2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark

Ran Fu, Timothy Remo, and Robert Margolis

National Renewable Energy Laboratory

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List of Acronyms

AC	alternating current
BOS	balance of system
CAES	compressed air energy storage
DC	direct current
DOE	U.S. Department of Energy
EPC	engineering, procurement, and construction
HVAC	heating, ventilating, and air conditioning
ILR	inverter loading ratio
LCOS	levelized cost of storage
Li	lithium
PV	photovoltaic(s)
SG&A	selling, general, and administrative

Executive Summary

The recent rapid growth of utility-scale photovoltaic (PV) deployment and the declining costs of energy storage technologies have stimulated interest in combining PV with energy storage to provide dispatchable energy (i.e., energy on demand) and reliable capacity (i.e., grid stability). In particular, the use of lithium-ion batteries in U.S. utility-scale applications has grown in recent years owing to the technology's favorable cost and performance characteristics. This study is our first time to use bottom-up modeling to benchmark the installed costs of various standalone lithium-ion storage (with storage connected to the grid only) and PV-plus-storage (with storage connected to PV and the grid) system configurations. The PV-plus-storage configurations include 1) co-located PV-plus-storage systems vs. PV-plus-storage systems in different locations, and 2) direct current (DC) coupled vs. alternating current (AC) coupled battery configurations for the co-located PV-plus-storage systems.

Figure ES-1 shows the modeled costs of standalone lithium-ion energy storage systems with an installed capacity of 60 MW able to provide electricity for several different durations. Assuming a constant per-energy-unit battery price of $209/kWh, the system costs vary from $380/kWh (4-hour duration system) to $895/kWh (0.5-hour duration system). The battery cost accounts for 55% of total system cost in the 4-hour system, but only 23% in the 0.5-hour system. At the same time, non-battery cost categories accounts for an increasing proportion of the system cost as duration declines.

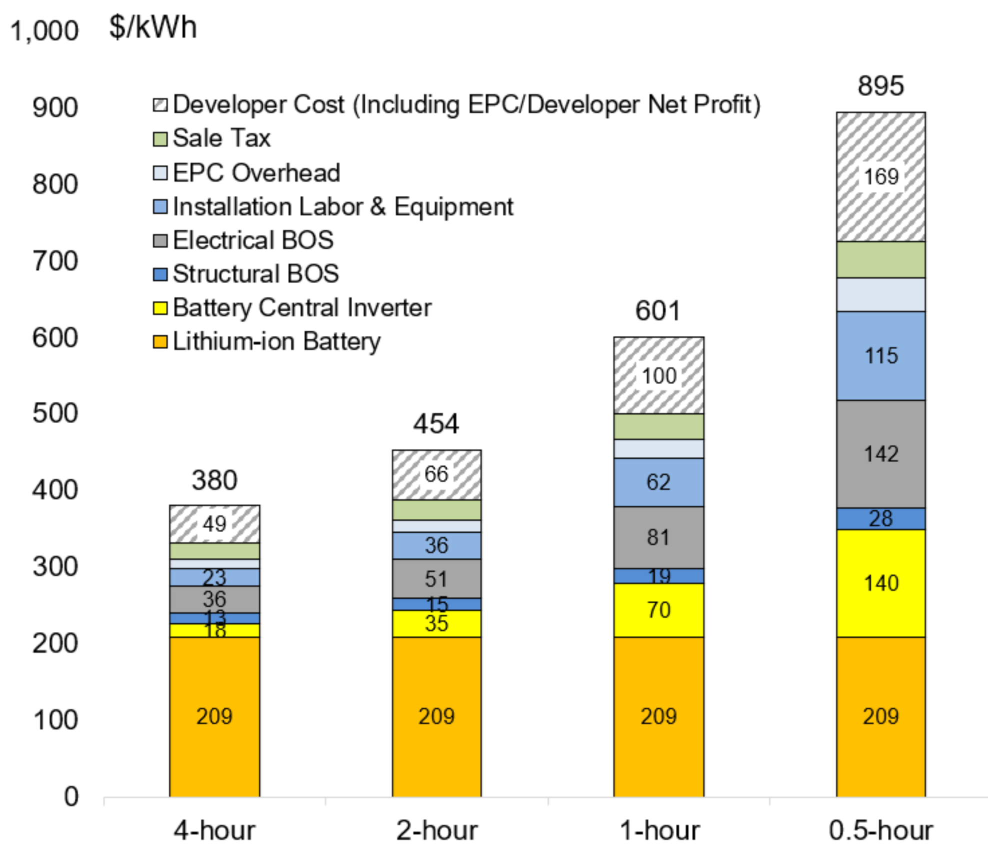

Figure ES-1. 2018 U.S. utility-scale lithium-ion standalone storage costs for durations of 0.5–4 hours (60 MW_{DC})

Figure ES-2 summarizes our PV-plus-storage model results for several system types and configurations. Each uses a 100-MW PV system and a 60-MW lithium-ion battery that provides 4 hours of storage:

- Standalone 100-MW PV system with one-axis tracking ($111 million)
- Standalone 60-MW/240-MWh, 4-hour-duration energy storage system ($91 million)
- Co-located, DC-coupled PV (100 MW) plus storage (60 MW/240 MWh, 4-hour duration) system ($186 million)
- Co-located, AC-coupled PV (100 MW) plus storage (60 MW/240 MWh, 4-hour duration) system ($188 million)
- PV (100 MW) plus storage (60 MW/240 MWh, 4-hour duration) system with PV and storage components sited in different locations ($202 million)

Co-locating the PV and storage subsystems produces cost savings by reducing costs related to site preparation, land acquisition, permitting, interconnection, installation labor, hardware (via sharing of hardware such as switchgears, transformers, and controls), overhead, and profit. The cost of the co-located, DC-coupled system is 8% lower than the cost of the system with PV and storage sited separately, and the cost of the co-located, AC-coupled system is 7% lower.

Using DC-coupling rather than AC-coupling results in a 1% lower total cost, which is the net result of cost differences between DC-coupling and AC-coupling in the categories of solar inverter, structural balance of system (BOS), electrical BOS, labor, EPC (engineering, procurement, and construction) and developer overhead, sales tax, contingency, and profit. For an actual project, however, cost savings may not be the only factor in choosing DC or AC coupling. Additional factors—such as retrofit considerations, system performance, design flexibility, and operations and maintenance—should be considered.

The benchmarked costs could facilitate PV-plus-storage project development, and the itemized cost savings could incentivize deployment of co-located PV-plus-storage systems. In addition, the model can help industry representatives evaluate the cost impacts of various battery durations for grid applications. Finally, the model can be used to estimate future potential cost-reduction opportunities for PV-plus-storage systems, helping to guide research and development aimed at advancing cost-effective system configurations.

