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Estimating the Cost of Grid-Scale Lithium-Ion Battery Storage in India

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List of Acronyms

AC	Alternating Current
BCD	Basic Custom Duty
BESS	Battery Energy Storage Systems
BNEF	Bloomberg New Energy Finance
BoS	Balance of System
BU	Billion Unit
CAGR	Compound Annual Growth Rate
CapEx	Capital Expenditure
CCTV	Closed-Circuit Television
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
COD	Commercial Operation Date
CUF	Capacity Utilization Factor
DC	Direct Current
DoD	Depth of Discharge
EPC	Engineering, Procurement, and Construction
ETC	Energy Transitions Commission
EV	Electric Vehicle
FY	Fiscal (or Financial) Year
GWh	Gigawatt-Hour
HT	High Tension
IGST	Integrated Goods and Services Tax
ISGF	India Smart Grid Forum
ITC	Investment Tax Credit
kW	Kilowatt
kWh	Kilowatt-Hour
LADWP	Los Angeles Department of Water and Power
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
LFP	Li-Ferrous-Phosphate
Li-ion	Lithium-Ion
LT	Low Tension
MERC	Maharashtra Electricity Regulatory Commission
MNRE	Ministry of New and Renewable Energy
MSEDCL	Maharashtra State Electricity Distribution Company Limited
MW	Megawatt
MWh	Megawatt-Hour
NITI	National Institution for Transforming India
NPV	Net Present Value
NV	Nevada
O&M	Operation & Maintenance

PLF	Plant Load Factor
PPA	Power-Purchase Agreement
PV	Photovoltaic
RE	Renewable Energy
RMU	Ring Main Unit
SCADA	Supervisory Control And Data Acquisition
SECI	Solar Energy Corporation of India
TWh	Terawatt-Hour
UPS	Uninterruptible Power Supply
U.S.	United States
WMS	Weather Monitoring Station

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Abstract

India has announced ambitious renewable energy targets (mainly for solar and wind sources): 175 GW by 2022, 275 GW by 2027, and 450 GW by 2030. However, the capacity value of these variable renewable energy sources is limited without grid-scale energy storage. An increasing number of battery storage projects are being built worldwide, and there is significant interest in storage among Indian utilities and policymakers. However, detailed India-specific cost benchmarks that could help utilities design solicitations and assess costs and benefits have been unavailable.

We estimate costs for utility-scale lithium-ion battery systems through 2030 in India based on recent U.S. power-purchase agreement (PPA) prices and bottom-up cost analyses of standalone batteries and solar PV-plus-storage systems. When we scale unsubsidized U.S. PV-plus-storage PPA prices to India, accounting for India's higher financing costs, we estimate PPA prices of Rs. 3.0–3.5/kWh (4.3–5¢/kWh) for about 13% of PV energy stored in the battery and installation years 2021–2022. These estimates are 34% higher than U.S. prices, excluding any impact of taxes and import duties. Our bottom-up estimates of total capital cost for a 1-MW/4-MWh standalone battery system in India are $203/kWh in 2020, $134/kWh in 2025, and $103/kWh in 2030 (all in 2018 real dollars). When co-located with PV, the storage capital cost would be lower: $187/kWh in 2020, $122/kWh in 2025, and $92/kWh in 2030. The tariff adder for a co-located battery system storing 25% of PV energy is estimated to be Rs. 1.44/kWh in 2020, Rs. 1.0/kWh in 2025, and Rs. 0.83/kWh in 2030; this implies that the total prices (PV system plus battery storing 25% of PV energy) are Rs. 3.94/kWh in 2020, Rs. 3.32/kWh in 2025, and Rs. 2.83/kWh in 2030. Such low battery storage prices could disrupt how India plans to meet its growing energy needs.

1. Introduction

Globally, the sharp decline in prices of lithium-ion (Li-ion) batteries is expected to transform how electricity from renewable sources, such as solar and wind, is integrated into the grid. Estimates of declines in Li-ion battery pack prices vary from 50% during 2012–2017 as per McKinsey & Co. (Frankel et al. 2018) to 73% during 2013–2018 as per Bloomberg New Energy Finance (BNEF). Based on BNEF 2010–2018 data, the learning rate (reduction in price for each doubling of cumulative volume) is 18%. BNEF uses this rate to project a price of $62/kWh by 2030 (Figure 1).[1]

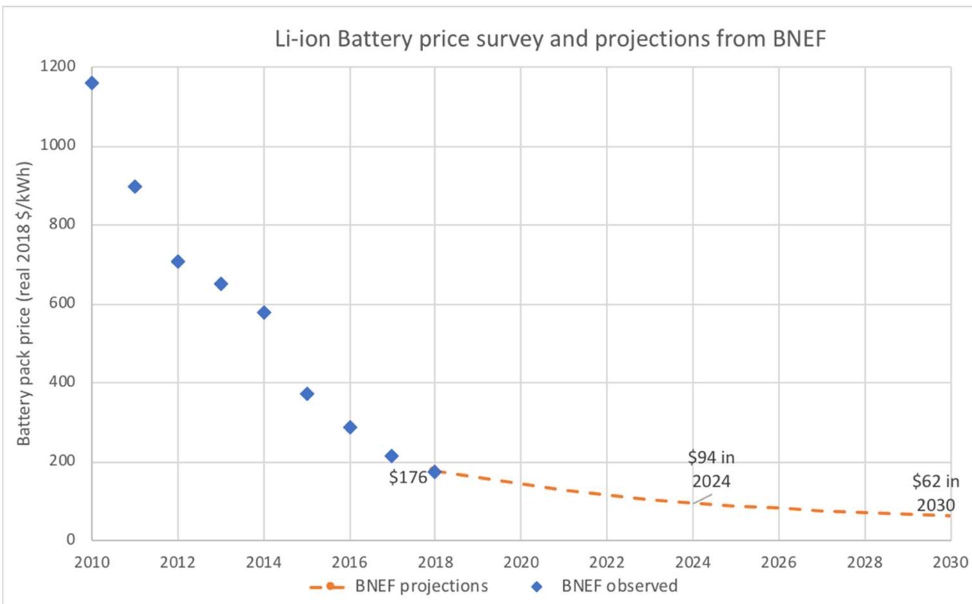


Figure 1. Li-ion battery pack historical prices and price projections

Source: BNEF (2019)

India is on the cusp of making major energy investment decisions over the next 2 decades. In its 19th Electric Power Survey, the Central Electricity Authority (CEA) projects that peak electricity demand in India will grow at about 6.32% per year, from 162 GW in 2016/2017 to about 300 GW in 2026/2027 (CEA 2017). Total energy consumption would exceed 1,500 TWh by fiscal year (FY) 2022 and 2,000 TWh by FY 2027.[2] India's National Electricity Plan states that about 123 GW of additional conventional capacity[3] would be required to meet this additional peak demand, because contributions of renewable sources to meeting the peak demand are assumed to be minimal (CEA 2018). This is primarily because India's peak demand occurs during the evening. Although wind resources are available in the evening, their output is highly seasonal. Hence, even

[1] Schmidt et al. (2017) estimate the learning rate at 12% ± 3% for grid-scale Li-Ion batteries and 16% ± 4% for batteries used in electric vehicles (EVs). They caution that using more recent data results in a more aggressive learning rate.
[2] In India, the FY runs from April 1 – March 31.
[3] Planned capacity additions through 2027 include 10 GW of nuclear, 19 GW of hydro, and 94 GW of coal.

with India's aggressive renewable energy (RE) targets (175 GW by 2022, 275 GW by 2027, 450 GW by 2030[4]), India is projected to require significant coal capacity for meeting evening load.

According to CEA, meeting India's 340-GW peak load and 2,400-TWh energy requirement in 2030 would require adding about 50 GW of coal between 2022 and 2027, in addition to 48 GW expected to come online by 2022 (CEA 2019). However, the last 130 GW of coal that provides power during non-solar hours, including morning and evening peak, would run at an effective plant load factor (PLF) of only 24%.[5] Running coal plants at such a low capacity factor would be operationally difficult and would result in total costs per unit of Rs. 6–8/kWh, without accounting for additional operations and maintenance (O&M) costs. This would be antithetical to the objective of cheap, reliable power for all.

As an alternative, battery energy storage systems (BESS)[6] based on low-cost Li-ion batteries may enable India to use stored solar energy to meet peak morning and evening demands. India's Ministry of New and Renewable Energy (MNRE) is tasked with the National Energy Storage Mission, with the objective of "creating an enabling policy and regulatory framework that encourages manufacturing, deployment, innovation and further cost reduction" in the energy storage sector (MNRE 2018). Solar Energy Corporation of India (SECI), a company established under the administrative control of MNRE, plays a major role in implementing MNRE's schemes and has been a key stakeholder in India's rapidly developing RE sector. SECI has recently solicited proposals for BESS projects—a few are still in process, but one recent large award comprises 1,200 MW of solar and/or wind projects with guaranteed supply during peak hours (SECI 2019a). The projects must supply power for at least 6 hours during peak times (6–9 AM, 6 PM–midnight). The off-peak tariff is fixed at Rs. 2.88/kWh (SECI 2019b); bids were invited for the peak tariff only. Utilities will offtake 50 MWh for every 100 MW of installed capacity during peak hours. The minimum expected capacity utilization factor (CUF) is 35% (SECI 2019b). The tender was won by Greenko Group (for 900 MW) and ReNew Power (for 300 MW).

Greenko won the bid at a peak power tariff rate of Rs. 6.12/kWh, and ReNew Power won at Rs. 6.85/kWh (SECI 2020). While Greenko plans to store RE in a pumped hydro system for meeting peak demand, ReNew will install Li-ion batteries in a solar and wind hybrid system. For ReNew, the blended tariff (not announced by SECI but reported in the media) is Rs. 4.07/kWh (5.8 ¢/kWh) (Times of India 2020). However, the percentage of energy routed through the battery is not confirmed. This tender is expected to kickstart the commercial deployment of grid-scale storage in India.

The state of Andhra Pradesh has also solicited expressions of interest for 400 MW of battery storage with 8 hours of discharge per day (3,200 MWh) and at least 3 hours of continuous discharge. Maharashtra State Electricity Distribution Co. Ltd. (MSEDCL) filed a petition with the Maharashtra Electricity Regulatory Commission (MERC) seeking approval of procurement of power from RE plus storage; MERC ordered MSEDCL to align the tender document with that of SECI.

[4] Per announcement made by the President of India in January 2020 (Economic Times, 2020)

[5] Half of 2,508 Billion Units (BUs) would be generated from coal; 130 GW running at 85% PLF would yield 968 BUs, and the remaining 137 GW would yield 286 BUs, with an effective PLF of 24%.

[6] In this report, "storage systems" mean chemical-based battery systems, excluding pumped hydro storage and thermal storage systems.

