

Solar Plus Storage Cost Assessment and Design Considerations: Executive Summary

Technical Update

Project Manager

E. Minear

3002016637

December 2019



Disclaimer of Warranties and Limitation of Liabilities

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2019 Electric Power Research Institute, Inc. All rights reserved.

Acknowledgments

The Electric Power Research Institute (EPRI) prepared this report.

Principal Investigator
E. Minear

The following organization(s), under contract to the Electric Power Research Institute (EPRI), contributed to the preparation of this report:

Bear Peak Energy Consulting, LLC
1195 Albion Road
Boulder, CO 80305

Principal Investigator
N. Lenssen

This report describes research sponsored by EPRI.

EPRI acknowledges the joint support of project members from the Energy Storage and Distributed Generation; Renewable Energy; and Energy and Environmental Analysis programs. The following staff contributed to this report:

M. Simpson
R. Bedilion
J. Stekli
N. Kern
J. Bistline
E. Mannarino

This publication is a corporate document that should be cited in the literature in the following manner:
Solar plus Storage Cost Assessment and Design Considerations: Executive Summary. EPRI, Palo Alto, CA: 2019. 3002016637.

Abstract

The deployment of paired solar PV and lithium ion battery storage systems is growing rapidly in the U.S. This is an executive summary of a study that evaluated the market applications and relative costs for paired solar plus storage systems, encompassing the multiple considerations a project designer needs to address in sizing such systems and configuring them to provide the intended grid services. The study emphasized the importance of understanding the full lifecycle cost of paired solar plus storage projects, and provides estimates for turnkey installed costs, maintenance costs, and decommissioning costs. Focus was placed on comparing the relative costs and operating characteristics of AC-coupled systems versus DC-coupled systems. Finally, the study examined the importance of understanding not just costs, but also performance and value of solar plus storage systems in comparing their relative competitiveness with incumbent technologies. Results of this analysis support the continued evaluation and potential deployment of paired solar plus energy storage as a grid asset.

Keywords

Solar plus storage

Solar energy

Energy storage

Costs

Resource planning

Contents

Setting the Stage for Evaluating Solar Plus Storage

Solar Plus Storage: Coupling Configurations	7
Solar Plus Storage: Sizing	8
Solar Plus Storage: ITC, Interconnection, Efficiency	9
Solar Plus Storage: Uses	10

Solar Plus Storage Cost Results

Installed Costs	12
O&M Costs	15
Decommissioning Costs	16

Understanding Performance and Valuation

Valuation Consideration: Energy	20
Performance Consideration: Capacity	21
Performance and Valuation Consideration: Grid Charging	22

References 24

Appendix A: List of Studies Reviewed 25

Appendix B: Solar Plus Storage Installation Cost Categories 26

Setting the Stage for Evaluating Solar Plus Storage

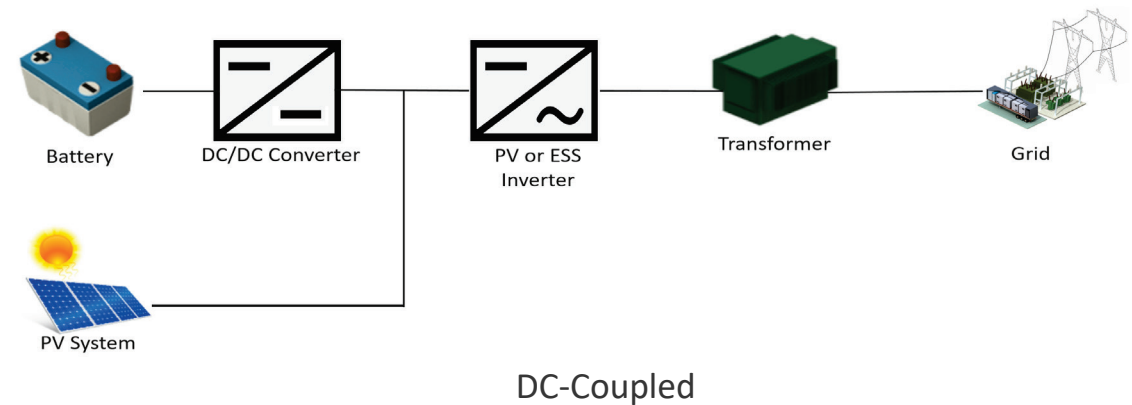
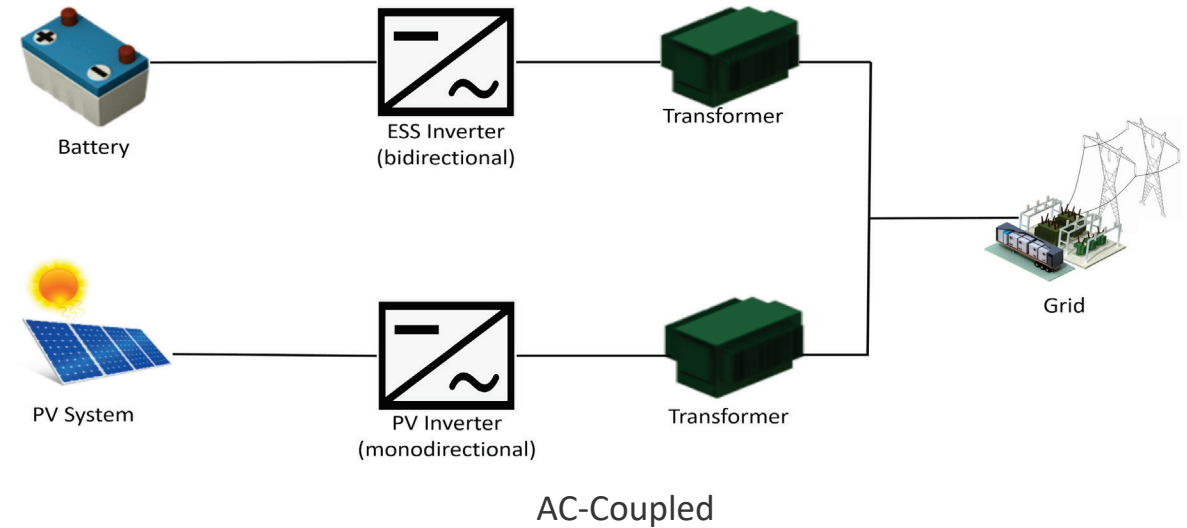
Solar Plus Storage: Coupling Configurations

There are two principal inverter configurations for solar plus storage systems that vary in the way the storage is charged from the PV or the grid.