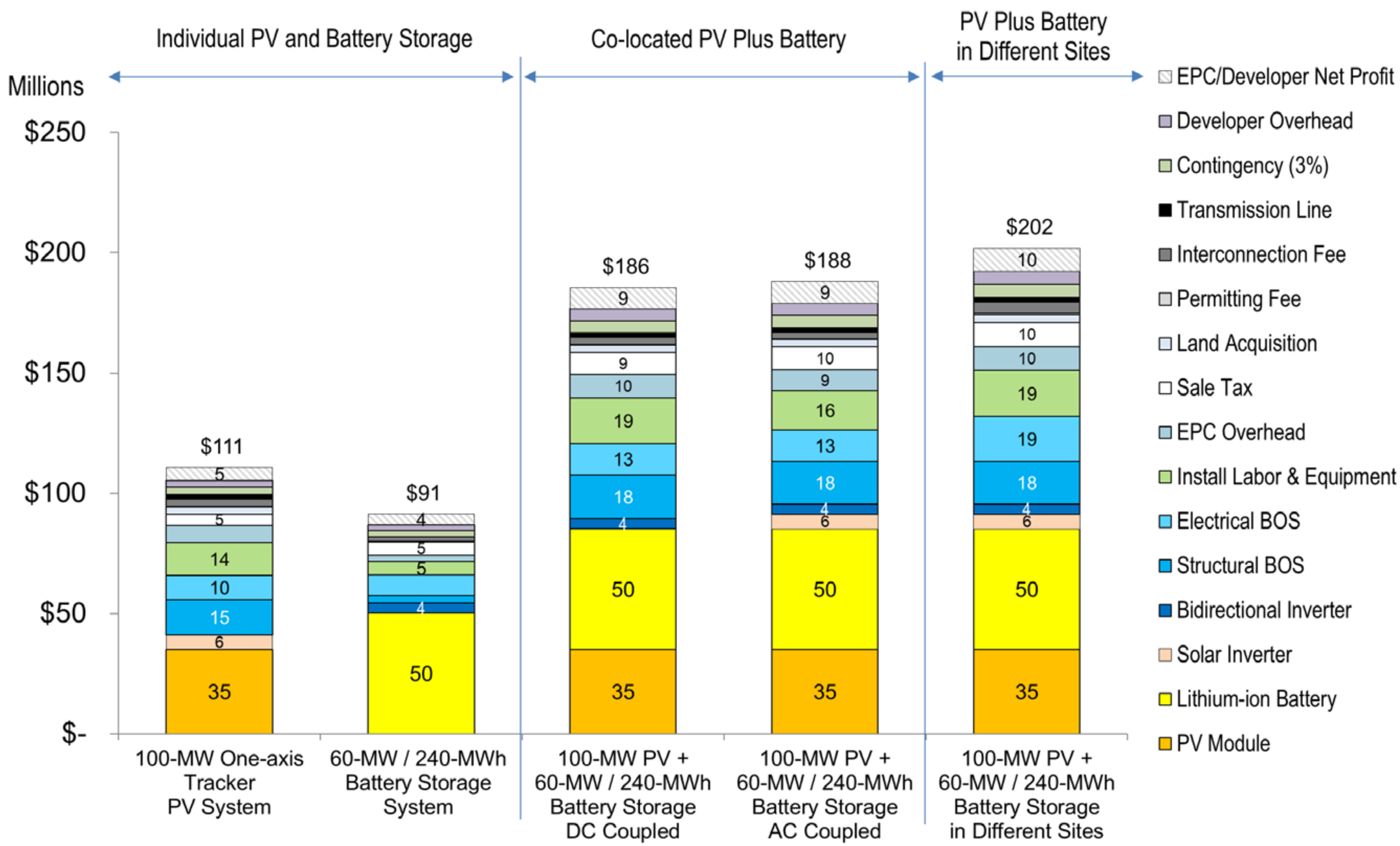

Figure ES-2. 2018 Cost benchmarks for PV-plus-storage systems (4-hour duration) in different sites and the same site (DC-coupled and AC-coupled cases)

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1 Introduction

The recent rapid growth of utility-scale photovoltaic (PV) deployment and the declining costs of energy storage technologies have stimulated interest in combining PV with energy storage to provide dispatchable energy and reliable capacity—particularly as the U.S. utility storage market has begun moving away from short-term power regulation and toward longer-term temporal shifting of renewable generation. The large-scale power interruptions caused by recent extreme weather/fire events in Puerto Rico, Houston, and California have also highlighted the need to improve the reliability and resiliency of U.S. electricity systems. The integration of renewable generation and energy storage offers a way to cost-effectively diversify and strengthen the nation's energy portfolio.

Historically, cost has been a barrier to deployment of PV and storage technologies, but improvements in both types of technologies are changing the economics rapidly. In particular, the use of lithium-ion (Li-ion) batteries in U.S. utility-scale applications has grown in recent years owing to the technology's favorable cost and performance characteristics. Still, utility-scale PV-plus-storage applications are in their infancy. The only such U.S. system recorded in the U.S. Department of Energy (DOE) Energy Storage Database is a 13-MW PV plus 52-MWh energy storage system in Kauai, Hawaii.

In order to provide a baseline for the accurate and transparent assessment of utility-scale PV-plus-storage systems, in this report we use the National Renewable Energy Laboratory's new bottom-up modeling tool to benchmark the installed costs of various standalone Li-ion storage and PV-plus-storage system configurations for utility-scale applications. Our analysis illustrates the tradeoffs between system choices including short- versus long-duration batteries, co-location versus separate location of battery and PV subsystems, and direct current (DC) versus alternating current (AC) coupling of co-located PV-plus-storage systems.

The remainder of this report is structured as follows. Section 2 provides a brief overview of energy storage technology options and deployment history. Section 3 focuses on Li-ion battery storage trends. Section 4 describes our cost models, and Section 5 shows the modeled cost results.

2 Energy Storage Technology Options and Deployment History

Numerous energy storage technologies have been deployed over the past century. Early large-scale systems typically employed physical or thermal storage media. However, widespread use of such systems has been hindered by cost, energy density, and siting disadvantages.

For example, in a pumped hydro storage system, water is pumped uphill into a reservoir and later released downhill through hydroelectric turbines to convert the stored potential energy into electricity. The first large-scale U.S. pumped hydro system was built in 1929 near New Milford, Connecticut (DOE 2018). In 1985, the country's largest pumped hydro system—with a generation capacity of 3 GW—was completed in Bath County, Virginia, after 8 years of construction (DOE 2018). Nationwide, 40 pumped hydro systems are operating today (DOE Energy Storage Database 2018). This technology typically has a roundtrip energy efficiency of 70%–80%, but siting presents major challenges. Cost-effective sites must have characteristics that enable damming of waterways to create a reservoir, usually requiring a large area remote from energy-demand centers. Even when a suitable site is identified, environmental and land-ownership considerations may hinder project approvals.

Compressed air energy storage (CAES) is another established technology that uses a physical storage mechanism. Energy is stored via air compression, and later the air is expanded to generate electricity. The lone large CAES system operating in the United States is the 110-MW plant in McIntosh, Alabama, which uses compressed air to run a natural gas turbine more efficiently (DOE Energy Storage Database 2018). CAES entails drawbacks that have hindered its deployment. Large-scale systems typically require specific geographical characteristics such as underground caverns that can be sealed to hold the compressed air. In addition, roundtrip efficiency of current technologies is only 40%–55% (Chen et al. 2013), and natural gas is consumed in the reconversion process. However, emerging CAES approaches offer higher theoretical efficiencies and generation without the need for fossil fuel combustion (Energy Storage Association 2018).

More recently, other types of energy storage have begun to be deployed at scale. Figure 1 shows the characteristics of energy storage technologies for systems built between 1958 and 2017 worldwide, categorized by storage type: electrochemical, electromechanical, thermal, and hydrogen.[1] Pumped hydro is not shown because its global capacity is much larger than the capacity of the other technologies. These technologies can be grouped into power applications (short duration or discharge time, such as Li-ion batteries) and energy applications (long duration or discharge time, such as CAES). Excluding pumped hydro, the technologies with the largest deployed capacities are molten salt thermal storage (associated with concentrating solar power plants), CAES, and Li-ion batteries.

[1] These data are from the DOE Energy Storage Database, an open-access source of energy storage project information that allows users to contribute data through a third-party vetting process; see the appendix for the figure data.

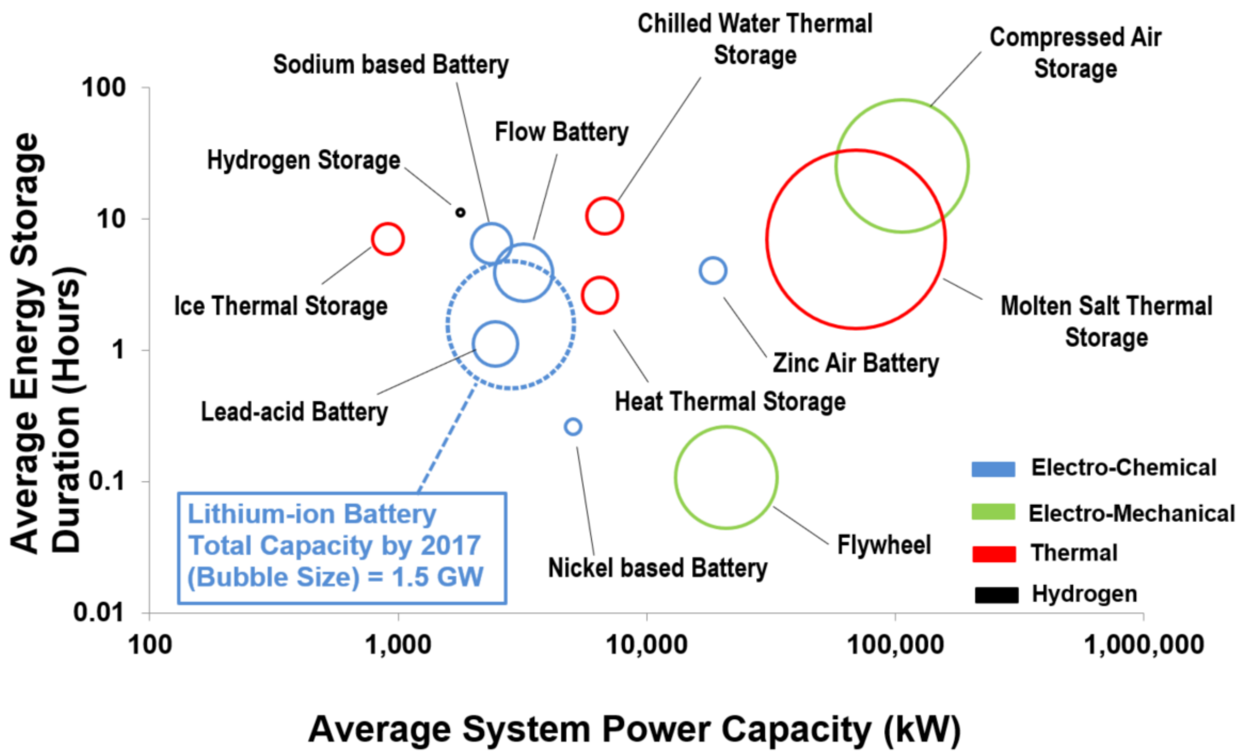


Figure 1. Average characteristics of energy storage systems built worldwide between 1958 and 2017, by technology, from the DOE Energy Storage Database (2018), sample size = 1,041 (pumped hydro not shown because of its very large global capacity)