Several studies have projected the capital costs of grid-scale energy storage in India. NITI Aayog and Rocky Mountain Institute (2017) estimate that India might account for 800 GWh of battery demand per year by 2030 (over a third of global demand), with battery pack prices dropping to $92–$99/kWh by 2025 and $60–$67/kWh by 2030. India Smart Grid Forum (ISGF) assumes capital costs for Li-ion batteries at the distribution transformer level of $184/kWh by 2022 and $150/kWh by 2028. CEA estimates an optimal capacity mix by 2029–2030 to include 34,000 MW/136,000 MWh of grid-scale storage (CEA 2019). In consultation with battery suppliers and manufacturers, CEA assumes battery capital cost of Rs. 7 Cr/MW in 2021–2022 and Rs. 4.3 Cr/MW in 2029–2030 for a 4-hour discharge duration, equivalent to $250/kWh in 2021–2022 and $154/kWh in 2029–2030.[7] However, the CEA report does not break down total costs into components such as the battery pack, inverter/converter and other power electronics, control system, and so forth.

The Energy Transitions Commission (ETC) projects that the levelized cost of storage systems in India will fall from $0.41/kWh in 2018 to $0.17/kWh in 2030, while the levelized cost of solar plus 3 hours of storage will fall from $0.19/kWh to $0.09/kWh (ETC 2019). However, recent energy storage bids in the United States suggest that significantly lower price points would be achieved by 2021–2022 (see Section 2).

In this study, we estimate costs for utility-scale Li-ion battery systems through 2030 in India. The previous studies cited above neither estimated component-level costs nor estimated levelized costs of utility-scale storage systems using the latest global bid data. These cost inputs are critical for analyzing the costs and benefits of battery storage vs. conventional technologies for meeting the flexibility requirements of the Indian grid as penetration of variable RE increases. We base our analysis on recent U.S. power-purchase agreement (PPA) prices and bottom-up cost analyses of storage and solar photovoltaic (PV)-plus-storage systems, adapted to the Indian context.

2. Review of Recent U.S. Energy Storage Contracts

Several grid-scale PV-plus-storage and standalone storage projects are being developed in the United States, and some have already been commissioned. At the end of 2017, 708 MW of large-scale battery storage capacity (representing 867 MWh of energy capacity) was in operation in the United States (EIA 2018).

(Bolinger & Seel, 2018) track recent PV-plus-storage bids, finding an incremental PPA price adder[8] of $5/MWh for storage, down from $15/MWh in the preceding year for a similarly configured project (each using 4-hour batteries and about 13%–15% of PV generation for charging). Specifically, three projects for Nevada (NV) Energy were signed at a levelized price of 2–3 ¢/kWh, for 12%–13% of solar energy stored in the battery. (Bolinger & Seel, 2018) underscore that "utility-scale PV plus battery storage is on its way to becoming the 'new normal.'" (Bolinger et al., 2019) track characteristics of 38 PV-hybrid projects. Most of these projects have 4 hours of battery storage. Excess solar energy generated during the day would be stored in these batteries

[7] Assuming an exchange rate of 1 U.S. dollar = 70 Indian rupees.
[8] The "price adder" or "tariff adder" for a solar-plus-storage system is the additional cost of storage as spread over all units (kWh) generated from solar.

and could be supplied during evening or nighttime hours when PV is not generating. Projects in Hawaii tend to have a higher premium due to high battery-to-PV capacity ratios, weaker solar resource (compared to the U.S. Southwest), as well as the remoteness of Hawaii. Compensation methods vary across projects, including bundling the storage price into the overall PPA price and separate fixed capacity payments. Table 1 lists PV-plus-storage projects for which PPA prices were available.[9]

A recent solicitation by the Los Angeles Department of Water and Power (LADWP) for 400 MW of PV plus 1,200 MWh of battery storage resulted in more than 130 bids; the lowest was $19.97/MWh for PV and $19.65/MWh for storage, with 36% of PV energy used for battery charging (PV-Magazine-USA 2019). A 25-year PPA has been signed, for delivery in December 2023.

Developers are increasingly pairing solar projects with on-site batteries. Recent research has shown that, "additional revenues from adding a 4-hour battery to solar can exceed additional costs" (Gorman et al. 2020).

[9] We determine the percentage of PV energy based on project information in (Bolinger & Seel, 2018) using an average CUF by state for new projects.

Table 1. Overview of U.S. PV-Plus-Storage Projects

	Project				Capacity (MW)			Battery Storage			
State	**Name**	**Sponsor**	**Offtaker**	**Actual or Expected COD**	**PV**	**Battery**	**Hours**	**MWh**	**Battery: PV Capacity Ratio**	**% of PV Energy Used for Battery**	**Levelized PPA Price (2018 $/MWh)**
AZ	Pinal Central	NextEra	SRP	Apr-18	20	10	4.0	40	50%	25%	68.9
AZ	Wilmot	NextEra	TEP	Dec-19	100	30	4.0	120	30%	15%	40.7
CA	RE Slate 2	ReCurrent	MBCP and SVCE	Jun-21	150	45	4.0	180	30%	14%	≤31.8
CA	BigBeau	EDF-RE	MBCP and SVCE	Dec-21	128	40	4.0	160	31%	15%	≤30.9
CA	Eland	8minute Solar	LADWP/Glendale	Dec-23	400	300	4.0	1,200	75%	36%	38.9[10]
HI	Kapaia	Tesla	KIUC	Apr-17	13	13	4.0	52	100%	85%	119.8
HI	Lawai	AES	KIUC	Oct-18	20	20	5.0	100	100%	71%	89.4
HI	Kekaha	AES	KIUC	Sep-19	14	14	5.0	70	100%	77%	85.5
HI	Waikoloa Solar	AES	Hawaiian Electric	Jul-21	30	30	4.0	120	100%	64%	59.8
HI	Kuihelani Solar	AES	Hawaiian Electric	Jul-21	60	60	4.0	240	100%	64%	58.5
HI	West Oahu	AES	Hawaiian Electric	Sep-21	13	12.5	4.0	50	100%	64%	79.5
HI	Hoohana Solar 1	174 Power Global	Hawaiian Electric	Dec-21	52	52	4.0	208	100%	64%	76.3
HI	Mililani I Solar	Clearway	Hawaiian Electric	Dec-21	39	39	4.0	156	100%	64%	68.0

[10] The PPA price in this table was modified to match other public sources available (PV-Magazine-USA 2019); $39.62/MWh in 2019 $ is then deflated using an inflation rate of 1.77%, giving $38.93/MWh in 2018 $.

HI	Waiawa Solar	Clearway	Hawaiian Electric	Dec-21	36	36	4.0	144	100%	64%	74.0
HI	Hale Kuawehi	Innergex	Hawaiian Electric	Jun-22	30	30	4.0	120	100%	64%	65.8
HI	Paeahu	Innergex	Hawaiian Electric	Jun-22	15	15	4.0	60	100%	64%	87.9
NV	Battle Mountain	Cypress Creek	NV Energy	Jun-21	101	25	4.0	100	25%	12%	22.3
NV	Dodge Flat	NextEra	NV Energy	Dec-21	200	50	4.0	200	25%	13%	23.1
NV	Fish Springs Ranch	NextEra	NV Energy	Dec-21	100	25	4.0	100	25%	13%	25.9
NV	Arrow Canyon	EDF-RE	NV Energy	Dec-22	200	75	5.0	375	38%	24%	21.8
NV	Southern Bighorn	8minute Solar	NV Energy	Sep-23	300	135	4.0	540	45%	23%	21.9
NV	Gemini	Quinbrook/Arevia	NV Energy	Dec-23	690	380	3.8	1,460	55%	27%	25.1

COD = commercial operation date

In 2018, the incremental cost of storage (beyond that of PV alone) appears to be about half as much as it was in 2017. In early June 2018, NV Energy released details on three PV-plus-storage projects (Battle Mountain, Dodge Flat, and Fish Springs Ranch) where the storage adder came in at ~$5/MWh, i.e., 0.5 ¢/kWh, for 12%–13% of energy stored in the battery.

Source: (Bolinger & Seel, 2018), (Bolinger et al., 2019)

An Xcel Energy solicitation in December 2017 (for delivery in 2023) garnered 87 PV-plus-storage bids at a median of $36/MWh, equivalent to a storage adder of $0.006/kWh for unknown quantities of storage (Table 2) (Xcel Energy 2017). The median of 28 bids for standalone storage was $11.3/kW-mo, which is equivalent to $58/MWh.[11]

Table 2. Responses to Xcel Energy's Solicitation by Technology

Generation Technology	# of Bids	Bid MW	# of Projects	Project MW	Median Bid Price or Equivalent	Pricing Units
Combustion turbine/internal combustion engines	30	7,141	13	2,466	4.80	$/kW-mo
Combustion turbine with battery storage	7	804	3	476	6.20	$/kW-mo
Gas-fired combined cycles	2	451	2	451	[redacted]	$/kW-mo
Standalone battery storage	28	2,143	21	1,614	11.30	$/kW-mo
Compressed air energy storage	1	317	1	317	[redacted]	$/kW-mo
Wind	96	42,278	42	17,380	18.10	$/MWh
Wind and solar	5	2,612	4	2,162	19.90	$/MWh
Wind with battery storage	11	5,700	8	5,097	21.00	$/MWh
Solar (PV)	152	29,710	75	13,435	29.50	$/MWh
Wind, solar, and battery storage	7	4,048	7	4,048	30.60	$/MWh
Solar (PV) with battery storage	87	16,725	59	10,813	36.00	$/MWh
Internal combustion engine with solar	1	5	1	5	[redacted]	$/MWh
Waste heat	2	21	1	11	[redacted]	$/MWh
Biomass	1	9	1	9	[redacted]	$/MWh
Total	430	111,964	238	58,284		

Xcel Energy's solicitation in December 2017 resulted in more than 25 bids for standalone storage and more than 85 bids for solar-plus-storage, for delivery in 2023. The median bid for standalone storage was $11.3/kW-mo. The average duration of storage bids is 6.5 hours. Assuming daily cycling, the storage cost is $11.3/(6.5 kWh × 30) = 5.8 ¢/kWh.
Source: Xcel Energy (2017) All Source Solicitation 30-Day Report

Figure 2 plots PPA prices vs. percentage of PV energy stored in batteries from Table 1 and the median Xcel Energy standalone storage bid (orange square). PPA prices vary by the ratio of battery to PV capacity, the percentage of PV output used to charge the battery, and the location. For example, the projects in Hawaii have relatively high PPA prices, ratios of battery to PV capacity, and percentages of PV output used to charge the battery. All else equal, the longer the discharge cycle, the lower the price per MWh, because the power-rating-based costs (such as inverter and soft costs) get distributed over a larger number of units. The bid prices in Nevada and Los Angeles