AC-coupled refers to an electrical connection between the solar and energy storage system (ESS) at the AC output of each system's inverter or, collectively, at the step-up transformer. The battery can be charged by the solar energy or by the grid.

DC-coupled systems tie the PV and storage together on the DC side of the inverter and can be engineered via several converter topologies. A common inverter/converter layout is shown in the figure to the right. DC-coupled can be further categorized as monodirectional or as bidirectional based on the inverter type.

- **Monodirectional DC-coupled system:** Power only flows out of the system to the grid and the storage system can only charge from the PV, not the grid.
- **Bidirectional DC-coupled system:** Power can flow in both directions, thus allowing the storage system to be charged from the solar and the grid.



Solar Plus Storage: Sizing

There are several dimensions to sizing solar plus storage systems that can be optimized for a given objective and location. These include:

Solar inverter loading ratio (ILR): The ratio of DC rating of the solar panels to AC rating of the solar inverter

Solar PV systems often oversize the DC power compared to the inverters' AC power rating to maximize the utilization of the inverters' capacity during low irradiance periods and to account for soiling and degradation. This oversizing results in periods of clipping, where the output of the solar is capable of supplying power greater than the inverter rating and therefore is normally lost.

DC-coupled systems are able to capture and store clipped PV power in the ESS, resulting in increased solar production as ILR increases. AC-coupled systems will have a lower total solar production than a solar only project due to efficiency losses associated with the battery.

The potential benefit of capturing clipped energy is likely to result in DC-coupled systems having a higher ILR than AC-coupled systems.

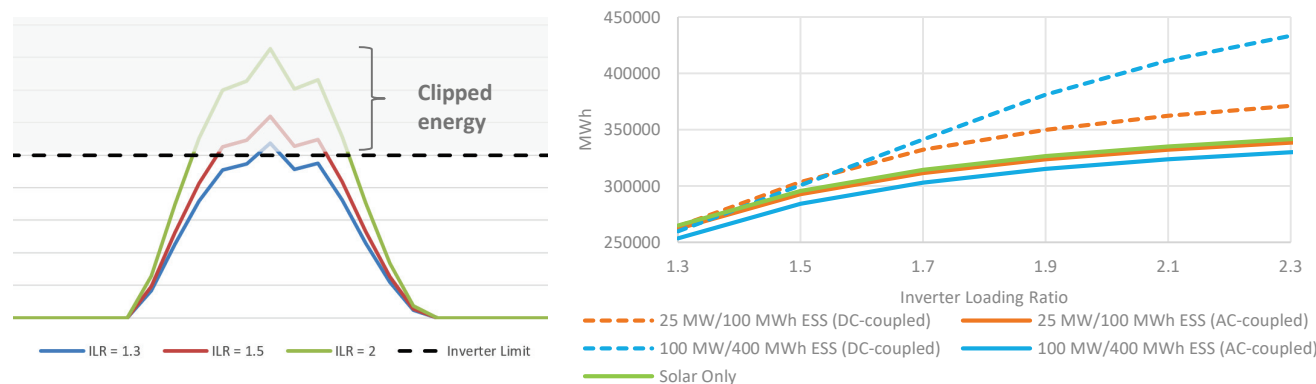
PV-to-storage capacity ratio and battery energy capacity

The PV-to-storage capacity ratio and the battery energy capacity will determine how much solar energy can be stored by the battery and dispatched at a later time. The approach to sizing the capacity ratio and energy depends on the objective.

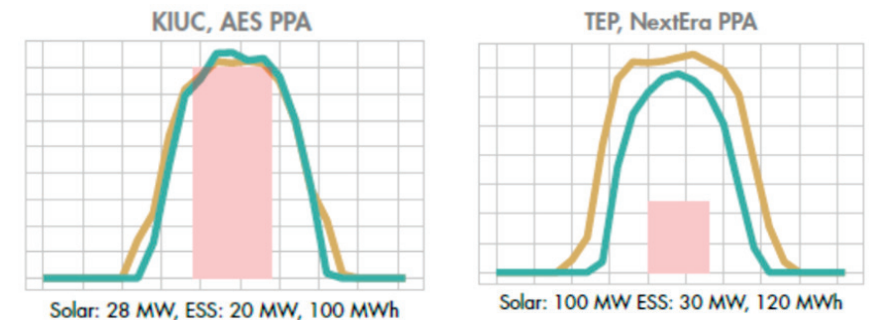
Systems with a 1:1 capacity ratio with a 4 hour storage duration can shift a significant amount of solar to periods where the energy is more valuable.

Applications with lower power and energy requirements, such as ramping support or smoothing, may have a higher PV-to-storage capacity ratio and lower battery energy capacity.

Example Solar Production with Various ILR (day and annual)



Example Utility-Scale Solar Plus Storage Projects PV-to-Storage Capacity Ratio and Storage Capacity



Note: Average monthly solar generation in January (blue line) and June (yellow line); storage power and energy are represented by the red rectangle.

Solar Plus Storage: ITC, Interconnection, Efficiency

Investment Tax Credit (ITC)

The federal Business Energy ITC incentivizes investment in solar energy systems and under certain conditions, energy storage coupled to solar is also eligible for the ITC. Eligibility depends on if the storage is “part of” the solar system. For more information NREL has issued a fact sheet on federal tax incentives for storage [1].

Certain solar plus storage topologies can make claiming the ITC for the storage portion easier than others, largely due to monitoring requirements to support the ITC claim.

- AC-coupled: Requires more complex and challenging approaches to document the source of charging for tax purposes
- DC-coupled monodirectional: Clearly qualifies for 100% of the ITC because the storage cannot be physically charged by the grid
- DC-coupled bidirectional: Is usually able to prevent charging from grid power through controls; requires careful documenting of the source of power used to charge the storage

Interconnection

An interconnection agreement defines the power capacity the system is able to export to the grid. A DC-coupled layout has an interconnection capacity equal to the capacity of the shared inverter(s). An AC-coupled layout has several options for interconnection:

- Sizing for the cumulative power capabilities of both the storage and PV inverters,
- Limiting the capacity to the PV system capacity, or
- Limiting the capacity somewhere in between the cumulative and PV system rating.