Figure 2 shows the rapid recent growth of Li-ion energy storage. The first recorded utility-scale Li-ion project, the 1-MW Altairnano-PJM Battery Ancillary Services Demo in Pennsylvania, was built in 2008. Between 2008 and 2015, Li-ion capacity grew at a compound annual growth rate of 173% in terms of cumulative capacity, and Li-ion capacity accounted for 89% of annual energy storage capacity in 2015. The data for 2016 and 2017 are preliminary and incomplete, because some projects built in this time frame are still being verified in the database.

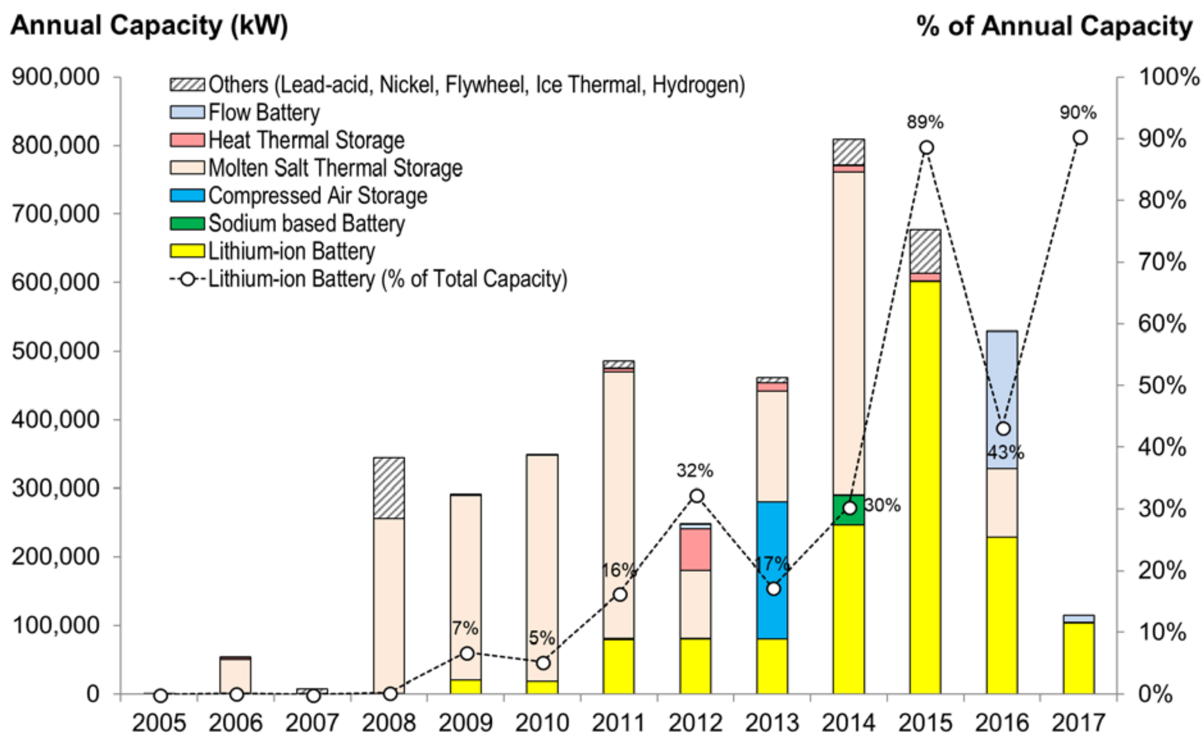


Figure 2. Annual capacities of energy storage systems built worldwide between 2005 and 2017, by technology, from the DOE Energy Storage Database (2018)[2]

[2] The data for 2016 and 2017 are preliminary and incomplete, because some projects built in this time frame are still being verified in the database.

3 Lithium-Ion Battery Storage Trends

Utilities have begun adopting Li-ion storage because of the technology's high roundtrip efficiency, high power density, ample supply chain availability, falling cell and system costs, and favorable performance metrics. Most Li-ion applications to date have provided short-duration power and grid stabilization, capturing value from various services including frequency response, voltage regulation, spinning reserves, transmission deferment, peak shaving, and demand response—and often providing a positive rate of return through this value stacking. Worldwide, Li-ion systems have an average duration of 1.6 hours and a power rating of 2.8 MW per system (Figure 1). Providing load shifting will require larger battery packs, which currently account for the largest share of system cost.

The United States is the world's leader in Li-ion storage deployment, mostly because of utility-scale storage systems. Between 2008 and 2017, it accounted for 40% of cumulative global Li-ion capacity (Figure 3). Of the U.S. Li-ion capacity through 2017, approximately 495 MW (92% of the capacity) was deployed in the utility-scale sector (systems larger than 1,000 kW), 8% in the commercial sector (systems of 10–1,000 kW), and less than 1% in the residential sector (systems smaller than 10 kW), as shown in Figure 4.

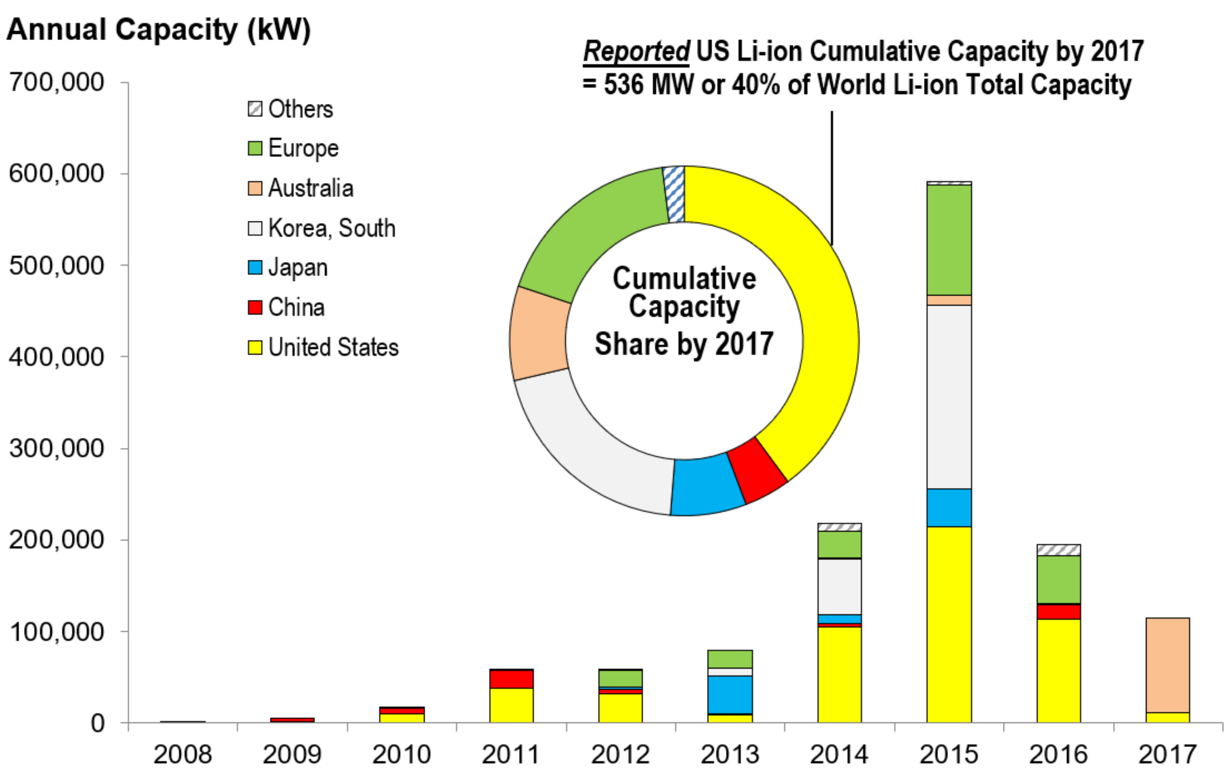


Figure 3. Li-ion storage deployment by region, 2008–2017 (DOE Energy Storage Database 2018)[3]

[3] The data for 2016 and 2017 are preliminary and incomplete owing to ongoing project verification for those years.