[11] The average duration of storage bids is 6.5 hours. Assuming daily cycling, the storage cost is $11.3/(6.5 kWh × 30) = $0.058/kWh.

for a 4-hour battery discharge cycle, which would be equivalent to intermediate load replacement, are already in the ballpark of wholesale electricity prices in California.[12]

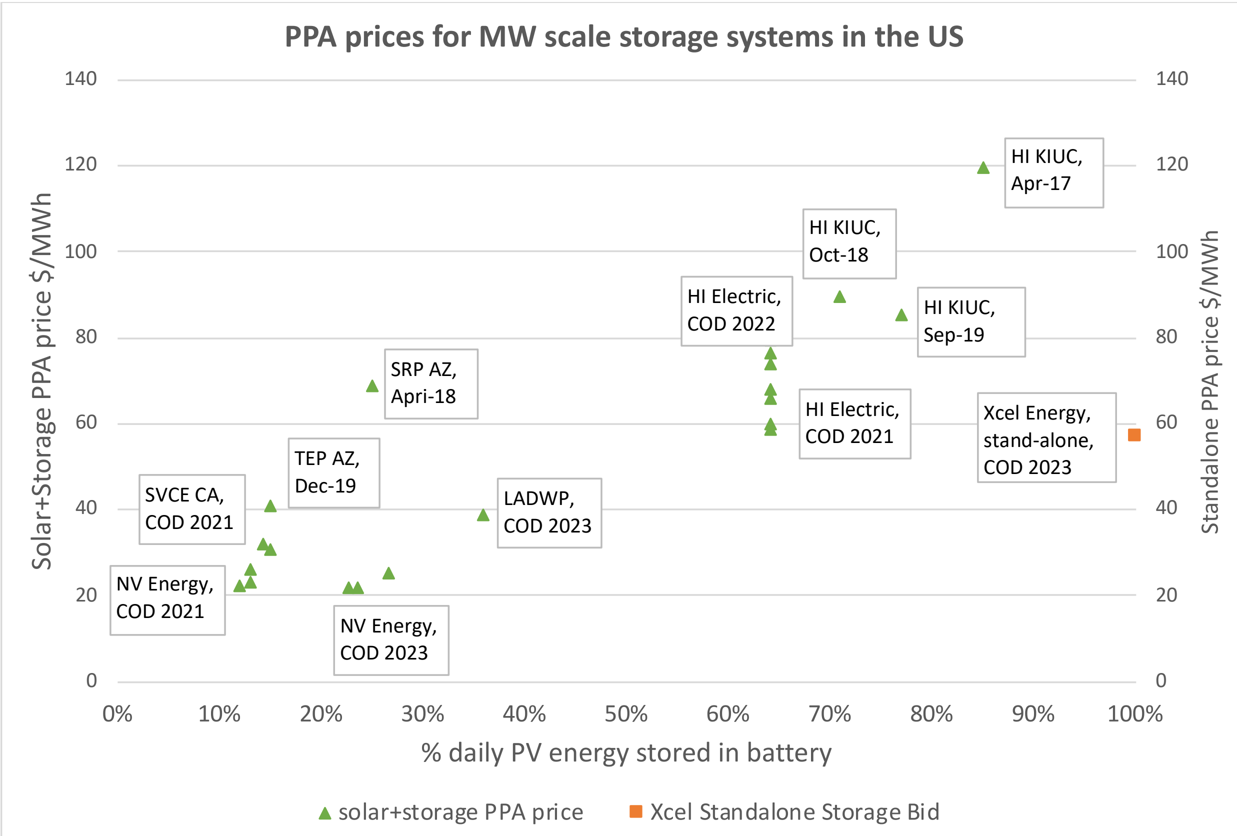


Figure 2. U.S. PV-plus-storage PPA prices vs. percentage of PV energy stored in batteries

We plot PV-plus-storage PPA prices (Bolinger et al., 2019) along with the median Xcel Energy standalone storage bid (Xcel Energy 2017).

3. Methods

This section summarizes our two-pronged method. First, we scale U.S. PPA prices (Figure 2) to indicate bid prices Indian utilities could expect, notwithstanding some benefits of economies of scale in the United States. The U.S. data points are first scaled up by 30% to remove the effect of the federal Investment Tax Credit (ITC), and then these unsubsidized prices are scaled to account for India's higher financing costs. For scaling the storage prices to India, we use the ratio of capital recovery factors, assuming an interest rate of 5.5% for the United States based on (Bolinger et al., 2015), and a rate of 11% for India based on Central Electricity Regulatory Commission (CERC) RE Tariff Order 2017-18 (CERC 2017).[13] An implicit assumption here is that, at scale, the capital cost of battery packs and core control system components would be very similar in the United States and India, mainly because of the globalized supply chain of batteries.

[12] Per EIA (2019), as of 07/23 2019, the weighted-average wholesale price in California was $37.03/MWh.
[13] Refer to Appendix I for details on how we estimated the capital recovery factors.

The solar price is scaled by a ratio of currently available average PPA price data, based on Bridge to India (2019) for India and (Bolinger et al., 2019) for the United States. Additionally, we demonstrate the effect of duties and taxes. As per industry sources, basic custom duty (BCD) for the battery pack is 5.5%, if sourced from China and deployed in non-EV applications; 10% Cess[14] is computed on BCD, plus 18% integrated goods and services tax (IGST) is applicable. If sold as part of a solar solution, IGST is 5%. Thus, we consider duties-plus-taxes to be in the range of 11%–24%.[15]

While commercial bids received are one indication, a more detailed bottom-up cost estimation is warranted to validate that the bid numbers are not outliers. For this second method, we hypothesize that a battery storage system is structurally similar to a PV system, wherein panels are replaced with battery packs, and a bidirectional inverter is deployed, along with the balance of system (BoS). Battery and PV BoS elements are similar (Table 3). We assume the cost of PV mounting structures is equivalent to the cost of battery thermal management systems. Therefore, with the exception of inverter costs—which would be higher for standalone BESS (for a bidirectional inverter) and absent in a co-located PV-plus-storage system (due to inverter sharing)—BoS costs are expected to be similar.

To determine the scaling factor between India and U.S. capital costs of a PV system, we look at the component-level cost breakdown of a typical MW-scale plant. For the United States, we use benchmark costs from the National Renewable Energy Laboratory (Fu et al. 2016). For India, we source the costs from CERC RE Tariff Order 2016-17 (CERC 2016).

Our analysis harmonizes the line items that are grouped into various cost components for utility-scale PV plants in the United States and India. We exclude permitting/interconnection fees, land costs, and taxes from the U.S. cost, because these items are highly localized, and some of the equivalent Indian cost components are unavailable. We also exclude inverter cost from the comparison, because we assume this cost is the same for BESS in India until the local market for bidirectional inverters matures.

The resulting ratios for scaling from U.S. costs to Indian costs are as follows, and the appendix provides further details:

- BoS (excluding inverters): -49%
- Engineering, procurement, and construction (EPC): -78%
- Soft costs: -60%

We apply the same scaling factors to a bottom-up cost estimate available for U.S. BESS from Fu et al. (2018)[16] to arrive at a BESS cost estimate for India. However, the pack prices are taken from BNEF (Figure 1), with total capital costs expressed in 2018 dollars.

[14] Cess is an additional tax (on tax) levied by the Indian Government for a specific purpose.

[15] We do not account for additional transportation costs.

[16] Frankel et al. (2018) also estimate component-level BESS costs, which are similar to the costs in Fu et al. (2018) except for soft costs, but that difference becomes less consequential for 4-hour systems. Because Fu et al. (2018) provide a more detailed breakdown of cost components, we use costs from that source.

Table 3. BoS Comparison Between Storage and PV projects

BoS for BESS	BoS for PV
Power conditioning system/bidirectional inverters	Power conditioning units/inverters
Weatherproofing, thermal design for components, heat-removal system, air-handling systems, filters to prevent dust intrusion	String combiner box with mounting structures
Step-up transformers	Step-up transformers
Low-tension (LT) and high-tension (HT) switchgear and panels	LT and HT switchgear and panels/ring main unit (RMU)
Performance monitoring and data acquisition/ supervisory control and data acquisition (SCADA)	SCADA
Protection and control	Protection and control
Auxiliary power system	Auxiliary supply system, uninterruptible power supply (UPS)
Wiring/cables - HT/LT/communication	Wiring/cables - HT/LT/communication
Controls and communication	Controls and communication
Auxiliaries and other design requirements: closed-circuit television (CCTV), weather monitoring station (WMS), illumination, fire alarm	Auxiliaries and other design requirements: CCTV, WMS, illumination, fire alarm

Source: SECI (2019a) for BESS, various industry sources for PV

Levelized cost of storage (LCOS) is the discounted cost per unit of discharged electrical energy (Schmidt et al. 2019), analogous to the levelized cost of electricity (LCOE) metric used for powerplants. Costs include capital costs, O&M costs, charging costs, and a credit for end-of-life value. The energy supplied is reduced by depth of discharge and a minor annual degradation rate. We compute LCOS using the equation below (assumptions listed in Table 4). The equation excludes charging cost, because we assume that excess RE is available to charge the battery at zero marginal cost.

$$LCOS\ (\$/kWh) = \frac{CAPEX}{\#cycles * DOD * C_{rated} * \sum_{n=1}^{N} \frac{(1-DEG*n)}{(1+r)^n}} + \frac{O\&M * \sum_{n=1}^{N} \frac{1}{(1+r)^n}}{\#cycles * DOD * C_{rated} * \sum_{n=1}^{N} \frac{(1-DEG*n)}{(1+r)^n}} - \frac{\frac{V_{residual}}{(1+r)^{N+1}}}{\#cycles * DOD * C_{rated} * \sum_{n=1}^{N} \frac{(1-DEG*n)}{(1+r)^n}}$$

Table 4. Assumptions for Calculating LCOS

Variable	Value
Exchange rate[17]	70 Rs./$
Total charging/discharging cycles available	3,650 cycles
Full charging/discharging cycles per year	365 cycles
Project lifetime (N)	10 years*
Depth of discharge (DOD)	90%
Rated capacity (C_{rated})	1 kWh
Annual degradation rate of capacity (DEG)	1.0% per year
Interest rate (r)	11%
O&M cost, assumed to be constant (O&M)	1% of CapEx
Residual project value after lifetime ($V_{residual}$)	10% of CapEx

CapEx = capital expenditure.
* Estimates of Li-ion battery lifetimes vary. Our estimate of 10 years is based on Schmidt et al. (2019). In addition, grid-scale storage does not require very high density, so Li-ferrous-phosphate (LFP) technology could be a practical option. LFP is purported to have longer life compared with nickel-manganese-cobalt (NMC), for example.