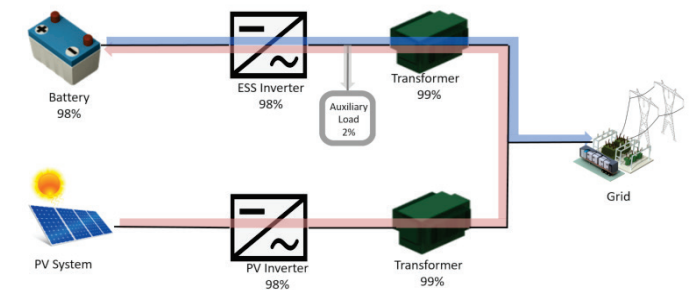
The first AC-coupled option has the highest cost, but allows the most flexibility for the storage to provide grid services. Limiting the capacity decreases interconnection costs, but requires plant controls or protection to ensure the interconnection capacity is not exceeded. An economic analysis can determine if the added cost of an increased interconnection capacity is justified based on the added value provided by the storage.

Efficiency

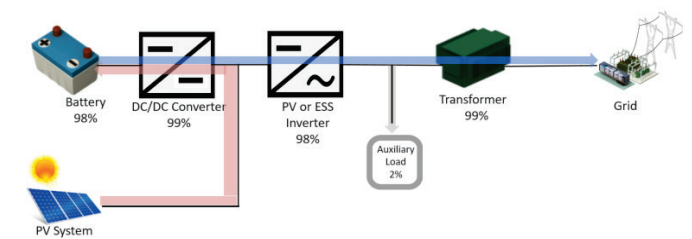
DC-coupled systems may have slightly higher efficiency when storing PV energy than AC-coupled systems, which can have additional inverter and transformer losses.

Although roundtrip efficiency affects overall lifetime project economics, it typically has a lower impact relative to other cost and benefit streams.

Example Efficiency Losses for AC- and DC-coupled systems



RTE: Inverter*Transformer*Transformer*Inverter*Battery*Inverter*Transformer-Auxiliary Load
RTE: $0.98*0.99*0.99*0.98*0.98*0.98*0.99-0.02=0.87$



RTE: DC/DC*Battery*DC/DC*Inverter*Transformer-Auxiliary Load
RTE: $0.99*0.98*0.99*0.98*0.99-0.02=0.91$

Solar Plus Storage: Uses

The intended application(s) of the solar plus storage system may help dictate the best topology for the system. The table to the right provides an overview of a system's ability to meet the application objectives based on topology. For AC-coupled systems, the table assesses two scenarios: one where the interconnection is not limited to the solar plant capacity and one where the interconnection is limited. For DC-coupled systems, there are also two scenarios: a monodirectional inverter and bidirectional inverter. Many of these applications may be provided by stand-alone storage, stand-alone PV, or separately located PV and storage.

Notes:

1. Stacked value streams are not considered in this summary table.
2. AC-coupled inverters require coordination and synchronization to perform curtailment mitigation on instantaneous oversupply and ramp rate control.
3. For energy time shift, firm capacity, T&D deferral, and transmission charge reduction, performance is limited in monodirectional DC-coupled systems by solar production. AC-coupled and bidirectional DC-coupled systems would have more energy and power available to perform this application than a monodirectional DC-coupled configuration if they charged from the grid. An AC-coupled system that is not limited by the interconnection capacity, may be able to provide additional value.
4. DC-coupled monodirectional systems are limited in their ability to perform regulation down and frequency response (due to loss of load) during non-solar hours, unless it is discharging at a non-zero power.

Application ¹	AC-Coupled	AC-Coupled (limited interconnection)	DC-Coupled (monodirectional)	DC-Coupled (bidirectional)
Curtailment Mitigation ²	●	●	●	●
Energy Time Shift ³	●	●	●	●
Firming Solar Capacity ³	●	●	●	●
Frequency Regulation ⁴	●	●	●	●
Frequency Response ⁴	●	●	●	●
Low Voltage Harvest	●	●	●	●
PV Clipping Loss Reduction	●	●	●	●
PV Ramp Rate Control ²	●	●	●	●
T&D Deferral ³	●	●	●	●
Transmission Charge Reduction ³	●	●	●	●
Volt-VAR Regulation	●	●	●	●

Solar Plus Storage Cost Results

Installed Cost Comparison

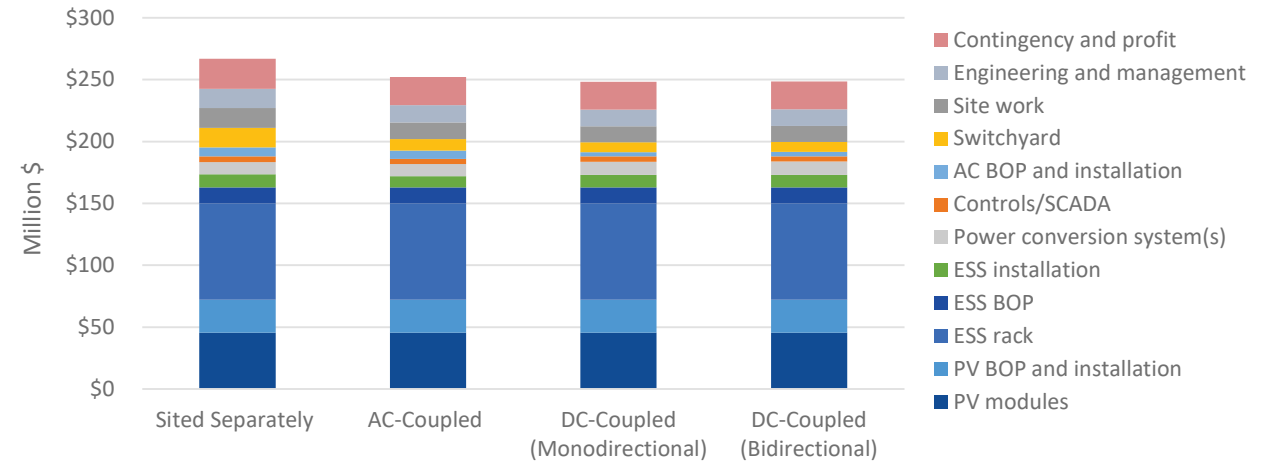
Top-line finding: AC- and DC-coupled solar plus storage systems have a cost advantage over systems sited separately, but there is currently no definitive advantage between the coupled configurations for all scenarios.