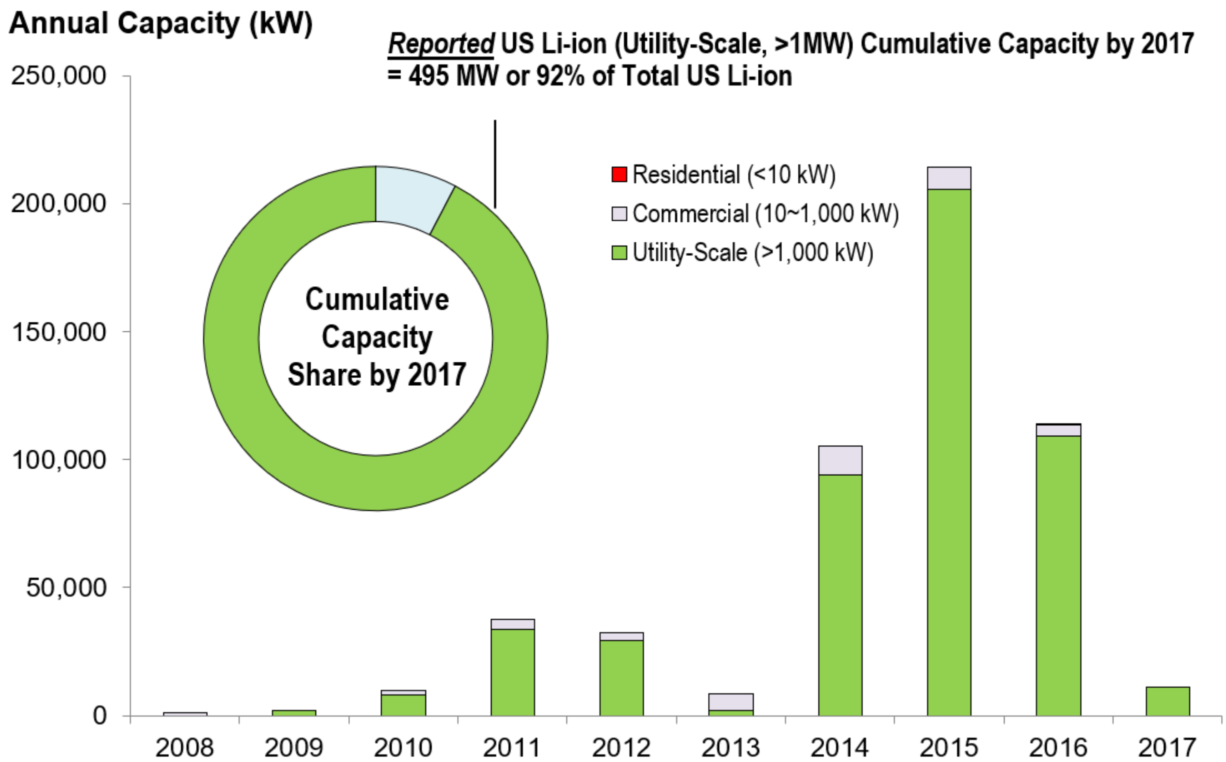


Figure 4. U.S. Li-ion energy storage by sector, 2008–2017 (DOE Energy Storage Database 2018)[4]

Figure 5 and Table 1 characterize U.S. Li-ion storage systems by sector. On average, utility-scale systems have a power rating of 9.9 MW and a duration of 1.7 hours. The utility-scale duration varies from about 0.5 to 4 hours between the 10th and 90th percentiles. For this reason, we model four utility-scale Li-ion storage duration cases: 0.5, 1, 2, and 4 hours. At the short end of the duration spectrum, the storage would mainly be used to maintain the real-time balance between generation and load as well as smooth short-term variations in voltage and current for frequency response. At the long end, the storage could defer transmission and distribution upgrades as well as mitigate variable energy output caused by renewable generation.

In this report, we focus on utility-scale storage systems. A previous report focused on residential storage systems (Ardani et al. 2017). For the baseline case, we use 4-hour storage 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 (Denholm et al. 2017).

[4] The data for 2016 and 2017 are preliminary and incomplete owing to ongoing project verification for those years.

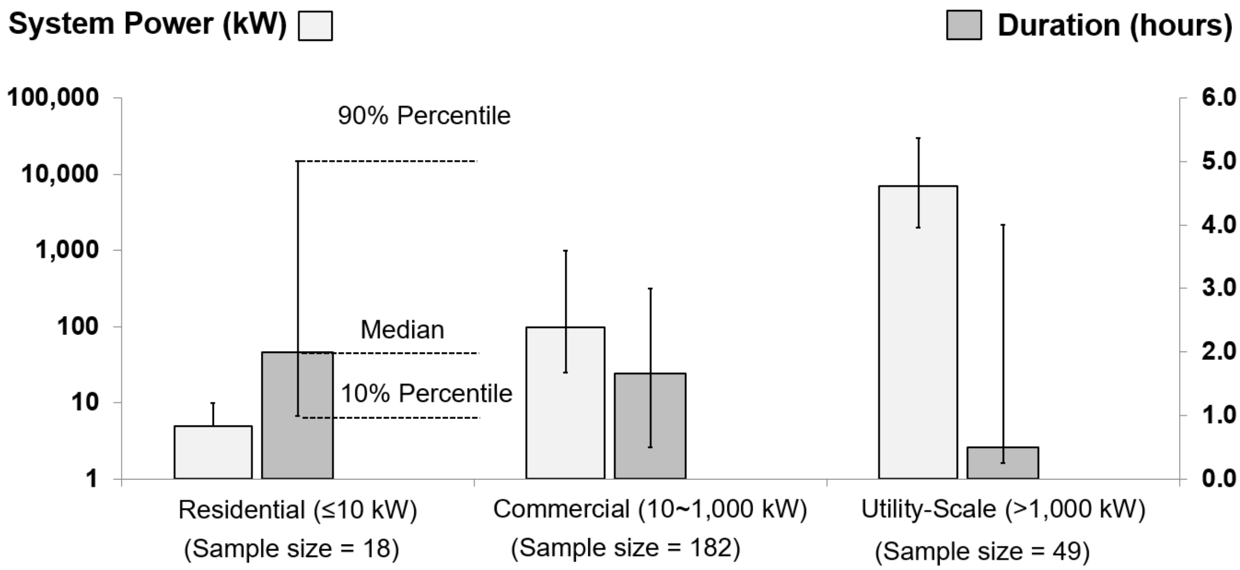


Figure 5. Distributions of U.S. Li-ion energy storage power and duration, by sector, 2008–2016 (DOE Energy Storage Database 2018)[5]