4. Results

Here we present our results in four subsections: estimates from scaling U.S. bids (4.1), Indian PV-plus-storage and standalone storage costs from bottom-up analysis (4.2), LCOS (4.3), and a sensitivity analysis (4.4).

4.1 Estimates for PV-Plus-Storage Systems from Scaling U.S. Bids

Table 5 gives the Indian PPA price estimates based on the U.S. PPA prices from Figure 2 (for cases with COD in the future), scaled for higher financing cost.[18] For example, the range of subsidized NV Energy PPA prices is $22.3–$25.9/MWh (Table 1) or $31.9–$37.0/MWh unsubsidized, which scale to Indian estimates of $42.5–$49.5/MWh or Rs. 2.98–3.46/kWh. For systems with 12%–13% PV energy routed via battery, the estimates for deployment in 2021 are in the same ballpark as current solar PPA prices in India, with a premium of about 20%. Estimates including duties and IGST are about Rs. 3.1–3.6/kWh, not incorporating exchange rate fluctuations. The estimate for a standalone system based on the Xcel Energy PPA is Rs. 7.29/kWh.

[17] The exchange rate risk may change our cost estimates for future years. However, that depends on several macroeconomic factors and is outside the scope of this study. In this report, we assume a single exchange rate for ease of comparison across years: 1 U.S. dollar = 70 Indian rupees.
[18] We are able to estimate only for cases where the storage cost component is available separately, from (Bolinger & Seel, 2018).

Table 5. India Estimates for Storage PPAs Derived by Scaling U.S. Market Data

Offtaker (COD)	Solar MW	Battery MWh	% of PV MWh Stored in Battery	PPA price ($/MWh, 2018 dollars)	Unsubsidized ($/MWh, 2018 dollars)	India Estimate ($/MWh, 2018 dollars)	India Estimate (Rs./kWh)	Estimate Including Duties & IGST[19] (Rs./kWh)
NV Energy (June 2021)	100	100	12%	22.30	31.86	42.53	2.98	3.05–3.13
NV Energy (Dec 2021)	200	200	13%	23.10	33.00	44.08	3.09	3.16–3.24
NV Energy (Dec 2021)	100	100	13%	25.90	37.00	49.48	3.46	3.53–3.62
TEP AZ (Dec 2019)	100	120	15%	40.70	58.14	77.03	5.39	5.60–5.85
LADWP (2023)	400	1,200	36%	38.93	55.61	73.18	5.12	5.39–5.72
Xcel Energy - standalone (2023)	N/A	variable	N/A	56.94	81.34	104.11	7.29	8.09–9.04

4.2 Indian PV-Plus-Storage and Standalone Storage Costs Using Bottom-up Analysis

The detailed breakdown of standalone storage capital costs from Fu et al. (2018)—shown in Table 6—enables us to map and group the cost components to the corresponding cost categories in a PV system. Fu et al. develop a detailed bottom-up model for cost structure of a traditional Li-ion battery, broken into EPC costs (hardware and other costs) and developer costs. They adapt EPC cost models from RSMeans,[20] and they determine costs for different battery durations for MW-scale battery systems.

[19] Range of duties & taxes is assumed to be 11%-24%

[20] RSMeans is a leading construction cost database in North America; Fu et al. use the 2017 version of the database.

Table 6. Bottom-up Cost Estimates of U.S. Utility-Scale Li-ion Battery Systems with Durations of 1 and 4 Hours, from Fu et al. (2018)

Category	Component	1-hour (1 MW/1 MWh) System ($/kWh)	4-hour (1 MW/4 MWh) System ($/kWh)
Battery pack	Li-ion battery	209	209
BOS hardware	Battery central inverter	70	18
	Structural BOS	19	13
	Electrical BOS	81	36
EPC	Installation labor and equipment	62	23
	EPC overhead	26	12
Soft cost	Sales tax	33	22
	Developer cost (including EPC and developer net profit)	100	49
	Total	**600**	**382**

Fu et al. build a PV-plus-storage model for several system configurations to determine benchmark costs for grid-scale storage systems. The battery cost accounts for 55% of total system cost in the 4-hour system, but only 35% in the 1-hour system. For the baseline case, 4-hour storage is assumed according to the California Public Utilities Commission's "4-hour rule," which credits storage that can operate for 4 or more consecutive hours with the ability to provide reliable peak capacity.

Except for battery pack costs that stay the same per kWh, other BoS, EPC, and soft costs are spread over a larger battery capacity—and hence are lower per kWh—for a battery with the same MW rating but higher MWh capacity. Table 7 shows the resulting scaling ratios by cost component.

Table 7. Cost Scaling Ratios Between 1- and 4-Hour Battery Systems, Based on Fu et al. (2018)

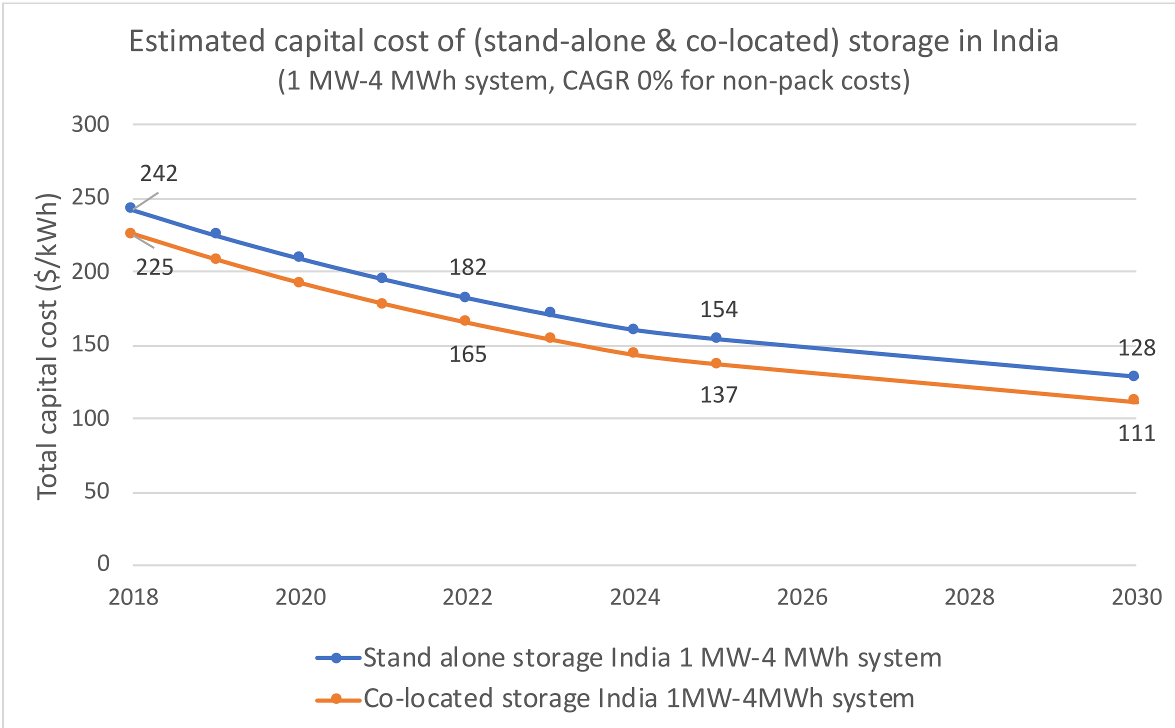
Component	1-hour (1 MW/1 MWh) System ($/kWh)	4-hour (1 MW/4 MWh) System ($/kWh)	Scaling Ratio Between 1- and 4-Hour System
BoS	100	49	-51%
Inverter	70	18	-74%
EPC	88	35	-60%
Soft cost (excluding taxes, land, permitting and interconnection fees)	61	39	-36%

Because many early storage projects are expected to be co-located with PV plants, we estimate storage costs for such a system as well. Denholm et al. (2017) conclude that a direct current (DC)-coupled PV-plus-storage system could save about 40% in BoS costs due to sharing of the inverter, cabling, and so forth. Table 8 combines this factor with our other scaling factors. Current India standalone and co-located system costs are hence estimated to be 31% lower than costs in the United States.

Table 8. Complete Scaling of U.S. to India Battery Cost Components (2018)

	U.S.	Scaling Ratio (U.S. to India)	India			
Component	**U.S. 1 MW/ 1 MWh System (standalone) ($/kWh)**		**India 1 MW/ 1 MWh System (standalone) ($/kWh)**	**Scaling Ratio (1-hour to 4-hour system)**	**India 1 MW/ 4 MWh System (standalone) ($/kWh)**	**India 1 MW/ 4 MWh System (with PV) ($/kWh)**
Battery pack (from Figure 1)	176	0%	176	0%	176	176
BoS	100	-49%	51	-51%	25	15
Inverter	70	0%	70	-74%	18	11
EPC	88	-78%	20	-60%	8	8
Soft cost (excluding taxes, land, permitting and interconnection fees)	61	-60%	25	-36%	16	16
Total	**495**		**341**		**242**	**225**

Because grid-scale batteries are expected to play a crucial role as penetration of variable RE increases on the Indian grid over time, we attempt to project future capital costs of BESS in India. We use the cost assessment in Table 8 and the battery pack price projections from Figure 1 to examine two scenarios of Indian storage costs over time. Figure 3 shows the results of the first scenario, in which non-pack costs remain constant. Figure 4 shows the results of the second scenario, in which non-pack costs decline at a nominal rate of 5%. This is a plausible scenario for India, with an assumed average inflation rate of 5%, i.e., the price per component is declining in real terms but fixed in nominal terms. In this scenario, the projected capital cost of a 1-MW/4-MWh PV co-located BESS in India drops to $122/kWh by 2025 and $92/kWh by 2030, which are 46% and 59% lower than the current estimated capital cost. Table 9 gives the component-level capital cost estimates for both a standalone and a PV co-located BESS for the second scenario. Further details can be found in the appendix.



CAGR = compound annual growth rate.