This modeled finding was confirmed via discussions with project developers and integrators and a review of published studies. The variation in results for which is the lower cost configuration and by what percentage may be due to several factors, such as differing PV-to-storage capacity ratios, system sizing, and scope of assessment. There are also factors specific to a particular developer, such as familiarity with a configuration, labor rates, and equipment pricing that could impact the estimated cost of the system. Therefore, the costs on this page show only an example scenario which should not be used to draw firm conclusions, but rather to provide insights as to how costs shift between different categories. The next two pages include additional discussion on cost variations between the configurations.

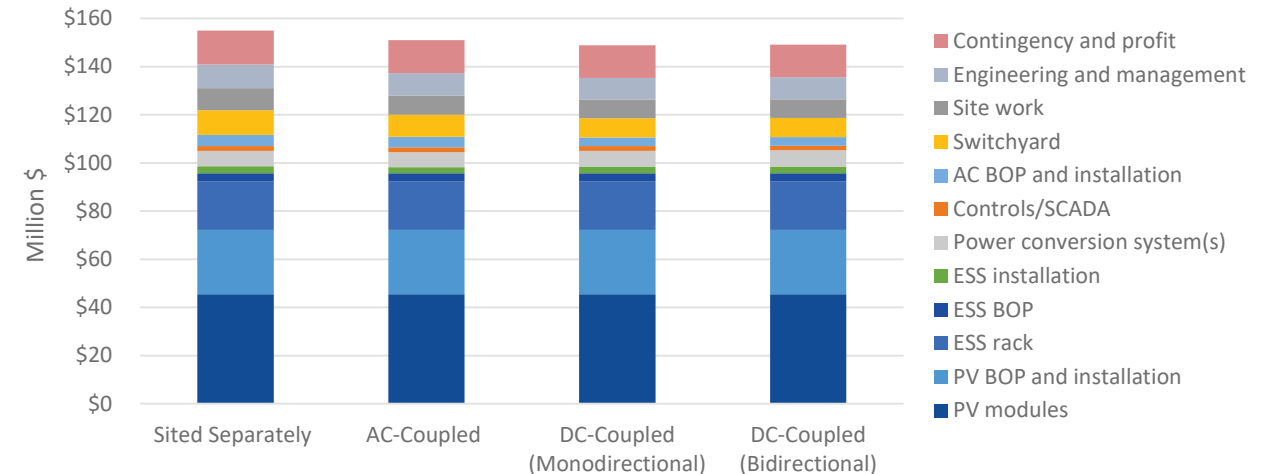
For the example cost breakdowns presented in the report, there was a collocation savings of 3%-7% from PV and energy storage systems sited separately, not including any potential tax benefits. For the three coupled configurations, cost differences were less than 2%.

The differences in the cost between coupled configurations could be moot compared to the potential swing of individual line items. For example, battery costs may swing $\pm 20\%$ depending on the volume purchased, their source, and the volatility of cobalt pricing; such a range in battery costs translate to a more than 5% difference in overall net project cost, more than double the cost difference found in the three configurations.

Installed Cost Breakdown for a 100 MW (130 MWdc) PV, 100 MW/400 MWh ESS, 2019

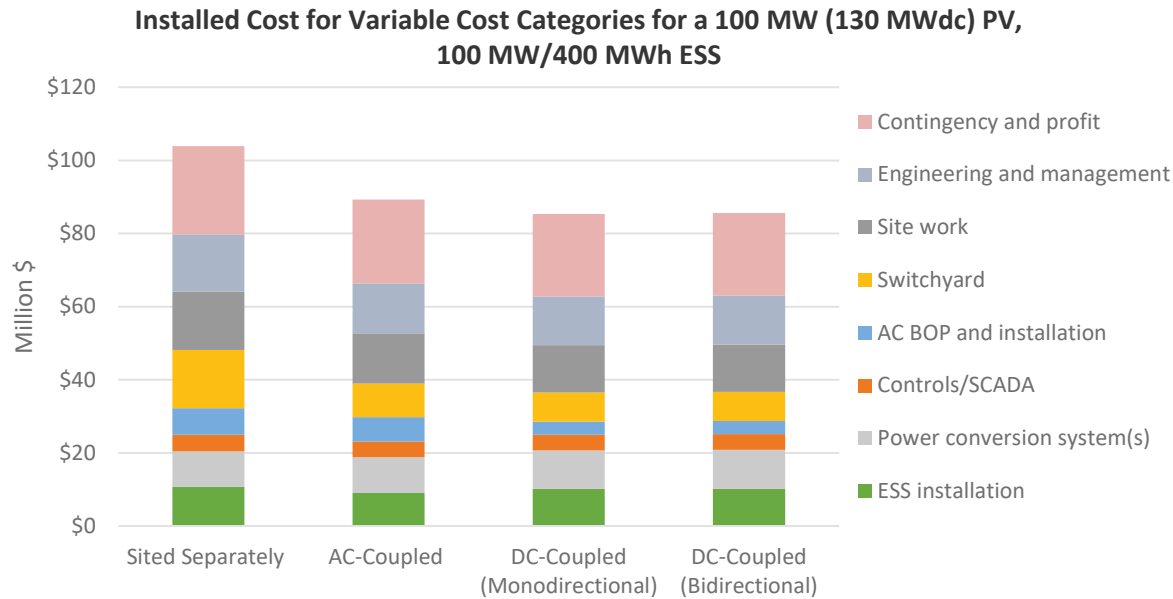


Installed Cost Breakdown for a 100 MW (130 MWdc) PV, 25 MW/100 MWh ESS, 2019



Discussion of Installed Cost Categories

The sources of cost variation between the four scenarios are highlighted in discussion of cost categories and in the figure below. PV module, PV BOP, ESS rack, and ESS BOP are assumed constant for all cases.