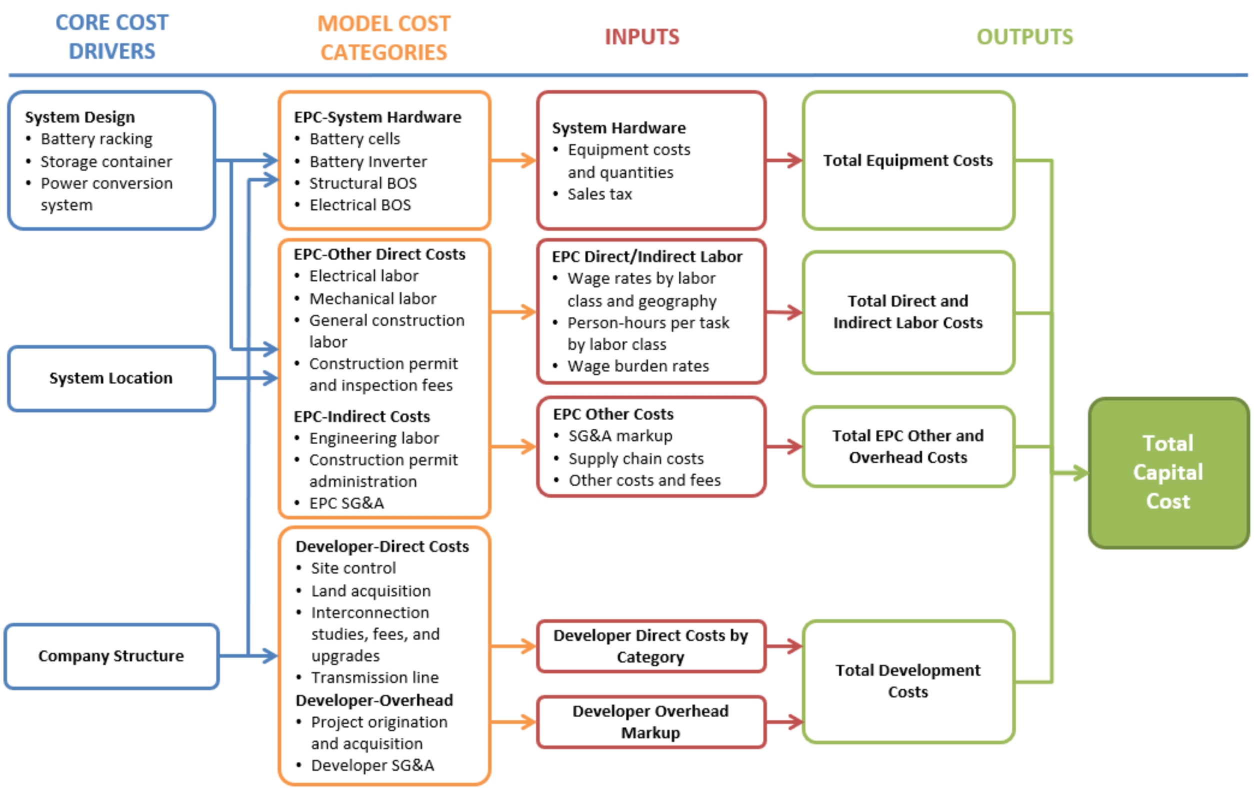
Table 1. U.S. Li-ion Energy Storage by Sector, 2008–2017 (DOE Energy Storage Database 2018)[5]

Sector	Total number of projects	Total kW	Total kWh	Average duration (hours)	Average system power rating (kW)	Average system energy (kWh)
Residential (< 10 kW)	18	116	278	2.4	6	15
Commercial (10–1,000 kW)	182	49,161	101,183	2.1	270	556
Utility-Scale (> 1,000 kW)	49	494,764	844,418	1.7	9,934	17,233
Total U.S.	**249**	**544,041**	**945,879**	**1.8**	**2,153**	**3,799**

[5] The data for 2016 and 2017 are preliminary and incomplete owing to ongoing project verification for those years.

4 Cost Models

Figure 6 shows the detailed bottom-up cost structure of our standalone storage model, which uses a similar structure to our previously developed PV cost model (Fu et al. 2015, 2016, 2017). Total system upfront capital costs are broken into engineering, procurement, and construction (EPC) costs and developer costs. EPC non-hardware or "soft" costs are driven by labor rates and labor productivities. We adapt engineering-design and cost-estimating models from RSMeans (2017) to determine the EPC hardware costs (including module/battery racking, mounting, wiring, containerization, and foundation) and related EPC soft costs (including related labor and equipment hours required in any given U.S. location). Section 4.1 presents additional detail on the Li-ion standalone storage model, and Section 4.2 shows results from the combined PV-plus-storage model.



BOS = balance of system, SG&A = selling, general, and administrative

Figure 6. Structure of the bottom-up cost model for standalone storage systems

4.1 Lithium-Ion Standalone Storage Cost Model

To reduce installation costs, some battery manufacturers may combine Li-ion battery cells, a battery management system, and the battery inverter in one compact unit (Sonnen Batterie 2018) as an AC battery. However, in this report, we focus on traditional DC batteries typically configured with the four major components shown in Figure 7 and Figure 8.

Battery cells → modules → packs → racking system (DC)

↓

Storage container
(HVAC system, thermal management, monitors and controls, fire suppression, switchgear, and energy management system)

↓

Power conversion system
(bidirectional inverter to convert AC to DC for battery charging and DC to AC for discharging)

↓

Transformer (to step up 480-V inverter output to 12–66 kV)

Figure 7. Traditional utility-scale Li-ion battery energy storage components

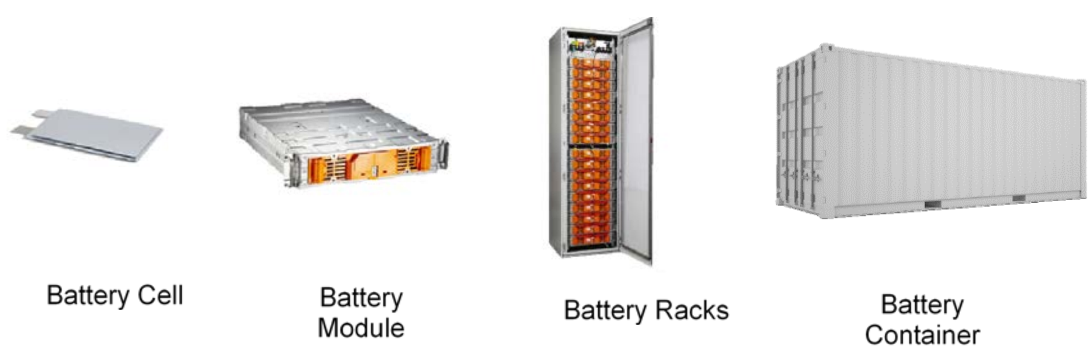


Figure 8. Battery system components (NAGF/ESIG Workshop 2018)

Table 2 lists our model inputs and assumptions for such a utility-scale energy storage system. We determined the battery size (60 MW_{DC})[6] using an inverter loading ratio (ILR) of 1.3 and an inverter/storage size ratio of 1.67, based on Denholm et al. (2017).

Table 2. Utility-Scale Li-ion Energy Storage System Model Inputs and Assumptions (NREL 2018, Fu et al. 2017, Denholm et al. 2017, Blattner Energy 2018, Escondido 2018, Curry 2017, Ortiz 2016, Gupta 2018)

Model Component	Model Input
Battery total size	60 MW DC
Battery size per container	5 MWh per 40-foot container
Number of containers	48 (if duration = 4 hours)
Li-ion battery price	$209/kWh
Duration	0.5–4 hours
Battery central inverter price	$0.07/W
Battery inverter size	2.5 MW per inverter
Number of inverters	24
Transformer price	$28,000 per transformer
Transformer size	2.5 MW per step-up transformer
Number of transformers	24
Foundation	76,800 square feet
Installation labor	Non-union at rates from Bureau of Labor Statistics survey average by state (BLS 2018)
Sales tax	7.5%
EPC overhead (% of equipment and labor costs)	8.67% for equipment and material (except for transmission line costs); 23%–69% for labor costs: varies by labor activity
Developer overhead	3% of EPC cost
Land acquisition	$250,000
Interconnection	$0.03/W
Permitting	$295,000 per system
Contingency	3% of EPC cost
EPC/developer net profit	5% of total installation cost (EPC + developer costs)

[6] For a 100-MW PV system with ILR = 1.3, the inverter size must be 77 MW AC (100 MW/1.3). Using the inverter/storage size ratio (1.67), the storage power capacity must be 46 MW AC (77/1.67). Thus, to match a 100-MW PV system, the storage power capacity must be 60 MW DC (46 × 1.3).

We use these inputs to calculate energy storage cost via the following equation[7]:

$$Energy\ storage\ installation\ cost\ \left(\frac{\$}{kWh}\right) =$$

$$Battery\ cost\ \left(\frac{\$}{kWh}\right) + \frac{Other\ cost\ components\ (\$)\ such\ as\ battery\ inverter\ and\ labor}{Storage\ system\ size\ (kW) \times Duration\ (hours)}$$

Figure 9 and Table 3 show the resulting $/kWh costs for 60-MW Li-ion energy storage systems, which vary from $380/kWh (4-hour duration) to $895/kWh (0.5-hour duration). Because the per-energy-unit battery cost remains constant at $209/kWh, the total battery cost—and the proportion of the cost attributed to the battery—decrease as system duration decreases. For example, the battery cost accounts for 55% of total system cost in the 4-hour system, but only 23% in the 0.5-hour system. At the same time, non-battery cost categories accounts for an increasing proportion of the system cost as duration declines.