Figure 3. Estimated cost of BESS in India, with reduction only in pack prices

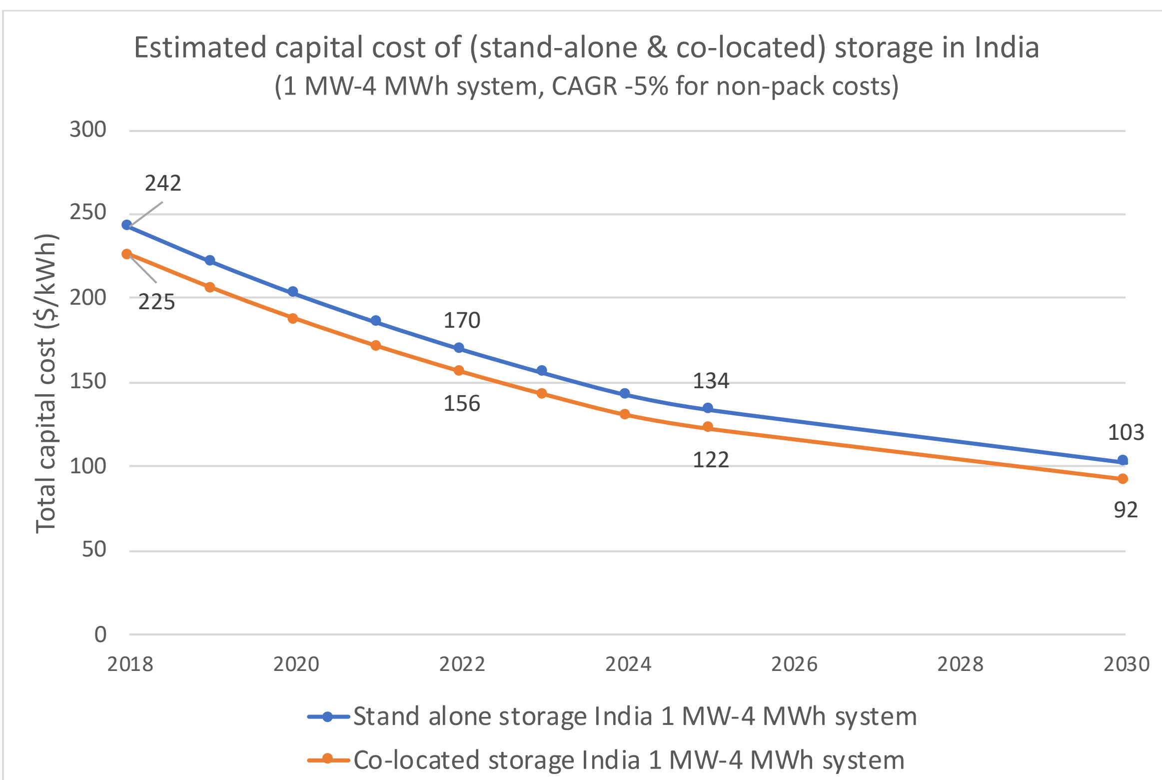


Figure 4. Estimated cost of BESS in India, with 5% annual reduction in non-pack prices

Table 9. CapEx Estimates for BESS in India with a 5% Annual Reduction in Non-Pack Prices

CapEx Estimates for 1 MW/4 MWh BESS in India	Standalone Year/Cost ($/kWh)			PV Co-located Year/Cost ($/kWh)		
Components	**2020**	**2025**	**2030**	**2020**	**2025**	**2030**
Battery pack	143	88	62	143	88	62
BoS hardware	22	17	15	13	10	9
BoS inverter	16	13	11	10	8	7
Soft costs	7	5	5	7	5	5
EPC	14	11	10	14	11	10
Total CapEx ($/kWh)	**203**	**134**	**103**	**187**	**122**	**92**

4.3 Levelized Cost of Storage (LCOS)

We use our capital cost estimates and the assumptions in Table 4 to estimate the LCOS for 4-hour battery storage (at rated capacity) in India. We assume a 20-year PPA contract for standalone battery storage systems as well as for PV-plus-storage co-located systems. For such a contract, we assume the battery is replaced at the end of year 10; the net present value (NPV) of the battery pack replacement cost in that year is added to the upfront capital cost.[21] For projects deployed in 2025 and 2030, we use the 2030 battery pack cost as the replacement cost.[22]

Figure 5 plots our LCOS estimates. We estimate that, by 2022, the LCOS would be about Rs. 6.13/kWh for a standalone BESS and Rs. 5.72/kWh for a BESS co-located with PV. By 2025, the LCOS of a co-located BESS would drop to Rs. 4.70/kWh, and by 2030 it would be less than Rs. 4/kWh. It is important to note that LCOS refers to the per-kWh cost of the electricity that is stored in and discharged by the battery.

For batteries co-located with PV (or any other generator), only a fraction of the total energy generated by the powerplant likely will be stored in the battery. Therefore, to estimate the total per-kWh cost of the co-located system, LCOS may not be directly added to the solar tariff. The battery cost needs to be spread over the entire amount of solar generation to determine the aggregate per-kWh cost of the system. ***Hence, for BESS co-located with solar (or other projects), a more appropriate metric for assessing the additional cost of storage would be a tariff adder, i.e., the additional battery cost when added to the solar (or other) PPA price.***

[21] NPV for pack replacement is determined using a discount factor of Real Interest Rate = Nominal Interest Rate – Average Inflation Rate, where average inflation is 5%.
[22] This is a conservative assumption, that battery pack prices become fairly steady after 2030.

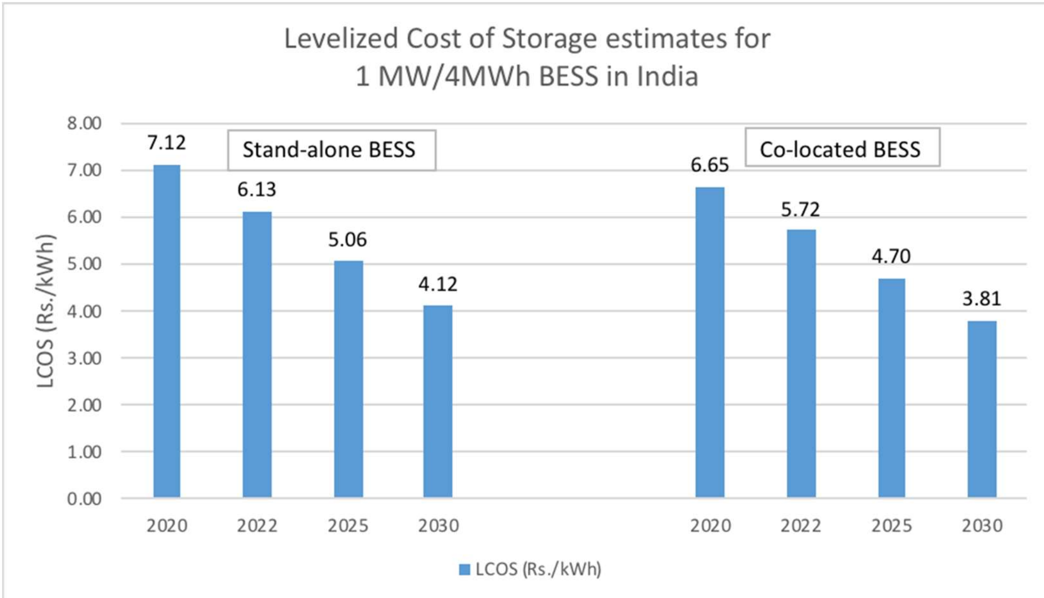


Figure 5. Estimated LCOS for standalone and co-located BESS in India

To quantify the tariff adder, we determine the annualized cost of storage and spread it over the units generated by PV. Figure 6 plots the tariff adder (in orange) on top of the solar tariff, based on the percentage of PV energy that is stored in the battery, for 2020. The adder increases proportionately as battery capacity vis-à-vis solar output is increased. For 25%[23] PV energy used to charge the battery and thereafter supplied by the battery, the tariff adder is estimated at Rs. 1.44/kWh in 2020, declining to Rs. 1.0/kWh by 2025. Assuming a solar PPA priced at Rs. 2.5–3.0/kWh (Bridge to India 2019), a combined PV-plus-storage PPA for FY 2020 could be estimated at Rs. 3.94–4.44/kWh.

For example, such a PPA price might be obtained for a 100-MW PV system generating an average of 480 MWh/day with a 30-MW battery system using 120 MWh for charging. Reducing the amount of PV energy consumed by the storage system would reduce the PPA price. For example, reducing the battery capacity to be equivalent to 12.5% of PV generation would halve the tariff adder as well, to Rs. 0.72/kWh by 2020, and to Rs. 0.67/kWh by 2021. The PV-plus-storage PPA estimate for 2021 would then be Rs. 3.17/kWh (assuming a solar tariff of Rs. 2.5/kWh), which is within the range of tariff estimates obtained from U.S. market data (Table 5). Similarly, for 33% of PV energy stored in the battery, the total tariff is estimated at Rs. 4.02/kWh in 2023, which is also comparable to the estimate based on U.S. market data. The marginal cost of coal units dispatched in several parts of India is Rs. 4–4.5/kWh[24] today. As the PLF of coal plants declines, the per-unit total cost (due to fixed cost recovery) increases.

The tariff adder will continue to decline as battery costs fall. By 2025, the tariff adder for 25% PV energy stored in the battery is projected to fall to Rs. 1.02/kWh (Figure 7), and to Rs. 0.83/kWh

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[23] Abhyankar et al. (forthcoming) show that, in India, for integrating the proposed RE capacity of 450 GW by 2030, about 150–200 GWh of battery storage (< 10% of average daily RE generation) is sufficient if the entire agricultural load could be shifted to solar hours. In the absence of agricultural load shifting, the battery storage requirement would be 300–400 GWh (about 15%–20% of average daily RE generation).
[24] As obtained for several days in October and November 2019 on meritindia.in.

by 2030 (Figure 8). Therefore, the estimated price for a PV-plus-storage PPA would be Rs. 3.32/kWh by 2025, falling to Rs. 2.83/kWh by 2030.[25]

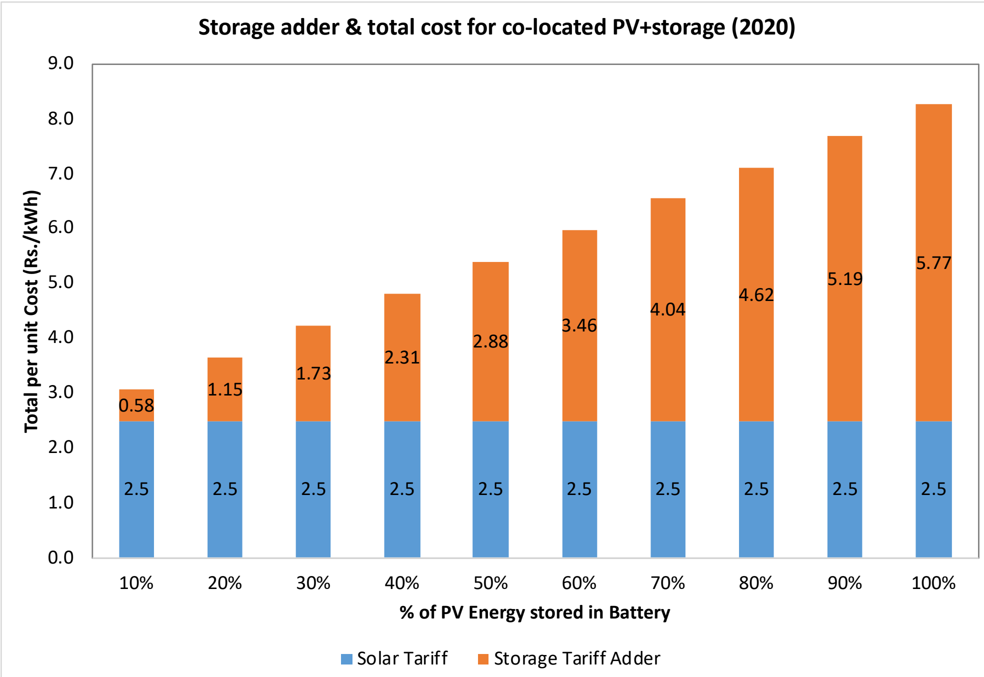


Figure 6. Solar tariff and storage tariff adder vs. percentage of PV energy stored in the battery, for year 2020

