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

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- Standalone Energy Storage Cost Model
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Introduction

- NREL has been modeling U.S. photovoltaic (PV) system costs since 2009.

- Interest in combining utility-scale PV and energy storage systems as "PV-plus-storage " has been increasing in order to maintain the value of PV production and capture new revenue sources (i.e. ancillary services, distribution and transmission deferrals, etc.).

- Although there are many utility-scale PV systems and a growing number of standalone utility-scale storage systems, there are very few co-located utility-scale PV plus storage systems in the U.S.

- In this study we developed new bottom-up cost models to estimate the PV-plus-storage systems for various configurations.

Introduction

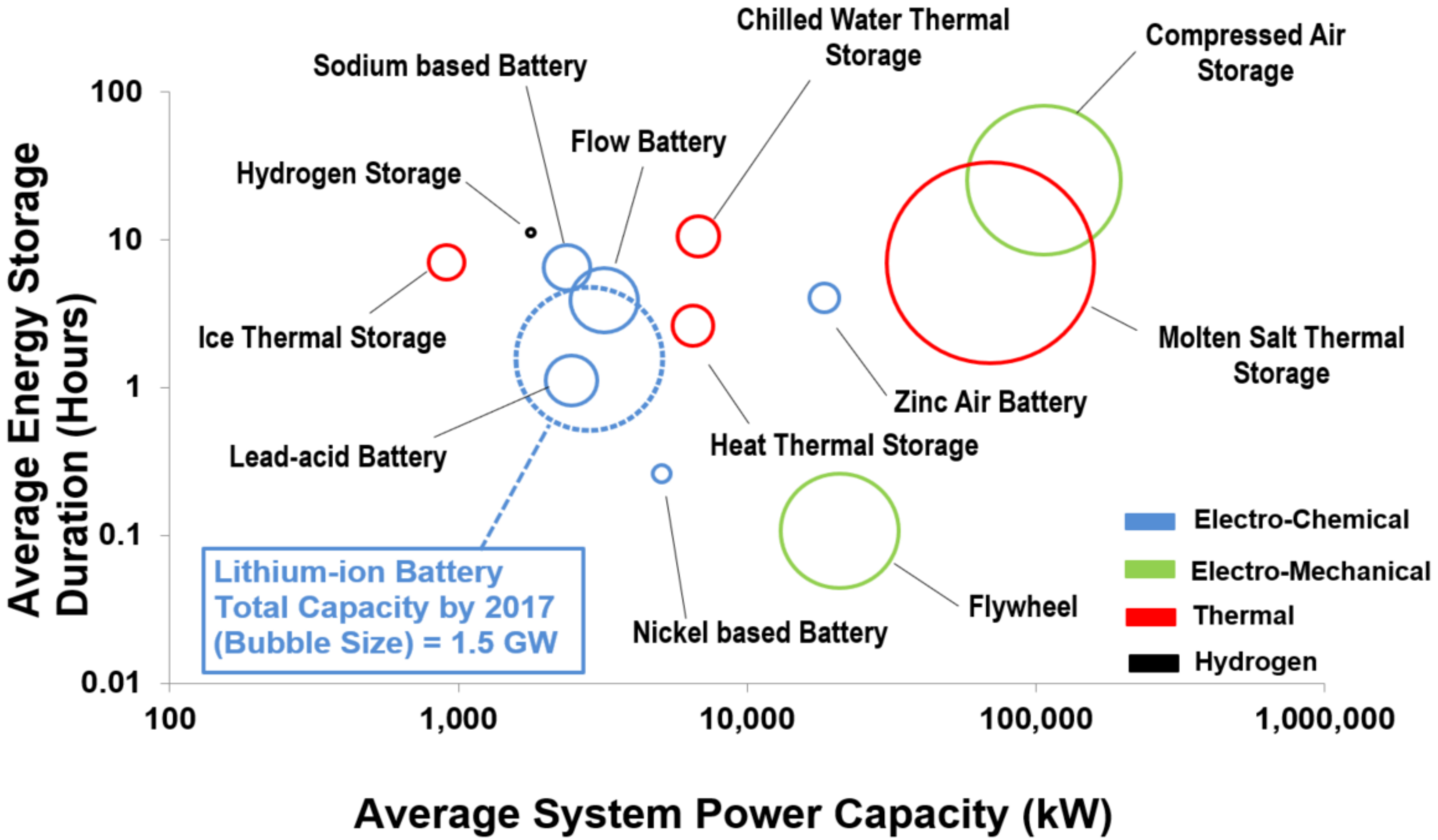

Fig. Energy storage application by technology, worldwide (1958 – 2017).