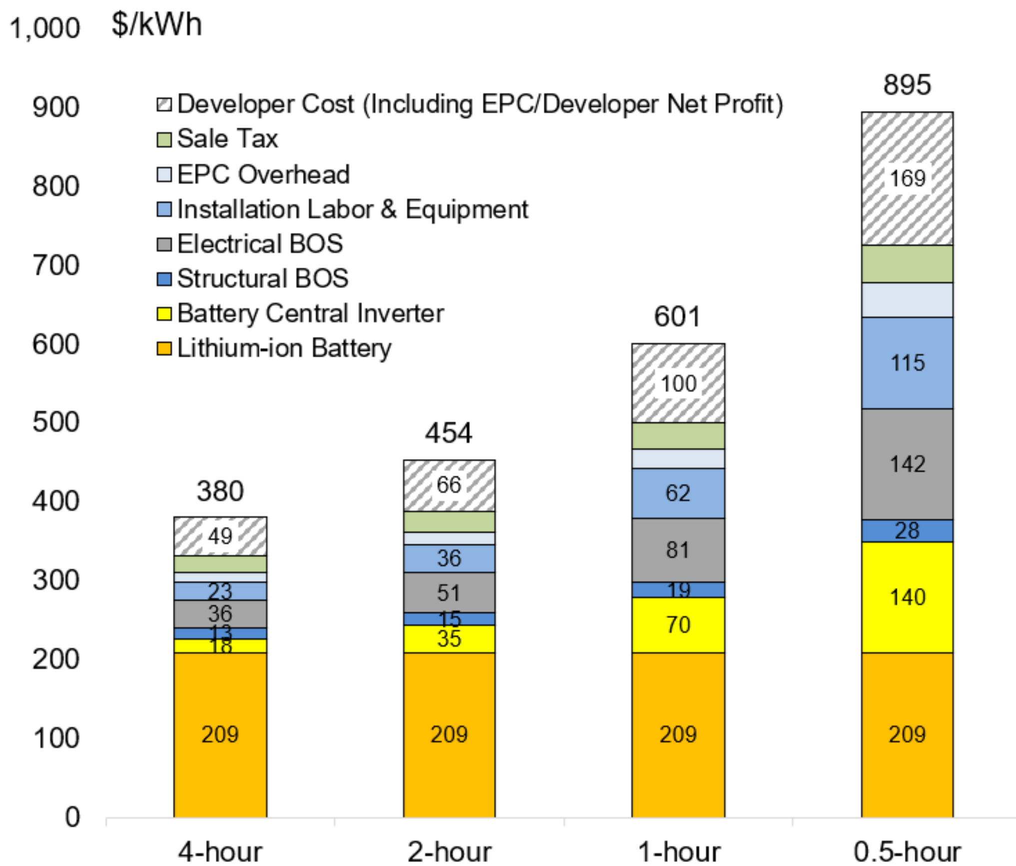


Figure 9. 2018 U.S. utility-scale Li-ion battery standalone storage costs for durations of 0.5–4 hours (60 MW_{DC})

[7] This equation is only for the energy storage installation cost calculation. For levelized cost of storage (LCOS), the equation would be different. LCOS is not covered in this report.

Table 3. Detailed Cost Breakdown for a 60-MW U.S. Li-ion Standalone Storage System with Durations of 0.5–4 Hours

	60-MW, 4-hour Duration, 240-MWh			60-MW, 2-hour Duration, 120-MWh			60-MW, 1-hour Duration, 60-MWh			60-MW, 0.5-hour Duration, 30-MWh		
Model Component	**Total Cost ($)**	**$/kWh**	**$/W**	**Total Cost ($)**	**$/kWh**	**$/W**	**Total Cost ($)**	**$/kWh**	**$/W**	**Total Cost ($)**	**$/kWh**	**$/W**
Li-ion battery	50,160,000	209	0.84	25,080,000	209	0.42	12,540,000	209	0.21	6,270,000	209	0.10
Battery central inverter	4,200,000	18	0.07	4,200,000	35	0.07	4,200,000	70	0.07	4,200,000	140	0.07
Structural BOS	3,121,131	13	0.05	1,813,452	15	0.03	1,159,612	19	0.02	832,692	28	0.01
Electrical BOS	8,602,825	36	0.14	6,119,167	51	0.10	4,877,337	81	0.08	4,256,423	142	0.07
Installation labor & equipment	5,479,149	23	0.09	4,322,275	36	0.07	3,743,838	62	0.06	3,454,619	115	0.06
EPC overhead	2,775,545	12	0.05	1,948,565	16	0.03	1,535,075	26	0.03	1,328,330	44	0.02
Sales tax	5,293,460	22	0.09	3,083,292	26	0.05	1,978,209	33	0.03	1,425,667	48	0.02
∑ EPC cost	**79,632,110**	**332**	**1.33**	**46,566,751**	**388**	**0.78**	**30,034,071**	**501**	**0.50**	**21,767,732**	**726**	**0.36**
Land acquisition	250,000	1	0.00	250,000	2	0.00	250,000	4	0.00	250,000	8	0.00
Permitting fee	295,289	1	0.00	295,289	2	0.00	295,289	5	0.00	295,289	10	0.00
Interconnection fee	1,802,363	8	0.03	1,802,363	15	0.03	1,802,363	30	0.03	1,802,363	60	0.03
Contingency	2,477,135	10	0.04	1,476,303	12	0.02	975,887	16	0.02	725,679	24	0.01
Developer overhead	2,477,135	10	0.04	1,476,303	12	0.02	975,887	16	0.02	725,679	24	0.01
EPC/developer net profit	4,346,702	18	0.07	2,593,350	22	0.04	1,716,675	29	0.03	1,278,337	43	0.02
∑ Developer cost	**11,648,623**	**49**	**0.19**	**7,893,608**	**66**	**0.13**	**6,016,101**	**100**	**0.10**	**5,077,347**	**169**	**0.08**
∑ Total energy storage system cost	**91,280,733**	**380**	**1.52**	**54,460,359**	**454**	**0.91**	**36,050,172**	**601**	**0.60**	**26,845,079**	**895**	**0.45**

4.2 PV-Plus-Storage System Cost Model

Here we combine our energy storage cost model with our PV system cost model in various configurations: 1) co-located PV-plus-storage systems vs. PV-plus-storage systems in different locations, and 2) DC-coupled vs. AC-coupled battery configurations for the co-located PV-plus-storage systems. As shown in Table 4, co-location enables sharing of several hardware components between the PV and energy storage systems, which can reduce costs. Co-location can also reduce soft costs related to site preparation, land acquisition, installation labor, permitting, interconnection, and EPC/developer overhead and profit.

Table 4. Cost Factors for Siting PV and Storage Together vs. Separately (NREL 2018, Blattner Energy 2018, Ardani et al. 2017)

Model Component	Co-located PV-Plus-Storage	PV-Plus-Storage in Different Sites
Site preparation[8]	Once	Twice
Land acquisition cost	Lower	Higher
Hardware sharing between PV and energy storage	Yes (step-up transformer, switchgear, monitor, and controls)	No
Installation labor cost	Lower (due to hardware sharing and single labor mobilization)	Higher
EPC/developer overhead and profit	Lower (due to lower labor cost, BOS, and total system cost)	Higher
Interconnection and permitting	Once	Twice

When PV and battery storage are co-located, the subsystems can be connected by a DC-coupled or AC-coupled configuration (Figure 10). A DC-coupled system needs only one bidirectional inverter, connects battery storage directly to the PV array, and enables the battery to charge and discharge from the grid. On the other hand, an AC-coupled system needs both a PV inverter and a bidirectional inverter, and there are multiple conversion steps between DC and AC to charge or discharge the battery. Also, the transmission line could be used for both PV and battery storage systems.

The advantages of the DC-coupled system include the following:

1. A DC-coupled system uses only a single bidirectional inverter (Table 5), thus reducing costs for the inverter, inverter wiring, and inverter housing.
2. Because of the extra conversion between DC and AC, an AC-coupled system may have lower roundtrip efficiency for battery charging compared with a DC-coupled system, which charges the battery directly. However, as power electronics are becoming more efficient, the actual efficiency difference is becoming smaller (Enphase 2018).

[8] Site preparation is a sub-category under labor cost, so it is not shown in the cost breakdown chart.

3. Because the battery is connected directly to the solar array, excess PV generation that would otherwise be clipped by an AC-coupled system at the inverter level can be sent directly to the battery, which could improve system economics (DiOrio 2018).