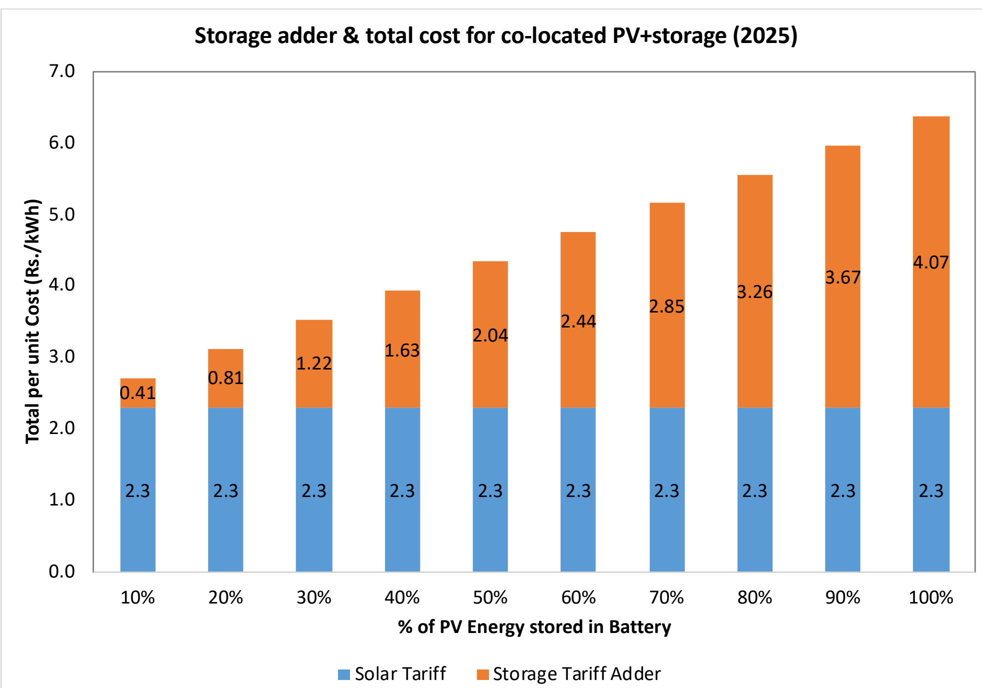


Figure 7. Solar tariff and storage tariff adder vs. percentage of PV energy stored in the battery, for year 2025

[25] Benchmark solar PPA price in 2025 = Rs 2.3/kWh; in 2030 = Rs 2.0/kWh (Abhyankar et al. forthcoming).

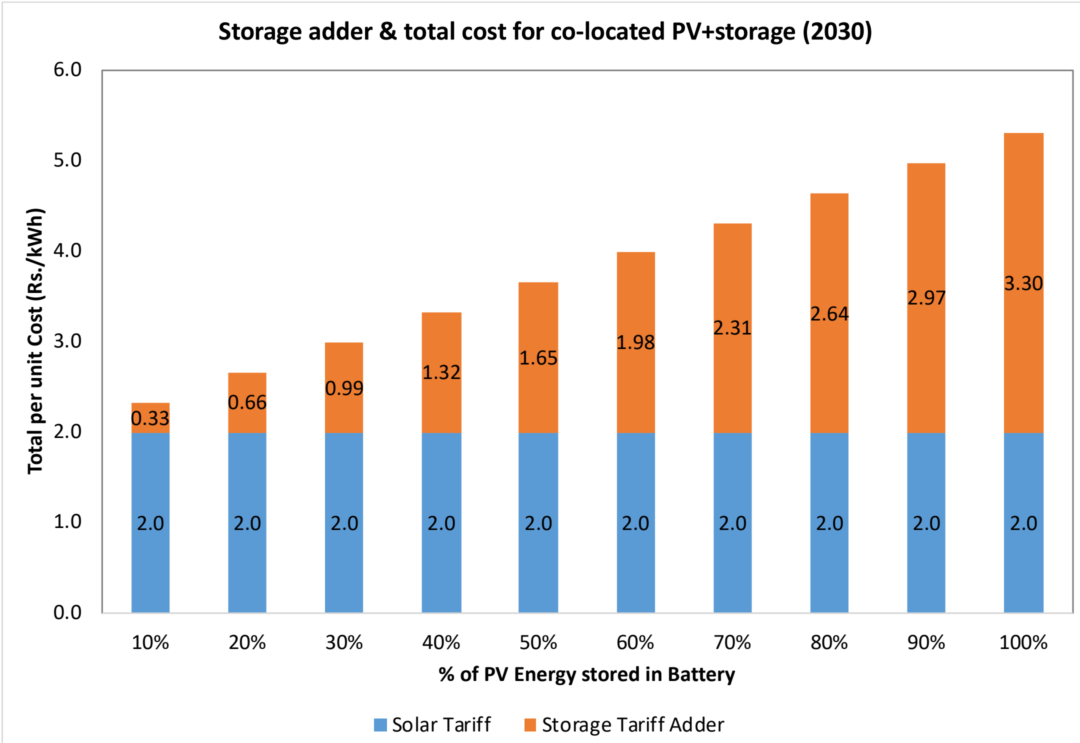


Figure 8. Solar tariff and storage tariff adder vs. percentage of PV energy stored in the battery, for year 2030

Thus, our bottom-up estimates align well with the scaled market prices, which validates the market bids (showing they are not outliers) and suggests such prices could be achieved in India as well. ***This analysis assumes the industry operates at scale—and hence can obtain international battery pack prices—and it does not include land costs, taxes, and fees.*** Table 5 demonstrates the impact of duties and taxes, which do not have a proportionate impact on the total tariff, because storage is a fraction of the total cost.

However, it is imperative to note the following additional factors in this analysis. First, the method of scaling PPA prices does not account for differences in CUF between India and the United States. Second, the bottom-up BESS cost estimates exclude certain costs such as transportation, contingencies, and the impact of exchange rate fluctuations. Third, our assumption that non-battery-pack system costs remain fairly steady over the next several years is conservative. Frankel et al. (2018) project rapidly decreasing battery BoS and soft costs over the next decade. Because the U.S. industry has a head start over India's industry (with 40% of the world's grid-scale battery storage installations to date), it might take longer for India to realize similar cost reductions as its industry matures. We also assume daily cycling of the battery, which is important to keep LCOS low.

In contrast, our capital cost estimates for standalone BESS are significantly (~33%) lower than the battery investment assumptions in CEA (2019). In the absence of details on CEA's assumptions, we speculate that CEA may not account for synergies between the EV and grid-scale battery industries and resulting global economies of scale.[26]

Policy and regulatory interventions have played a major role in development of the battery industry and large-scale battery deployment in the United States. In addition to rulings by the Federal Energy Regulatory Commission that created a level playing field for battery storage projects to participate in wholesale electricity markets, several state-level policies (such as a storage procurement mandate in California) have created early demand for battery storage. The evolution of business models for grid-scale batteries in India will also depend heavily on the policy and regulatory frameworks put in place over the next few years. India has announced plans to establish battery manufacturing plants with a total capacity of 50 GW (Singh 2019). With large-scale local manufacturing, India may further transform the economics of grid-scale battery systems.

4.4 Sensitivity Analysis

We consider a standalone BESS along with a PV-plus-storage co-located system installed in 2020. We determine the sensitivity of LCOS to changes in three important variables: discount rate (baseline value is 11%), battery life (baseline value is 3,650 cycles), and capital cost (baseline values are $203/kWh for standalone and $187/kWh for co-located), in the year 2020 (Figure 9). For sensitivity to capital cost, we separate the impact of battery pack vs. BoS costs. That is, in one case we estimate the effect on LCOS if battery pack costs are 10% to 20% lower/higher than our baseline estimates, while keeping BoS costs constant. In the second case, we examine the sensitivity of LCOS if BoS costs are 10% to 20% lower/higher than the baseline, while keeping pack-only costs constant.

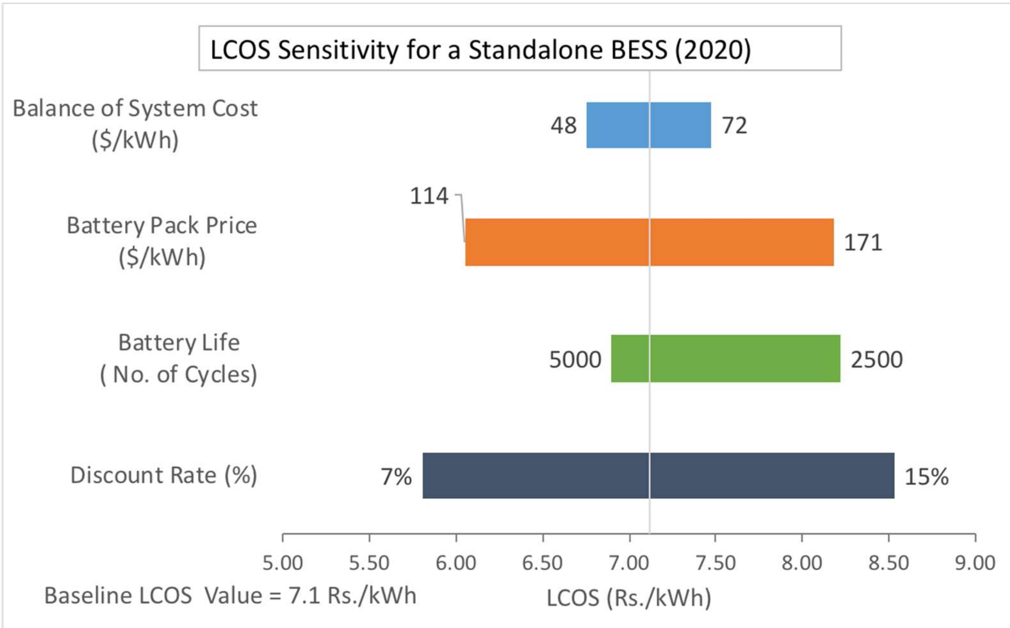
A discount rate range of 7%–15% is plausible depending on the cost of capital: the low end represents low-cost financing from a multilateral institution, whereas the high end corresponds with commercial lending for a new technology project. Discount rate has the largest effect in our sensitivity analysis, altering the LCOS of a standalone system by 18%–20% at the high and low ends. This demonstrates the importance of policy interventions to lower financing costs for projects based on new technologies.