Based on the Department of Energy Global Energy Storage Database, lithium-ion battery systems had an average duration of 1.6 hours and an average power rating of 2.8 MW per system. This report focuses on PV-plus-storage systems using Li-ion batteries.

Introduction

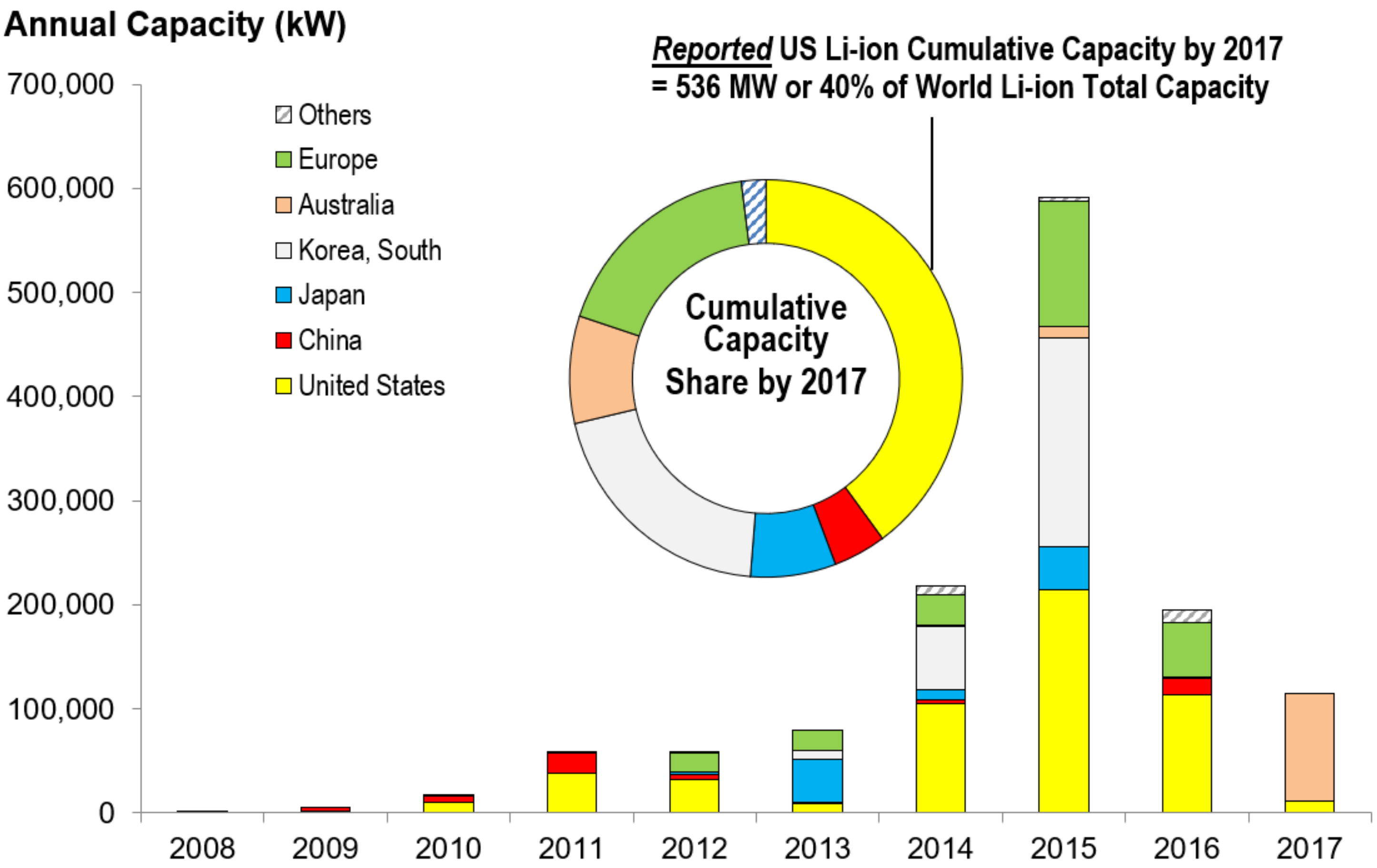

Fig. Li-ion storage deployment by region, 2008–2017.

The US is the world's leader in lithium-ion storage deployment, mostly because of utility-scale storage systems. Between 2008 and 2017 it accounted for 40% of cumulative global Li-ion capacity (DOE Energy Storage Database 2018).