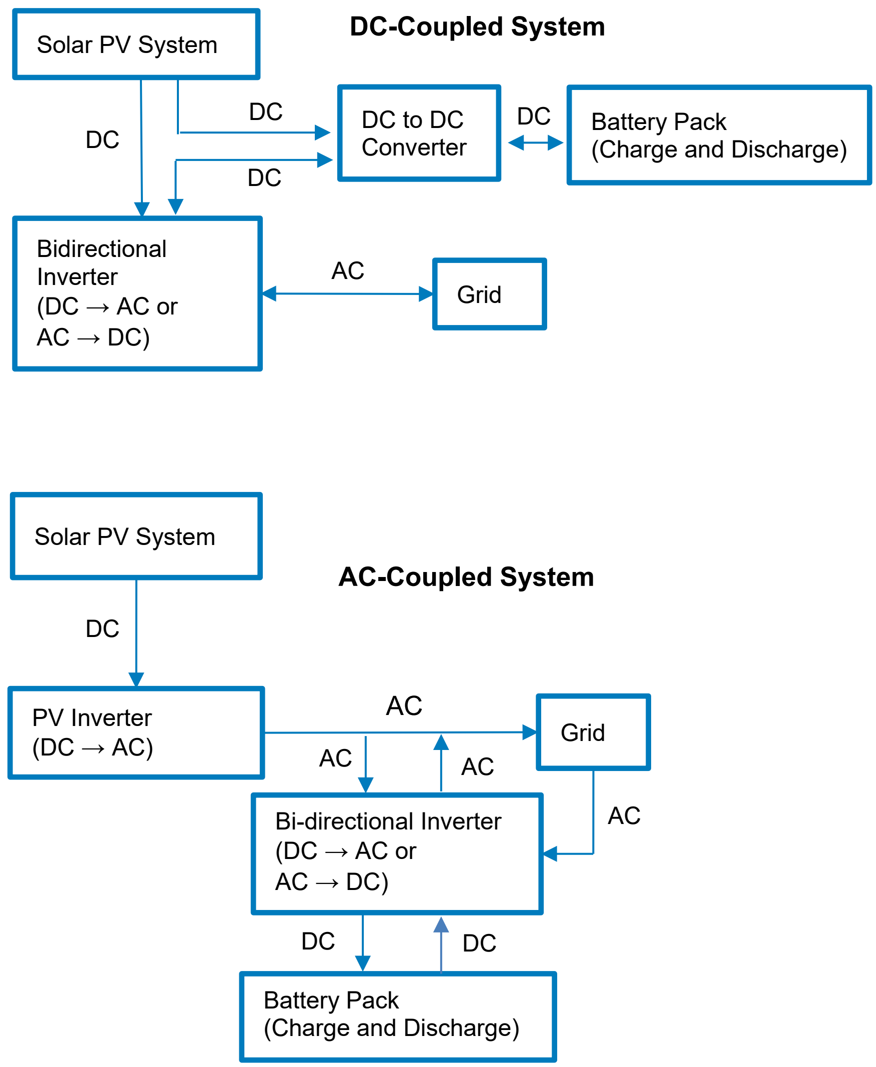


Figure 10. DC-coupled and AC-coupled PV-plus-storage system configurations

Table 5. Comparison of DC and AC Coupling for PV-Plus-Storage Systems (Denholm et al. 2017, Ardani et al. 2017, Cole et al. 2016)

Model Component	DC-Coupled Configuration	AC-Coupled Configuration
Number of inverters	1 (bidirectional inverter for battery)	2 (bidirectional inverter for battery plus grid-tied inverter for PV), resulting in higher costs for the inverter, inverter wiring, and inverter housing
Battery rack size	Smaller (because battery is directly connected to PV), resulting in more heating, ventilating, and air conditioning (HVAC) and fire-suppression systems required	Larger
Structural BOS	More (due to smaller battery rack size)	Less
Electrical BOS	Less (but needs additional DC-to-DC converters)	More (due to additional wiring for inverters)
Installation labor cost	More (due to smaller battery rack size and more skilled labor and labor hours required for DC work)	Less
EPC overhead	More (due to higher installation labor cost)	Less
Sales tax	Less	More (due to higher total hardware costs)
EPC/developer profit	Less	More (due to higher total EPC and developer costs)

The advantages of the AC-coupled system include the following:

1. Because the battery racks are not directly connected to the PV system in AC-coupled systems, these systems can use larger battery racks and thus reduce the number of HVAC and fire-suppression systems in the containers. This feature also reduces installation labor costs compared with DC-coupled systems.
2. For a retrofit (i.e., adding battery storage to an existing PV array), an AC-coupled battery may be more practical than a DC-coupled battery, because DC-coupled systems require installers to replace the existing PV inverter with a bidirectional inverter. Thus, the additional costs due to replacing the inverter and rewiring the system could make retrofit costs higher for a DC-coupled system compared with an AC-coupled system (Ardani et al. 2017). In addition, AC-coupled systems enable the option of upgrading the PV and battery separately, because these systems are independent of one another.
3. Because AC-coupled systems have separated PV and battery systems, installers have more flexibility to adjust the battery location. For instance, DC-coupled systems require batteries to be installed next to the bidirectional inverter, and the resulting need for maintenance crews to enter the PV field can make maintenance more time consuming. Because AC-coupled systems can have batteries located outside of the PV field, maintenance work can be quicker and easier.

5 Model Results and Summary

Figure 11 summarizes our model results for several system types and configurations:

- Standalone 100-MW PV system with one-axis tracking ($111 million)
- Standalone 60-MW/240-MWh, 4-hour-duration energy storage system ($91 million)
- Co-located, DC-coupled PV (100 MW) plus storage (60 MW/240 MWh, 4-hour duration) system ($186 million)
- Co-located, AC-coupled PV (100 MW) plus storage (60 MW/240 MWh, 4-hour duration) system ($188 million)
- PV (100 MW) plus storage (60 MW/240 MWh, 4-hour duration) system with PV and storage components sited in different locations ($202 million)

Table 6 shows detailed costs for the three PV-plus-storage configurations. Co-locating the PV and storage subsystems produces cost savings by reducing costs related to site preparation, land acquisition, permitting, interconnection, installation labor, hardware (via sharing of hardware such as switchgears, transformers, and controls), overhead, and profit. The cost of the co-located, DC-coupled system is 8% lower than the cost of the system with PV and storage sited separately, and the cost of the co-located, AC-coupled system is 7% lower.

Using DC-coupling rather than AC-coupling results in a 1% lower total cost, which is the net result of cost differences between DC-coupling and AC-coupling in the categories of solar inverter, structural BOS, electrical BOS, labor, EPC and developer overhead, sales tax, contingency, and profit. For an actual project, however, cost savings may not be the only factor in choosing DC or AC coupling. Additional factors—such as retrofit considerations, system performance (including energy loss due to clipping), design flexibility, and operations and maintenance—should be considered.

In summary, the National Renewable Energy Laboratory's new bottom-up cost model can be used to assess the costs of utility-scale PV-plus-storage systems using various configurations. The itemized cost savings could incentivize deployment of co-located PV-plus-storage systems. In addition, the model can help industry representatives evaluate the cost impacts of various battery durations for grid applications. Finally, the model can be used to estimate future potential cost-reduction opportunities for PV-plus-storage systems, helping to guide research and development aimed at advancing cost-effective system configurations. In the future, we will continue updating the model inputs and expand our model to cover more economic metrics, such as LCOS (Levelized Cost of Storage).