ESS Installation

- Construction efficiencies are gained when going from separately sited to a coupled configuration
- DC-coupled approach has higher costs than the AC-coupled given that the amount of DC cabling and associated installation increases.
- Energy storage in DC-coupled systems is decentralized, which can result in an increase in the cost of supplying auxiliary power and integrating safety systems

Power Conversion Systems (Inverters and Converters)

- Cost difference between the configurations depends on solar plus storage sizing and component cost assumptions.
- Range of data collected for inverter/converter costs: Monodirectional inverter - \$0.03-\$0.055/Wac; Bidirectional inverter - \$0.05-\$0.07/Wac; DC-DC converters \$0.05-\$0.08/Wac¹. DC-DC converters may have a cost premium due to lower production volumes and smaller capacity ratings.
- Variation in cost comes from discounts due to project economies of scale, packaging, functional requirements, voltages, and differences between manufacturers.

Controls/SCADA

- Controls and SCADA in a solar plus storage system were assumed to have a slight discount from systems installed separately, though no cost difference is evident between the three coupled configurations
- DC-coupled advantage: Systems may have fewer devices to control at a SCADA level and implementation of the SCADA (programming/configuration) may be easier, as AC-coupled systems often use different inverter models within the same project.
- DC-coupled disadvantage: Few common options exist for DC power meters and even less are certified for use in accounting for grid services from DC-coupled plants; DC-coupled plant controls often have complexities (e.g., providing a certain grid service while simultaneously optimizing PV consumption and minimizing curtailment), which may require additional controls development.

¹ DC-DC converter costs normalized to \$/Wac assuming similar inverter sizing

Discussion of Installed Cost Categories, continued

AC Balance of Plant and Installation

- AC BOP costs offer a major cost advantage for DC-coupled systems over AC-coupled systems.
- DC-coupled systems share the medium voltage transformer, reducing the total number of transformer required and the associated medium voltage wiring.
- Savings become more pronounced for the 1:1 capacity ratio where the DC-coupled system can eliminate half of the transformers otherwise required.

Site Work

- AC-coupled systems were assumed to have a discount from systems sited separately due to construction efficiencies, such as having a single mobilization, reduced construction management, reduced temporary site facilities, shared equipment resources, and general efficiencies in labor utilization.
- DC-coupled systems can similarly take advantage of construction efficiencies and can achieve further cost reductions derived from the need for less trenching between transformers and less concrete foundation work.

Switchyard

- Both AC- and DC-coupled systems save on switchyard costs compared to separately sited systems, as only one switchyard is needed.
- AC-coupled switchyards would require additional protection to limit the output of the combined system, a function that the DC-coupled system's inverter would perform.
- AC-coupled systems may also require additional switching equipment and/or switching capacity.

Engineering and Management and Contingency and Profit

- Engineering and management and contingency and profit costs were assumed to be a set percentage of other project costs. The efficiencies gained in the other cost categories will also be reflected in this category.

O&M Costs

There will likely be O&M cost savings with solar plus storage compared to standalone systems given ongoing improvements in managing contracts, monitoring system health and performance, and coordination of planned maintenance tasks. However, there was insufficient data available to determine the potential scale of such savings, especially given there is still uncertainty about the true O&M cost of standalone energy storage. In the absence of vendor- or project-specific information, standalone solar and storage costs can be combined to estimate O&M costs for coupled systems.

Between the coupling configurations, the cost difference may depend upon how contracts are structured and who is providing maintenance services. If separate contractors are servicing the battery from those servicing the solar system, some EPCs have noted a minor cost advantage to AC-coupled with the storage system centrally located, rather than distributed throughout the solar field. However, if a single contractor is servicing both the solar and storage, the cost advantage may go away.

Solar O&M Costs: The solar O&M costs in the table below are based on EPRI's 2018 solar analysis for single axis tracking, crystalline silicon technology, adjusted for an ILR of 1.3 [2]. Total O&M costs include preventative maintenance, module cleaning, unscheduled maintenance, inverter maintenance reserve, and other owners costs such as monitoring, insurance, taxes, and administrative fees. O&M service costs represent the cost of a third party maintenance contract and exclude owners' costs. Note, preliminary findings from EPRI's 2019 solar cost assessment indicate the total O&M costs have decreased by a few \$/kW-year.

Solar PV O&M Cost Estimates	Cost
Total O&M (AC)	\$20/kWac-year
Total O&M (DC)	\$15/kWdc-year
O&M Services (DC)	\$12/kWdc-year

ESS O&M Costs: The table below summarizes O&M cost estimates based on data gathered in EPRI's 2018 storage cost analysis for lithium ion batteries [3]. There may exist additional costs such as owners' costs or performance guarantees, which were excluded from the scope of the analysis.

ESS O&M Category	Cost
Fixed Maintenance	1.5% of installed cost per year
Warranty	1% of installed cost per year after 3 years
Augmentation	\$200-\$300/kWh

Decommissioning Costs

As with solar plus storage O&M costs, the lack of experience and data for standalone solar and storage decommissioning costs presents a challenge to identify savings from collocation.

EPRI has published conceptual decommissioning estimates for standalone solar and storage plants [4], [5] and similar methodologies can be applied to solar plus storage systems. The tables to the right are based on the previous EPRI estimates, adjusted for the example system sizes.

Although this assessment did not gather additional information on decommissioning costs, one consideration in assessing solar plus storage disposal costs is the life and operating regime of the project. Standalone lithium ion projects often have a shorter life or contract period than standalone solar projects. Solar plus storage contracts with durations matching the solar PV life will likely require battery replacements. This may add removal and disposal costs (though they will likely be logged as O&M costs) during the operating life, in addition to the removal and disposal at the system end of life.

Between the coupling configurations, for equally sized systems, AC-coupled may have lower decommissioning costs than DC-coupled. AC-coupled systems require more medium voltage transformers and while this is a disadvantage for installation costs, it is an advantage during decommissioning because the transformer copper and steel salvage value is significantly higher than the cost of removal labor. However, as with installed costs, there may be swings in the disposal cost or salvage value of PV modules and batteries that have more impact to the overall disposal number than the variations between configurations, particularly given that recycling infrastructure still needs to be developed.

Solar Decommissioning Costs: Assumes the removal and disposal of all mechanical and electrical equipment and the land is returned to a renovated state (topsoil, mulched, and seeded with grass).

	100 MWac (130 MWdc)
Decommissioning Cost (\$/kWac)	\$77
Decommissioning Cost (% of installed cost)	7%

ESS Decommissioning Costs: Limited to removal and disposal of energy storage system products and does not include any grid integration equipment decommissioning or site restoration work.