Introduction

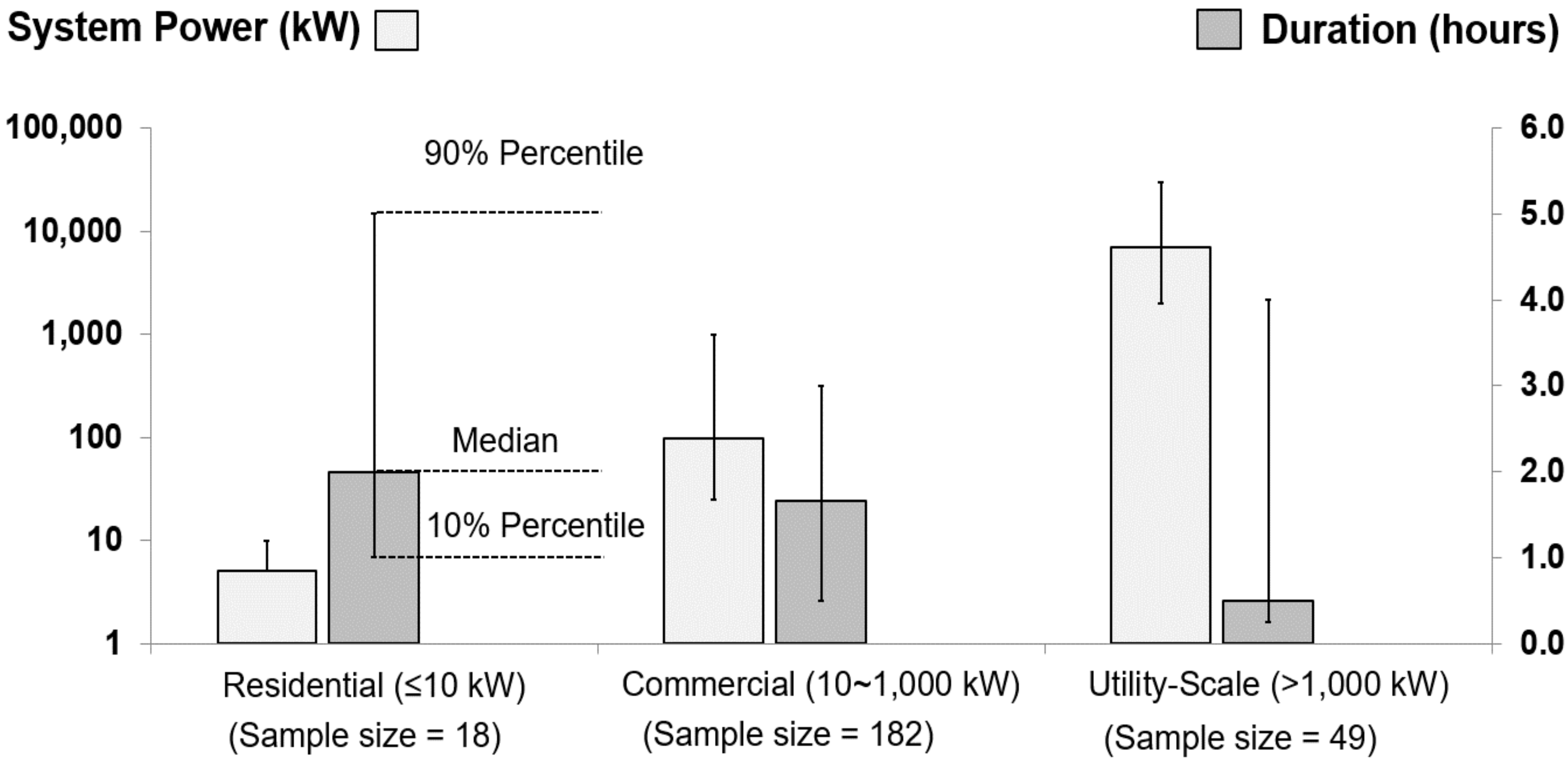

Fig. U.S. lithium-ion battery storage (2008 – 2016)

Utility-scale battery storage systems in the US (>1 MW, 30 mins to 4 hours duration) using lithium-ion batteries had an average duration of ~30 mins and an average power rating of 10 MW per system. For the baseline case, we use 4-hour storage according to the California Public Utilities Commission's "4-hour rule" (Denholm et al. 2017).

Introduction

This study uses bottom-up modeling to benchmark the installed costs of three different PV-plus-storage configurations.