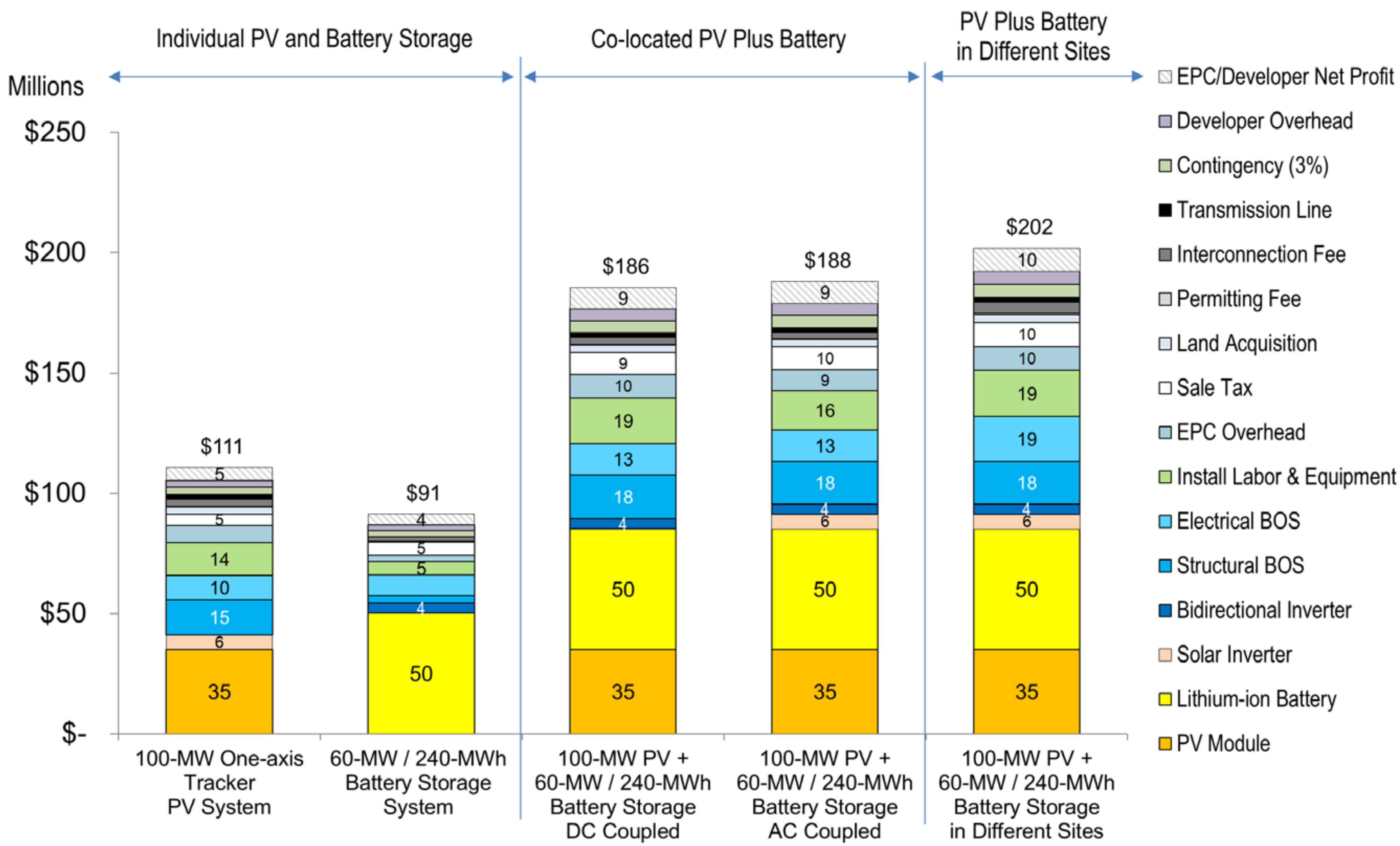


Figure 11. 2018 Cost benchmarks for PV-plus-storage systems (4-hour duration) in different sites and the same site (DC-coupled and AC-coupled cases)

Table 6. Detailed Cost Breakdown for Utility-Scale Li-ion PV-Plus-Storage Systems

Model Component	Total Cost		
	100-MW PV Plus 60-MW/240-MWh Battery, DC-Coupled, Co-located	**100-MW PV Plus 60-MW/240-MWh Battery, AC-Coupled, Co-located**	**100-MW PV Plus 60-MW/240-MWh Battery, In Different Sites**
PV module	$35,000,000	$35,000,000	$35,000,000
Li-ion battery	$50,160,000	$50,160,000	$50,160,000
Solar inverter	n/a	$6,153,846	$6,153,846
Bidirectional inverter	$4,200,000	$4,200,000	$4,200,000
Structural BOS	$18,346,829	$17,685,150	$17,735,564
Electrical BOS	$12,987,780	$13,115,425	$18,649,611
Installation labor & equipment	$18,863,868.05	$16,326,680.01	$19,058,910
EPC overhead	$9,879,642	$8,550,831	$9,981,792
Sales tax	$9,178,323	$9,605,687	$10,030,372
∑ EPC cost	**$158,616,442**	**$160,797,619**	**$170,970,095**
Land acquisition	$3,000,000	$3,000,000	$3,250,000
Permitting fee	$295,289	$295,289	$590,578
Interconnection fee	$2,919,545	$2,919,545	$4,721,908
Transmission line	$1,883,302	$1,883,302	$1,883,302
Contingency	$5,001,437	$5,066,873	$5,455,816
Developer overhead	$5,001,437	$5,066,873	$5,455,816
EPC/developer net profit	$8,835,873	$8,951,475	$9,616,376
∑ Developer cost	**$26,936,884**	**$27,183,357**	**$30,973,796**
∑ Total energy storage system cost	**$185,553,326**	**$187,980,975**	**$201,943,890**

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Appendix. Figure Data from DOE Energy Storage Database

Figure 1 Data

Specific Type	Category	Number of projects	Total kW	Total kWh	Average Duration (hours)	Average System Power Rating (kW)	Average System Energy (kWh)
Lead-acid Battery	Electro-chemical	79	194,300	216,578	1.1	2,459	2,741
Li-ion Battery	Electro-chemical	523	1,485,898	2,321,097	1.6	2,841	4,438
Flow Battery	Electro-chemical	101	322,702	1,251,215	3.9	3,195	12,388
Sodium-based Battery	Electro-chemical	71	168,634	1,090,820	6.5	2,375	15,364
Nickel-based Battery	Electro-chemical	6	30,385	7,925	0.3	5,064	1,321
Zinc-air Battery	Electro-chemical	4	73,750	297,008	4.0	18,438	74,252
Compressed Air Storage	Electro-mechanical	15	1,592,590	39,974,670	25.1	106,173	2,664,978
Flywheel	Electro-mechanical	46	961,435	103,414	0.1	20,901	2,248
Molten Salt Thermal Storage	Thermal	41	2,850,520	19,845,210	7.0	69,525	484,030
Heat Thermal Storage	Thermal	20	129,740	338,430	2.6	6,487	16,922
Ice Thermal Storage	Thermal	110	99,675	703,363	7.1	906	6,394
Chilled Water Thermal Storage	Thermal	20	135,206	1,421,741	10.5	6,760	71,087
Hydrogen Storage	Hydrogen	5	8,920	100,060	11.2	1,784	20,012
Total Non-Hydro Storage		1,041	8,053,755	67,671,531	8.4	7,737	65,006
Open-loop Pumped Hydro	Pumped Hydro	69	39,321,700	390,411,510	9.9	569,880	5,658,138
Closed-loop Pumped Hydro	Pumped Hydro	7	4,288,006	31,533,369	7.4	612,572	4,504,767
Total Hydro Storage (not shown in Figure 1)		76	43,609,706	421,944,879	9.7	573,812	5,551,906

Figure 2 Data

Worldwide (kW)		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Lead-acid Battery	Electro-chemical	0	16	60	0	12	1,000	44,625	445	3,010	2,114	1,050	0	0
Li-ion Battery	Electro-chemical	0	0	0	1,000	2,000	5,400	1,662	21,020	17,116	90,748	264,615	96,110	104,000
Flow Battery	Electro-chemical	0	0	100	0	0	10	800	5,190	370	30	300	200,200	10,200
Sodium-based Battery	Electro-chemical	0	1,000	0	0	0	0	1,195	298	0	44,555	10	11	800
Nickel-based Battery	Electro-chemical	0	0	0	0	0	0	0	0	0	0	0	0	0
Zinc-air Battery	Electro-chemical	0	0	0	0	0	0	0	0	0	0	62,500	0	0
Compressed Air Storage	Electro-mechanical	0	0	0	0	0	0	350	0	201,000	500	1,000	0	0
Flywheel	Electro-mechanical	1,100	0	500	0	500	500	1,600	100	2,000	290	0	0	0
Molten Salt Thermal Storage	Thermal Storage	0	49,900	0	255,720	269,900	330,000	390,000	100,000	160,000	470,000	0	100,000	0
Heat Thermal Storage	Thermal Storage	11,000	2,000	1,500	0	1,500	0	3,600	61,155	12,000	10,100	0	0	0
Ice Thermal Storage	Thermal Storage	0	0	5,320	0	375	0	0	0	1,000	0	0	0	0
Chilled Water Thermal Storage	Thermal Storage	0	0	0	90,000	0	0	0	0	0	0	0	0	0
Hydrogen Storage	Hydrogen Storage	0	0	0	0	0	0	0	0	1,320	0	0	0	0
Total Non-Hydro Storage		**12,100**	**52,916**	**7,480**	**346,720**	**274,287**	**336,910**	**443,832**	**188,208**	**397,816**	**618,337**	**329,475**	**396,321**	**115,000**