	100 MW 400 MWh
Disposal cost (\$/kWh)	\$32
Disposal cost (% of installed cost)	8%

Understanding Performance and Valuation

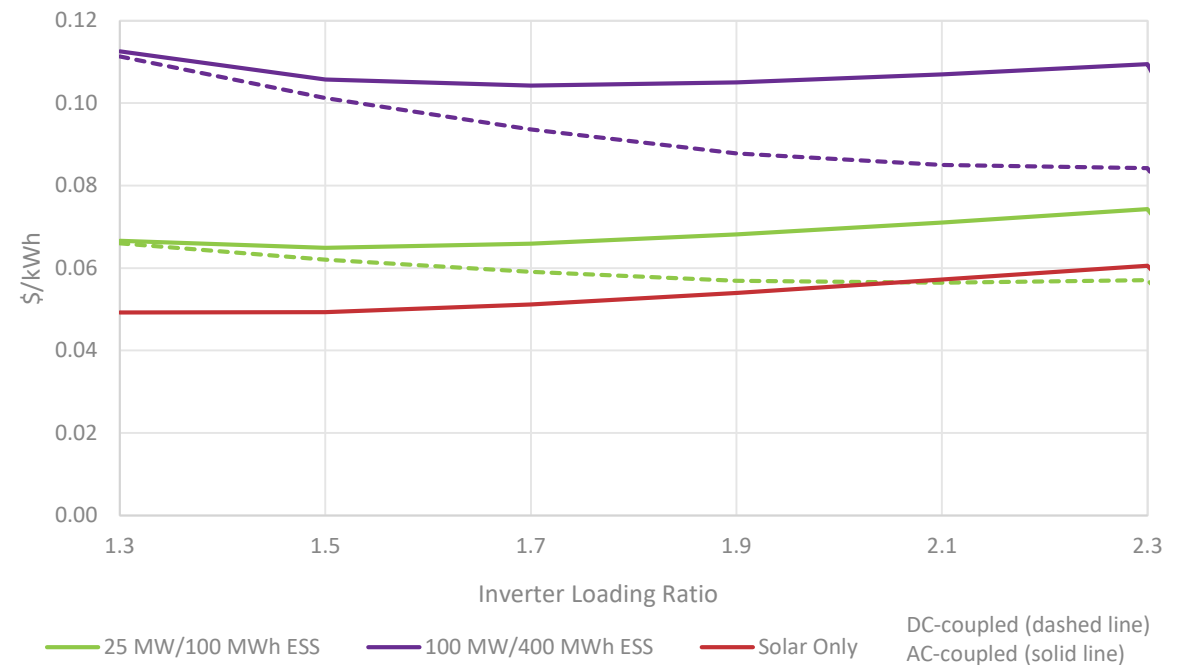
Valuation Consideration: Energy

The analyses conducted for this report confirm that cost difference between the three solar plus storage configurations are relatively minor. But even if one configuration ends up being a preferred option in terms of direct costs, the operational and potential tax benefits will remain as key factors for the broader cost-benefit assessment for a specific project. The examples in this section highlight additional considerations for utility-owned solar plus storage.

Comparisons of generation technologies often use levelized cost of energy (LCOE) as a metric for their relative value. However, LCOE is not a useful metric to evaluate solar plus storage systems that are providing grid services or shifting the time-of-use for the energy. The limitation of using LCOE for solar plus storage projects is illustrated in the figure to the right. In this example, the solar-only installation has the lowest cost and the solar with 100 MW battery has the highest cost. The value of the storage is clearly not being captured by this LCOE calculation.

If the primary objective of the solar plus storage system is to provide energy, then a DC-coupled system with a high inverter loading ratio would be a more cost effective solution compared to an AC-coupled system; the DC-coupled system can produce more energy than a AC-coupled system of equal rating. However, it is unlikely that solar plus storage systems would be used solely to supply energy, as the cost of adding storage to only capture clipped energy is currently significantly higher than the cost of energy from adding solar only. More importantly, adding storage provides additional value by enabling the energy to be shifted to times of higher energy prices, or to firm the solar output for ensuring delivery of energy at specific time periods.

Simplified LCOE Evaluation of Solar Plus Storage Systems, 100 MWac Solar PV

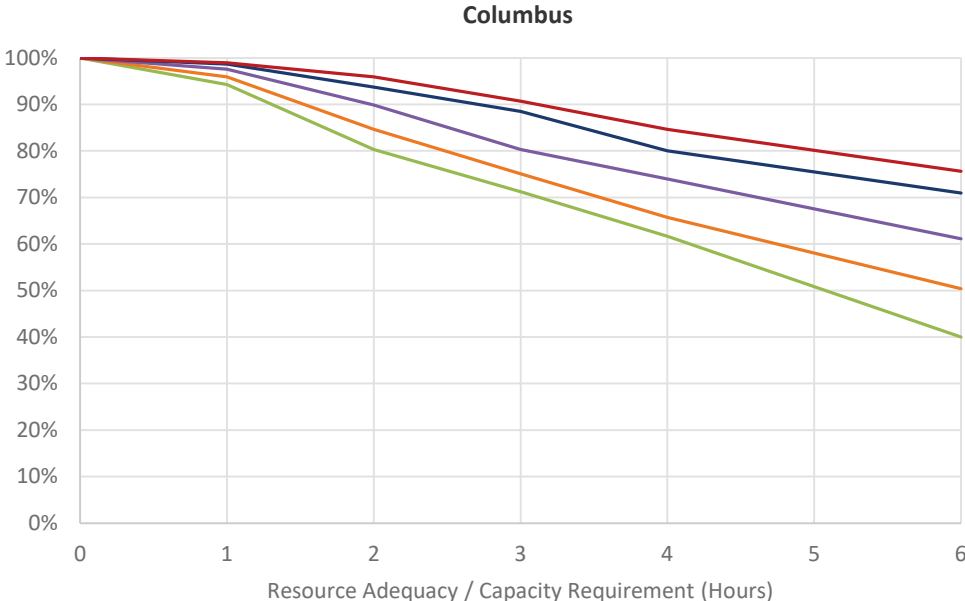
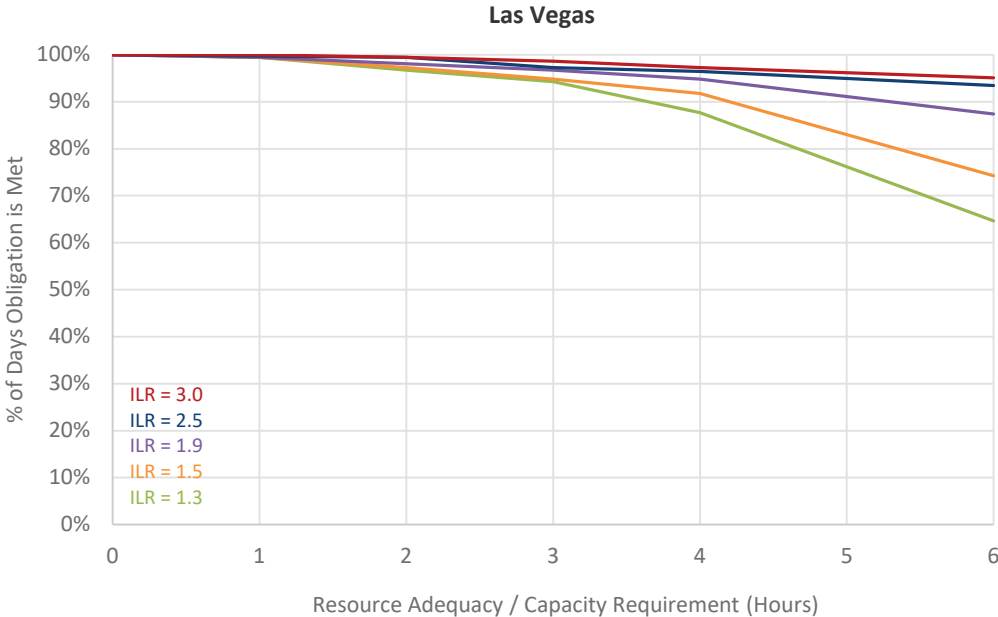