We vary the battery life between 2,500 and 5,000 cycles, finding that LCOS for a standalone system could increase by 15% at 2,500 cycles (about 7 years, requiring two battery pack replacements during a 20-year contract). On the other hand, assuming a longer battery life of 5,000 cycles does not reduce LCOS by much, because a 20-year contract still requires one pack-replacement cycle.

In our baseline cost estimate, the pack costs constitute 70%–76% of total capital costs, depending on whether the system is standalone or co-located with PV. Therefore, the LCOS estimate is highly sensitive to pack costs, varying by as much as 15% if the actual pack costs in 2020 are 20% higher/lower than our assumptions. As global Li-ion battery manufacturing continues to expand

[26] Our analysis and the CEA analysis both assume a battery life of 10 years. CEA assumes an O&M cost equivalent to 2% of CapEx, whereas we assume 1%.

due to EV demand, battery pack price projections are expected to become more reliable. Sensitivity for the year 2030 can be found in the appendix.



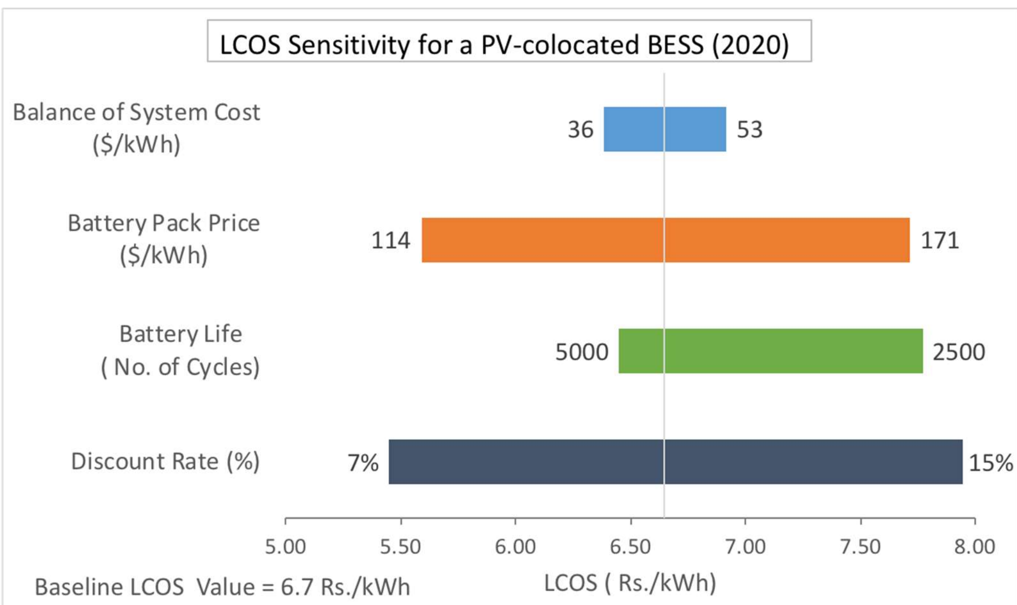


Figure 9. Sensitivity of LCOS to key assumptions for standalone storage (top) and storage co-located with PV (bottom) in 2020

Table 10 shows the sensitivity of a PV-plus-storage system tariff to battery CapEx and the percentage of PV energy routed through the battery, in 2020, assuming a PV tariff of Rs. 2.5/kWh. Our CapEx estimate for a co-located system in 2020 is $222/kWh. Even if the storage CapEx is 35% higher—reaching $300/kWh—the total tariff for a system with 30% of PV energy stored in the battery only increases by 14%.

Table 10. Sensitivity of PV-Plus-Storage System Tariff (Rs./kWh) to CapEx and Percentage of PV Energy Stored in Battery for the Year 2020

CapEx ($/kWh) vs % of PV Energy Stored	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
150	2.89	3.28	3.67	4.06	4.45	4.84	5.23	5.62	6.01	6.40
200	3.02	3.54	4.06	4.58	5.10	5.62	6.14	6.66	7.18	7.70
222	3.08	3.65	4.23	4.81	5.38	5.96	6.54	7.12	7.69	8.27
250	3.15	3.80	4.45	5.10	5.75	6.40	7.05	7.70	8.35	9.00
300	3.28	4.06	4.84	5.62	6.40	7.18	7.96	8.74	9.52	10.30

5. Conclusion

We adopt a two-pronged approach to estimate the costs of Li-ion based MW-scale battery storage systems in India. First, we examine market data from the United States, where several utilities have signed long-term PPAs for PV-plus-storage projects. We scale the contract prices to account for India's higher financing costs. At the low end—for Nevada projects coming online in 2021, with 12%–13% of PV energy used to charge the battery—PPA prices are in the range $0.032–$0.037/kWh (unsubsidized equivalent). When we scale these values to the Indian context, we estimate PPA prices of $0.043–$0.05/kWh (Rs. 3.0–3.5/kWh). These prices are 9%–27% higher than current PV PPA prices in India (which are around Rs. 2.75/kWh). These market-based estimates assume at-scale deployment and an appropriate policy and regulatory framework.

Second, we undertake a bottom-up analysis to estimate capital costs for MW-scale battery storage projects in India, with projections to 2030. Our analysis suggests that capital costs for batteries co-located with PV would fall to $187/kWh in 2020 and $92/kWh in 2030 (excluding land costs, taxes, and fees). The LCOS of standalone BESS is estimated to be Rs. 7.12/kWh ($0.10/kWh) by 2020, Rs. 5.06/kWh ($0.07/kWh) by 2025, and Rs. 4.12/kWh ($0.06/kWh) by 2030. LCOS here refers to the per-kWh cost of the electricity stored in and discharged by the battery. For BESS co-located with PV (or other projects), a tariff adder is a more appropriate metric for assessing the additional contribution of storage to the PPA price. The additional per-unit cost for a PV-plus-storage system, or the tariff adder for a battery charged using 25% PV energy, is estimated to be Rs. 1.44/kWh ($0.02/kWh) in 2020, Rs. 1.02/kWh ($0.014/kWh) in 2025, and Rs. 0.83/kWh ($0.01/kWh) in 2030. This implies that PV-plus-storage bids could be Rs. 3.94/kWh ($0.056/kWh) by 2020, Rs. 3.32/kWh ($0.047/kWh) by 2025, and Rs. 2.83/kWh ($0.040/kWh) by 2030. These values approximate closely with the market-estimated prices, and they are already competitive with the marginal cost of coal units that are currently dispatched in several states in India. Additionally, these costs are inflation-proof; they are flat for the next 25 years, while coal prices may keep increasing each year. In the future, the cost difference between PV-plus-storage assets and thermal assets likely will increase. Therefore, new investments in thermal power plants with lifetimes of 25–30 years may present extreme financial risk.

Such low battery storage prices, coupled with low RE prices, could disrupt how India plans to meet its growing energy needs. Not only do RE (especially PV) and storage systems offer a strong economic case, but also their planning and development cycles are much shorter than those of conventional thermal power plants (1–1.5 years compared with 4–6 years). As a result, deploying RE and storage systems could largely mitigate the risk of energy supply undershooting or overshooting energy demand in a dynamic economy.

However, concerted policy and regulatory efforts are needed to scale-up India's RE and storage deployment and achieve the low prices that we estimate are possible. Such efforts could include a clear policy direction to boost domestic battery manufacturing via guaranteed demand as well as a roadmap for skill development and the addition of new jobs.

This analysis only presents an economic case for battery storage systems and does not investigate the technical and operational feasibility of replacing new coal investments with PV-plus-storage. Such considerations require a comprehensive grid-dispatch analysis, which is the focus of our ongoing and future work. In an upcoming report, we will analyze how grid-scale battery storage can integrate with India's resource planning over the next decade, along with the associated impacts on electric system costs. In the meantime, the economic analysis presented in this report might facilitate cost-benefit analysis for capacity-expansion and investment decisions in India.

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Appendix

I. Scaling U.S. Market Prices for India

To scale prices of U.S. PV-plus-storage projects, we first determine distinct scaling factors for the PV and storage components of the tariff. For scaling the PV component, we compare average U.S. PV PPA prices against average Indian prices in 2019. Large-scale projects in India are mostly located in high-resource areas, but U.S. projects are distributed across areas with more variable solar resources. Therefore, we use the average PPA price in the high-resource U.S. Southwest for this comparison: $20/MWh in 2018 dollars[27] (Bolinger et al. 2019). For India we assume the median of the range Rs. 2.5–3.0/kWh from Bridge to India (2019).

- Average India PV price ($) 3.93 ¢/kWh
- Average U.S. PV price (2019 $) 2.04 ¢/kWh
- Unsubsidized U.S. PV price (2019 $) 2.91 ¢/kWh
- Scaling ratio (India-U.S.) 1.35

For Li-ion battery projects, we approximate the scaling factor by examining the impact of financing costs, with an implicit assumption of equivalent capital costs:

- Interest rate 5.5% (U.S.), 11% (India)
- Capital recovery factor (for $1, over 10 years) 0.13 (U.S.), 0.17 (India)
- Scaling ratio (India-U.S.) 1.28

We use these ratios to scale U.S. market prices of storage and PV-plus-storage projects to India (Table 11). We also demonstrate the effect of customs duty and taxes in India on these estimates.

[27] The average U.S. inflation rate for 2010–2019 was 1.77 (source: https://www.usinflationcalculator.com/inflation/historical-inflation-rates/).

Table 11. Scaling U.S. Market Prices to India

Utility (COD)	% of PV MWh used	Battery storage hours	Total PV-plus-storage PPA price ($/MWh, 2018$)	Solar component ($/MWh, 2018$)	Unsubsidized total ($/MWh, 2018$)	Total PV-plus-storage India Estimate ($/MWh), 2018$	Total PV-plus-storage India Estimate (Rs./kWh)	Estimate with 11% Duty on storage (Rs./kWh)	Estimate with 24% Duty on storage (Rs./kWh)
NV Energy (Jun 2021)	12%	4	22.30	17.30	31.86	**42.53**	**2.98**	3.05	3.13
NV Energy (Dec 2021)	13%	4	23.10	18.10	33.00	**44.08**	**3.09**	3.16	3.24
NV Energy (Dec 2021)	13%	4	25.90	20.90	37.00	**49.48**	**3.46**	3.53	3.62
TEP AZ (Dec 2019)	15%	4	40.70	25.70	58.14	**77.03**	**5.39**	5.60	5.85
LADWP (2023)	36%	4	38.93	19.62	55.61	**73.18**	**5.12**	5.39	5.72
Xcel Energy - standalone (2023)	100%	6.50	56.94		81.34	**104.11**	**7.29**	8.09	9.04

II. Comparing Benchmark Costs of Large-Scale PV Plants in the United States and India

Here we compare component costs for a typical large-scale PV plant in the United States and India. Table 12 shows benchmark costs by component for a large-scale PV plant in India. We exclude inverter costs from the BoS comparison, because they are explicitly included in the bottom-up cost estimate for a battery system. We also exclude taxes and fees from U.S. costs, because they are not available in the India benchmark costs. Finally, we exclude land costs owing to their high variability by site. In Table 13, the components that are grouped together in BoS (highlighted in yellow), EPC (gray), and soft costs (green) are determined by the cost components in India benchmarks.

