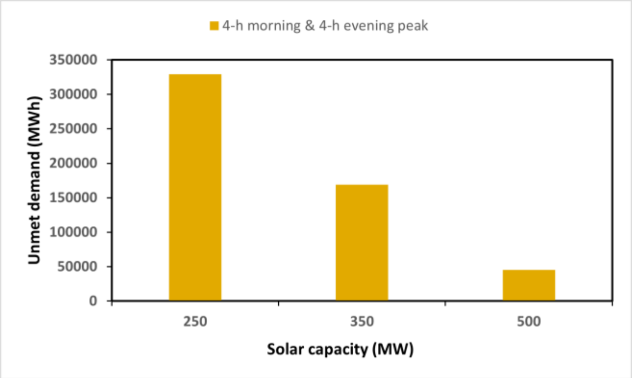

Fig. 5 Variation in unmet demand with different solar photovoltaic sizing for an 8-hour firm block supply

Another key inference from the analysis is that the installed solar photovoltaic capacity should be at least 50% of the total firm energy requirement for reliable daily block delivery. Maintaining this ratio ensures adequate generation for both direct supply and battery charging, thereby minimizing unmet demand and improving the overall reliability of the hybrid system.

3.3 Economic analysis of the various solar and BESS configurations

The hybrid project lifetime was considered 25 years, with no replacement required for solar photovoltaic and other BOP systems. The battery was assumed to be replaced in the 13th year of the 25-year project lifetime. The replacement cost of BESS was considered at a reduced cost of ₹5000/kWh without BOP. The unmet demand penalty cost was set at ₹3/kWh, and a discount rate of 10% per annum was applied for the entire hybrid project. The detailed solar and BESS economics is listed in Table 2 and Table 3.

Table. 2 Solar plant economics

CAPEX	₹45,000,000 per MW
O&M costs	1% of CAPEX, escalates at 1% per year
Solar panel degradation	1%

Table. 3 BESS plant economics

CAPEX (without BOP)	₹8,925 per kWh
CAPEX (with BOP)	₹12,750 per kWh
O&M costs	2% of CAPEX with BOP, escalates at 0.05% per year
Battery degradation	2.5%

Table 4 shows LCOE trends for various flat block configurations of the solar plus BESS hybrid system. The analysis reveals that the LCOE strongly depends on the relative sizing of solar photovoltaic and BESS capacities, as well as on the chosen dispatch durations. Moreover, LCOE decreases with increasing solar capacity, reflecting the benefit of greater generation availability for both direct supply and battery charging. Among all combinations, the lowest LCOE of 3.22 ₹/kWh was achieved with a 500 MW solar photovoltaic plant and a 1,650 MWh BESS operating under a 4 + 2-hour dispatch pattern. This configuration demonstrates optimal synergy between generation and storage, enabling firm 250 MW block delivery at the least cost. Overall, the results indicate that maintaining a solar-to-firm block ratio of approximately 2:1 or greater is essential for achieving cost-effective and reliable firm power delivery.

Table. 4 LCOE trends for various flat block configurations

BESS capacity (MWh)	**Solar capacity (MW)**	**Morning peak duration (hour)**	**Evening peak duration (hour)**	**LCOE (₹/ kWh)**
1,100	250	2(8-9)	2(19-20)	4.89
		0	4(18-21)	5.37
		4(7-10)	0	4.58
1,650		2(8-9)	4(18-21)	9.79
		4(7-10)	2(19-20)	5.18
		0	6(17-22)	6.20
2,200		4(7-10)	4(18-21)	6.58
1,100	350	2(8-9)	2(19-20)	4.88
		0	4(18-21)	5.44
		4(7-10)	0	4.49
1,650		2(8-9)	4(18-21)	7.46
		4(7-10)	2(19-20)	3.96
		0	6(17-22)	5.32
2,200		4(7-10)	4(18-21)	4.96
1,100	500	2(8-9)	2(19-20)	4.51
		0	4(18-21)	5.37
		4(7-10)	0	4.09
1,650		2(8-9)	4(18-21)	6.16
		4(7-10)	2(19-20)	3.22
		0	6(17-22)	4.89
2,200		4(7-10)	4(18-21)	4.03

4. CONCLUSIONS

This study analyzed multiple solar photovoltaic and BESS configurations to deliver firm 250 MW power blocks during daily morning and evening peaks. The results demonstrate that the LCOE and overall system reliability are strongly influenced by the relative sizing of solar photovoltaic and storage, as well as by dispatch duration. Increasing solar capacity reduces LCOE up to an optimal solar-to-firm ratio of about 2:1, beyond which additional capacity offers limited benefit due to curtailment and higher capital costs. Maintaining a solar photovoltaic capacity roughly twice the firm block requirement—or sufficient to meet at least 50% of the daily firm energy directly—ensures adequate generation for both direct supply and battery charging, thereby improving reliability and reducing unmet demand. Balanced split-peak dispatch configurations, particularly the 4 + 2-hour pattern, demonstrate the best techno-economic performance when coupled with a sized storage of approximately 1.6 GWh per 250 MW block. The analysis underscores the importance of coordinated sizing between solar photovoltaic and BESS for cost-effective and reliable hybrid operation.

Future work will expand the analysis to a broader range of photovoltaics-to-storage ratios and dispatch combinations by using optimization-based methods, enabling the identification of cost-optimal configurations under realistic resource and operational conditions.

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