Performance Consideration: Capacity Contribution

The primary objective of adding energy storage to a solar plant is often to shift the time for providing energy to the grid (“time shifting”) and/or to provide firm capacity outside of solar production hours. The example below shows the percentage of days a system is able to meet the given capacity requirement (e.g., MW capacity over a set number of hours), assuming that capacity must be provided during non-solar hours for a 100 MW PV, 100 MW/400 MWh battery DC-coupled system only charged from the solar. As expected, systems with a higher ILR can meet the required capacity for a greater percentage of days, though there is a point where adding DC solar capacity provides incrementally less gain in availability.

The solar resource in Las Vegas, Nevada enables the solar plus storage system with an ILR of 1.3 to meet a 4 hour capacity requirement 88% of the time. Increasing the ILR results in minimal gains in availability, which minimizes the value of increasing the ILR for this purpose. In Columbus, Ohio, however, the availability of a system with an ILR of 1.3 to meet a 4 hour capacity requirement is only 62% of the time, and increases in ILR have a higher impact to availability than Las Vegas.

Availability of DC-coupled Systems at Different Inverter Loading Ratios with a 100 MWac Solar Plant and 100 MW/400 MWh ESS

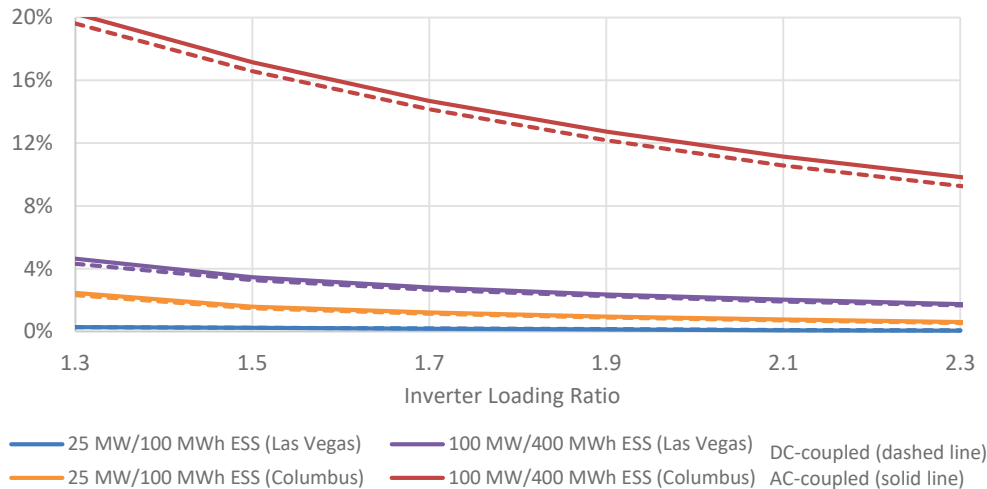


Performance and Valuation Consideration: Grid Charging

Given the intermittent nature of solar, there will be days when there is not enough solar to charge the battery and meet capacity requirements. To improve performance in providing capacity, it could make economic sense to charge from the grid when the solar production is insufficient. The left figure below shows the percentage of grid charging required to meet 100% availability for a 4 hour capacity requirement in Las Vegas and Columbus. When solar irradiance is deficient, clipped energy would be minimal, thus reducing the advantage to DC-coupled systems on these days. The primary difference between the grid charging required for the two configurations is the lower efficiency in the AC-coupled system. (The analysis does not account for potential system unavailability due to planned or unplanned maintenance.)

An economic evaluation shows the trade-off between the value of grid capacity requirements with the attainable ITC revenue. The table to the right shows an AC-coupled system *with* grid charging provides higher availability at a lower cost than a DC-coupled system *without* grid charging and higher ILR of 1.9, in spite of the former's lower energy production. In this example, however, the DC-coupled system *with* grid charging can provide higher availability and energy output at a lower cost, even with a lower ILR of 1.3. A full cost benefit analysis would also consider availability requirements, penalties for non-performance, charging costs, and the value of energy.