Table 12. Benchmark Costs by Component for Large-Scale PV Plant in India

Component	Cost in Indian Rupees Millions/MW	Percentage of Total Cost	Cost in $/kW*
PV module	32.84	62%	469.46
Land cost	2.5	5%	35.74
Civil and general works	3.5	7%	50.04
Mounting structures	3.5	7%	50.04
Power-conditioning units	3.5	7%	50.04
Evacuation cost up to interconnection points (cables and transformers)	4.4	8%	62.90
Preliminary and pre-operative expenses including interest during construction and contingency	2.76	5%	39.50
Total	**53.00**		**757.71**

* Exchange rate: 1 U.S. dollar = 70 Indian rupees
Source: CERC (2016)

Table 13. Comparison of Component Costs for PV Plant in United States vs. India

Component	United States ($/kW)	India ($/kW)	U.S. to India Cost-Scaling Factor	
Module	$640.00	$469.46		
Inverter only	$100.00	$50.04		
Structural BOS	$108.02	$50.04	-49%	BOS ratio
Electrical BOS	$95.92	$62.90		
Install labor & equipment	$149.72	$50.04	-78%	EPC ratio
EPC overhead	$73.83			
Sales tax (if any)	$76.25			
Total EPC cost	**$1,243.74**			
Land acquisition	$30.00	$35.74		
Permitting fee (if any)	$2.95			
Interconnection fee	$28.45			
Transmission line (if any)	$18.52			
Contingency (3%)	$39.73	$39.50	-60%	Soft cost ratio
Developer overhead	$39.73			
EPC/developer net profit	$18.71			
Total developer cost	**$178.09**			
Total system cost	**$1,421.82**	**$757.72**		

Source for U.S. costs: Fu et al. (2016), for fixed-tilt 100-MW system

III. BESS Cost Estimates for India

Table 14. Cost estimates for standalone storage in India, with constant non-pack costs

Standalone Storage	**India 1 MW/4 MWh System**		**Year/Cost ($/kWh)**						
Components	**CAGR (2018–2024)**	**CAGR (2024–2030)**	**2018**	**2020**	**2022**	**2023**	**2024**	**2025**	**2030**
Battery pack	**-9.93%**	**-6.70%**	176	143	116	104	94	88	62
BoS hardware			25	25	25	25	25	25	25
BoS-inverter			18	18	18	18	18	18	18
Soft costs			8	8	8	8	8	8	8
EPC			16	16	16	16	16	16	16
Total CapEx ($/kWh)			**242**	**209**	**182**	**171**	**160**	**154**	**128**

Table 15. Cost estimates for co-located storage in India, with constant non-pack costs

PV Co-located Storage	India 1 MW/4 MWh System		Year/Cost ($/kWh)						
Components	**CAGR (2018–2024)**	**CAGR (2024–2030)**	**2018**	**2020**	**2022**	**2023**	**2024**	**2025**	**2030**
Battery pack	**-9.93%**	**-6.70%**	176	143	116	104	94	88	62
BoS hardware			15	15	15	15	15	15	15
BoS-inverter			11	11	11	11	11	11	11
Soft costs			8	8	8	8	8	8	8
EPC			16	16	16	16	16	16	16
Total CapEx ($/kWh)			**225**	**192**	**165**	**154**	**143**	**137**	**111**

Table 16. Cost estimates for standalone storage in India, with non-pack costs declining at 5%

Standalone Storage	India 1 MW/4 MWh System		Year/Cost ($/kWh)						
Components	**CAGR (2018–2024)**	**CAGR (2024–2030)**	**2018**	**2020**	**2022**	**2023**	**2024**	**2025**	**2030**
Battery pack	**-9.93%**	**-6.70%**	176	143	116	104	94	88	62
BoS hardware	-5%	-5%	25	22	20	19	18	17	15
BoS-inverter	-5%	-5%	18	16	15	14	13	13	11
Soft costs	-5%	-5%	8	7	6	6	6	5	5
EPC	-5%	-5%	16	14	13	12	12	11	10
Total CapEx ($/kWh)			**242**	**203**	**170**	**156**	**143**	**134**	**103**

Table 17. Cost estimates for co-located storage in India, with non-pack costs declining at 5%

PV Co-located Storage	India 1 MW/4 MWh System		Year/Cost ($/kWh)						
Components	**CAGR (2018–2024)**	**CAGR (2024–2030)**	**2018**	**2020**	**2022**	**2023**	**2024**	**2025**	**2030**
Battery pack	**-9.93%**	**-6.70%**	176	143	116	104	94	88	62
BoS hardware	-5%	-5%	15	13	12	12	11	10	9
BoS-inverter	-5%	-5%	11	10	9	8	8	8	7
Soft costs	-5%	-5%	8	7	6	6	6	5	5
EPC	-5%	-5%	16	14	13	12	12	11	10
Total CapEx ($/kWh)			**225**	**187**	**156**	**142**	**130**	**122**	**92**

IV. LCOS Sensitivity as Estimated for 2030

For a system installed in 2030, the sensitivity of LCOS to changes in three important variables is demonstrated: discount rate (baseline value is 11%), battery life (baseline value is 3,650 cycles), and capital cost (baseline values are $103/kWh for standalone and $92/kWh for co-located). The impact of battery pack price vs. BoS cost is separated. For a system installed in 2030, battery life has the biggest impact on LCOS.

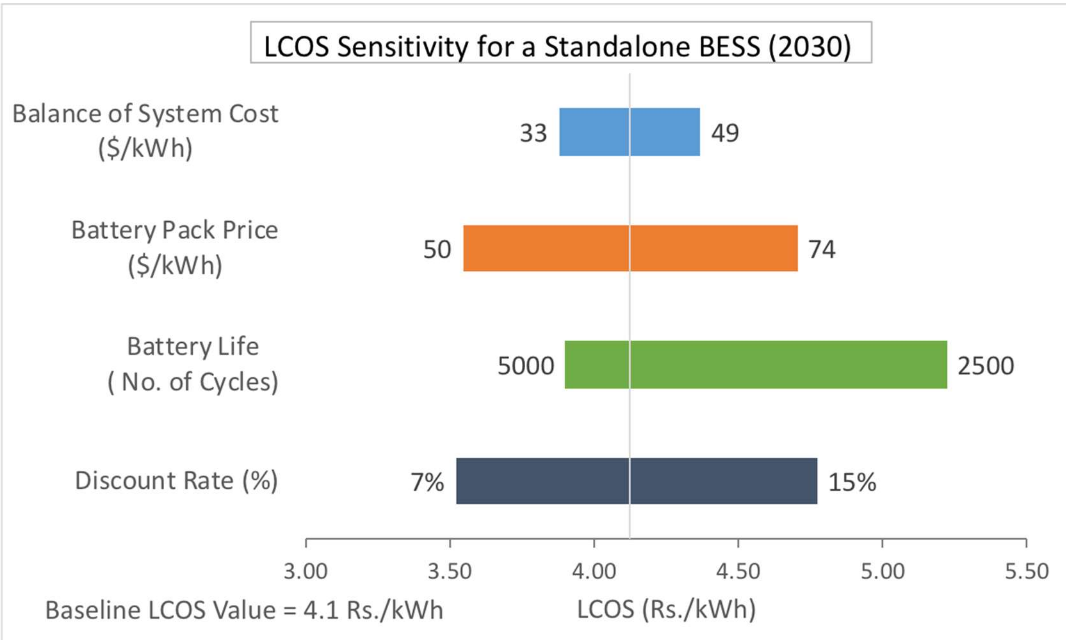

Figure 10. LCOS sensitivity for a standalone BESS, 2030

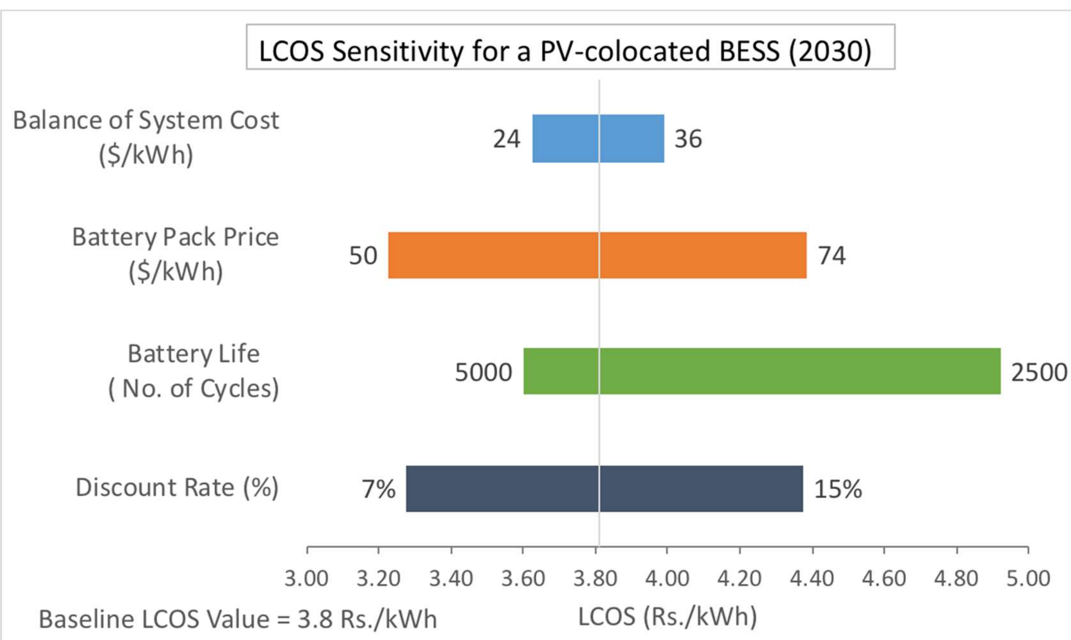

Figure 11. LCOS sensitivity for a PV co-located BESS, 2030