Type	PV and storage in the same location (co-located)?	Connected to
Standalone	No	Grid only
DC-coupled	Yes	Grid and PV
AC-coupled	Yes	Grid and PV

In the report, we benchmarked:

- **Standalone 60-MW/240-MWh energy storage system;**
- **Co-located, DC-coupled PV (100 MW) plus storage (60 MW/240 MWh) system;**
- **Co-located, AC-coupled PV (100 MW) plus storage (60 MW/240 MWh) system;**
- **PV (100 MW) plus storage (60 MW/240 MWh) system with PV and storage components sited in different locations.**

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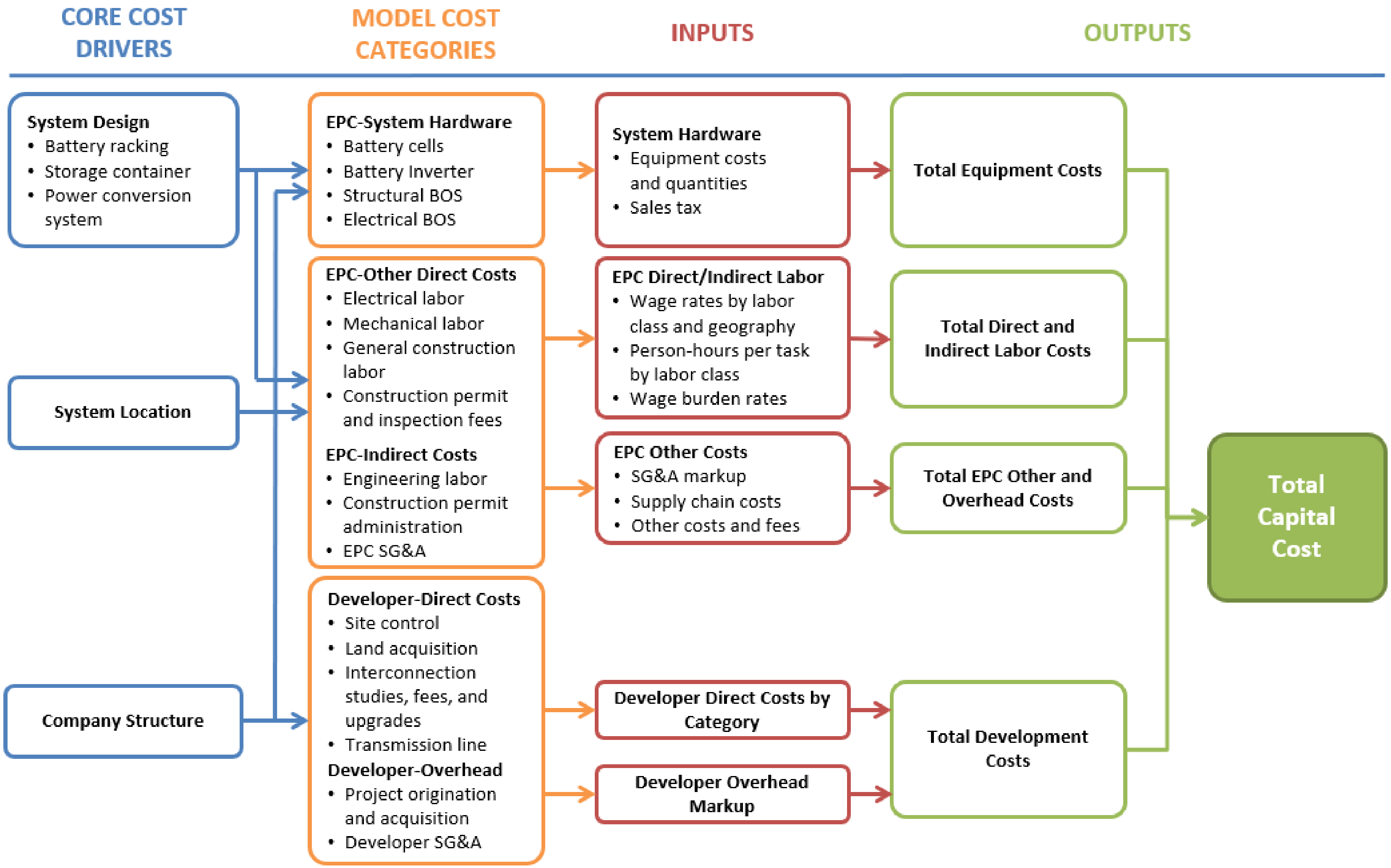
Energy Storage Cost Model