Grid Charging Required to Meet a 4-hour Capacity Requirement with a 100 MW_{ac} Solar Plant



Example Installed Costs Differences for 100 MW PV, 100 MW/ 400 MWh ESS under Different Sizing and Charging Strategies, Sited in Columbus

Configuration	AC-coupled	DC-coupled monodirectional	DC-coupled monodirectional	DC-coupled bidirectional
ILR	1.3	1.3	1.9	1.3
Grid charging	Yes	No	No	Yes
Charge from grid	20.2%	0%	0%	19.6%
Days capacity met	100%	62%	74%	100%
Solar energy supplied	185 GWh	190 GWh	280 GWh	190 GWh
ITC eligibility	24%	30%	30%	24%
Cost delta from AC-coupled (including ITC)	-	-9%	+6%	-1%

References and Appendices

References

- [1] *Federal Tax Incentives for Energy Storage Systems*, National Renewable Energy Laboratory, January 2018. NREL/FS-7A40-70384.
- [2] *2018 Solar Technology Status, Cost and Performance*, EPRI, Palo Alto, CA: 2018. 3002014573.
- [3] *Energy Storage Technology and Cost Assessment*, EPRI, Palo Alto, CA: 2018. 3002013957.
- [4] *PV Plant Decommissioning Salvage Value: Conceptual Cost Estimate*, EPRI, Palo Alto, CA: 2018, 3002013116.
- [5] *Recycling and Disposal of Battery-Based Grid Energy Storage Systems: A Preliminary Investigation*. EPRI, Palo Alto, CA: 2017. 3002006911.

Full Report

Solar plus Storage Cost Assessment and Design Considerations. EPRI, Palo Alto, CA: 2019. 3002016636.

For more information visit www.epri.com

Appendix A: List of Studies Reviewed

- Bloomberg New Energy Finance. *2018 Lithium-ion Battery Price Survey*. Bloomberg New Energy Finance, New York: NY: December 19, 2018.
- Bloomberg New Energy Finance. *2018 Long-term PV Market Outlook*. Bloomberg New Energy Finance, New York: NY: August 24, 2018.
- Bloomberg New Energy Finance. *2019 Long-term Energy Storage Outlook*. Bloomberg New Energy Finance, New York: NY: July 31, 2019.
- Lawrence Berkeley National Laboratory (LBNL). *Utility-Scale Solar: Empirical Trends in Project Technology, Cost, Performance, and PPA Pricing in the United States – 2018 Edition*. Berkeley, CA: September 2018.
- Lazard. *Lazard's Levelized Cost of Energy Analysis – Version 12.0*. November 2018.
- Lazard. *Lazard's Levelized Cost of Storage – Version 4.0*. November 2018.
- National Renewable Energy Laboratory. *Cost Projections for Utility-Scale Battery Storage*. Golden, CO: June 2019. NREL/TP-6A20-73222.
- National Renewable Energy Laboratory. *2018 U.S. Utility-scale Photovoltaics-plus-Energy Storage System Costs Benchmark*. Golden, CO: November 2018. NREL/TP-6A20-71714.
- Pacific Northwest National Laboratory, Argonne National Laboratory, and Oak Ridge National Laboratory. *Energy Storage Technology and Cost Characterization Report*. Richland, WA, July 2019. PNNL-28866.
- Wood Mackenzie Power. *Solar-plus-Storage System Architectures: Design, Pricing, and Economics in the U.S.* January 2019.
- Wood Mackenzie Power & Renewables and Energy Storage Association. *U.S. Energy Storage Monitor Q2 2019 Full Report*. June 2019.
- Wood Mackenzie Power & Renewables and Solar Energy Industries Association. *U.S. Solar Market Insight Q3 2019 Full Report*. September 2019.

Appendix B: Solar plus Storage Installation Cost Categories

PV modules. This line item covers the costs of the PV modules. This study assumes monocrystalline silicon.

PV BOP + installation. Costs associated with this category include the labor and materials to install the PV system. Balance of plant systems include structural components such as the mounting and racking system and electrical components such as raceways, wiring, conduits, and combiner boxes.

ESS rack. The ESS rack cost line item covers an integrated lithium ion DC battery rack; this includes the battery modules that typically form a string, rack hardware, and battery management system (BMS).

ESS BOP. The balance of plant is all the remaining items required to have a fully integrated DC system, such as the enclosure, thermal management systems, fire suppression, and other battery BOP components.

ESS installation. ESS installation costs include labor and materials to interconnect the fully integrated DC battery system to the inverter, from the inverter to the grid integration equipment, and other communication and control wiring.

Power conversion system(s). The PCS includes all of the conversion equipment in the hybrid configurations, such as PV inverters, bidirectional storage inverters, and DC-DC converters.

Controls/SCADA. This category includes equipment, materials, and installation of the supervisory control and data acquisition (SCADA), all instrumentation and controls (I&C) equipment, and backup DC power system.

AC BOP + installation. This includes pad mounted transformers that step up the voltage from the inverter output to the secondary voltage of the switchyard, medium voltage wiring, and installation.

Switchyard + installation. This line item includes the equipment, materials, and installation of the main power transformer, switchgear, substation structure, and civil and electrical works related to the control building.

Site work. Site preparation work includes clearing of any existing infrastructure, grubbing, grading, access and site road works, fencing, excavations and concrete work for building and equipment foundations, finishing, and site security. Systems are assumed to be installed at locations that require minimal site preparation.

Engineering and management. This overhead category includes construction mobilization, construction management, field office costs, safety expenses, contractor's general and administrative expenses, engineering and procurement services, and commissioning. This is assumed to be 15% of the project costs, excluding the PV modules and ESS rack capital costs.

Contingency and profit. The contractor's profit and construction contingency are included in this line item. This is assumed to be 10% of the EPC costs. This is separate from owner's contingency which would be included in owner's costs and is excluded from this assessment.



Export Control Restrictions

Access to and use of this EPRI product is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is taken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or U.S. permanent resident is permitted access under applicable U.S. and foreign export laws and regulations.

In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI product, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case by case basis an informal assessment of the applicable U.S. export classification for specific EPRI products, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes.

Your obligations regarding U.S. export control requirements apply during and after you and your company's engagement with EPRI. To be clear, the obligations continue after your retirement or other departure from your company, and include any knowledge retained after gaining access to EPRI products.

You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of this EPRI product hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electricity generated and delivered in the United States with international participation extending to 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; Dallas, Texas; Lenox, Mass.; and Washington, D.C.

Together...Shaping the Future of Electricity

© 2019 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

3002016637

Electric Power Research Institute

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com