CORE COST DRIVERS

MODEL COST CATEGORIES

INPUTS

OUTPUTS

System Design
- Battery racking
- Storage container
- Power conversion system

System Location

Company Structure

EPC-System Hardware
- Battery cells
- Battery Inverter
- Structural BOS
- Electrical BOS

EPC-Other Direct Costs
- Electrical labor
- Mechanical labor
- General construction labor
- Construction permit and inspection fees

EPC-Indirect Costs
- Engineering labor
- Construction permit administration
- EPC SG&A

Developer-Direct Costs
- Site control
- Land acquisition
- Interconnection studies, fees, and upgrades
- Transmission line

Developer-Overhead
- Project origination and acquisition
- Developer SG&A

System Hardware
- Equipment costs and quantities
- Sales tax

EPC Direct/Indirect Labor
- Wage rates by labor class and geography
- Person-hours per task by labor class
- Wage burden rates

EPC Other Costs
- SG&A markup
- Supply chain costs
- Other costs and fees

Developer Direct Costs by Category

Developer Overhead Markup

Total Equipment Costs

Total Direct and Indirect Labor Costs

Total EPC Other and Overhead Costs

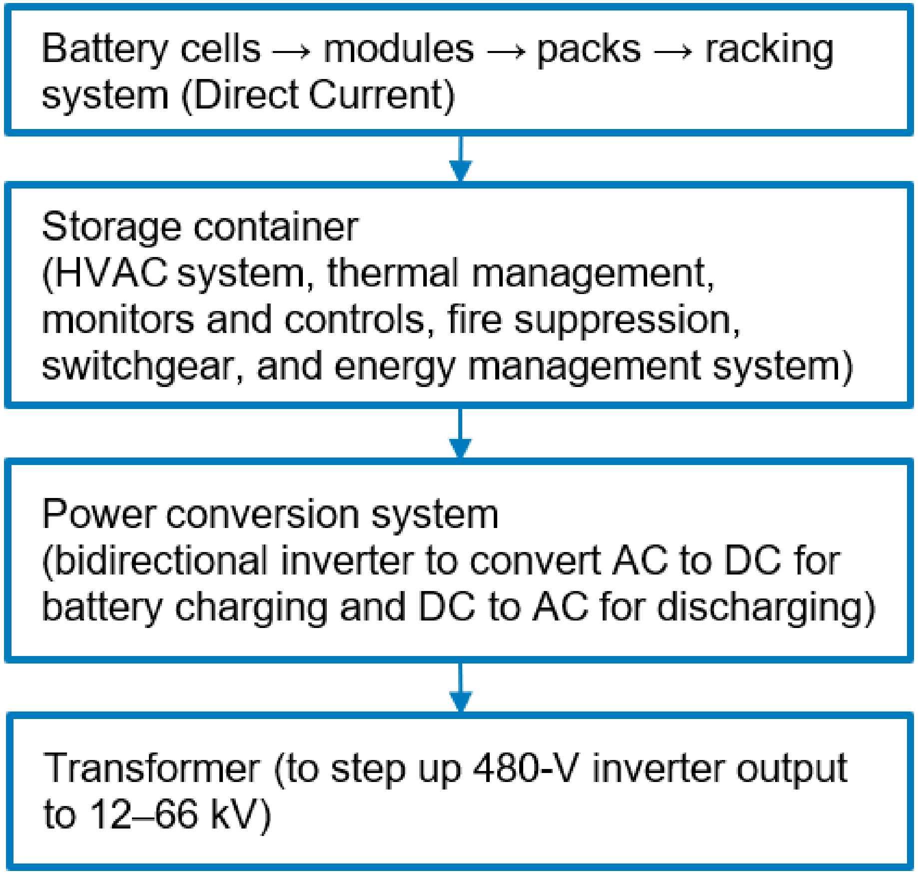
Total Development Costs

Total Capital Cost

Fig. Structure of the bottom-up storage cost model.

Like our PV system cost models, this new energy storage cost model uses a bottom-up approach to summarize all the cost components, including EPC and developer costs.

Energy Storage Cost Model



Battery cells → modules → packs → racking system (Direct Current)

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)

Fig. Standalone utility-scale lithium-ion battery energy storage components.

A typical battery energy storage system is composed of battery racking, battery containers, power conversion systems, and step-up transformers.

Energy Storage Cost Model Inputs

Category	Modeled Input	Description	Sources
Battery total size	60 MW DC	A baseline case to match a 100-MW PV system	Denholm (2017), NREL (2018)
Battery size per container	5 MWh per 40’ container	To compute the number of containers	NREL (2018)
Li-ion battery price	$209/kWh	Ex-factory gate (first buyer) prices. We use an aggregated Li-ion battery price in the model, and cell types for different durations are not included.	NREL (2018), Curry (2017)
Duration	0.5 to 4 hours	Duration determines energy (MWh)	DOE Energy Storage Database (2018)
Battery Central inverter price	$0.07/W	Ex-factory gate (first buyer) prices	Gupta (2018)
Inverter size	2.5 MW per inverter	Used to determine the number of battery inverters	NREL (2018)
Transformer size	2.5 MW per step-up transformer	Used to determine the number of transformers	NREL (2018)
Foundation	76,800 square feet	Determined by the number of containers, inverters, transformers, and the spacing between containers	RS Mean (2017), NREL (2018)
Installation labor	Non-union at rates taken from BLS statistics survey average by state	Modeled labor rate assumes non-union and union labor and depends on state; national benchmark uses weighted average of state rates	BLS (2018), NREL (2018)
Sales tax	7.5%	Model assumption. Determined by the sales tax in California	NREL (2018)
EPC overhead and profit	8.67% for equipment and material; 23%–69% for labor costs; varies by system size, labor activity, and location	Costs associated with EPC SG&A, warehousing, shipping, and logistics	Fu (2017)
Developer overhead	3% of total installation cost	Includes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions	Fu (2017)
Permitting and interconnection	$0.03 to $0.04/W	For construction permits fee, interconnection study, interconnection inspection, and interconnection fee	NREL (2018)
Contingency	3%	Estimated as markup on the total EPC cost	Fu (2017)
EPC/Developer Net Profit	5%	Applies a percentage margin to all costs including hardware, installation labor, EPC overhead, developer overhead, etc.	Fu (2017)

Energy Storage Cost Model Results

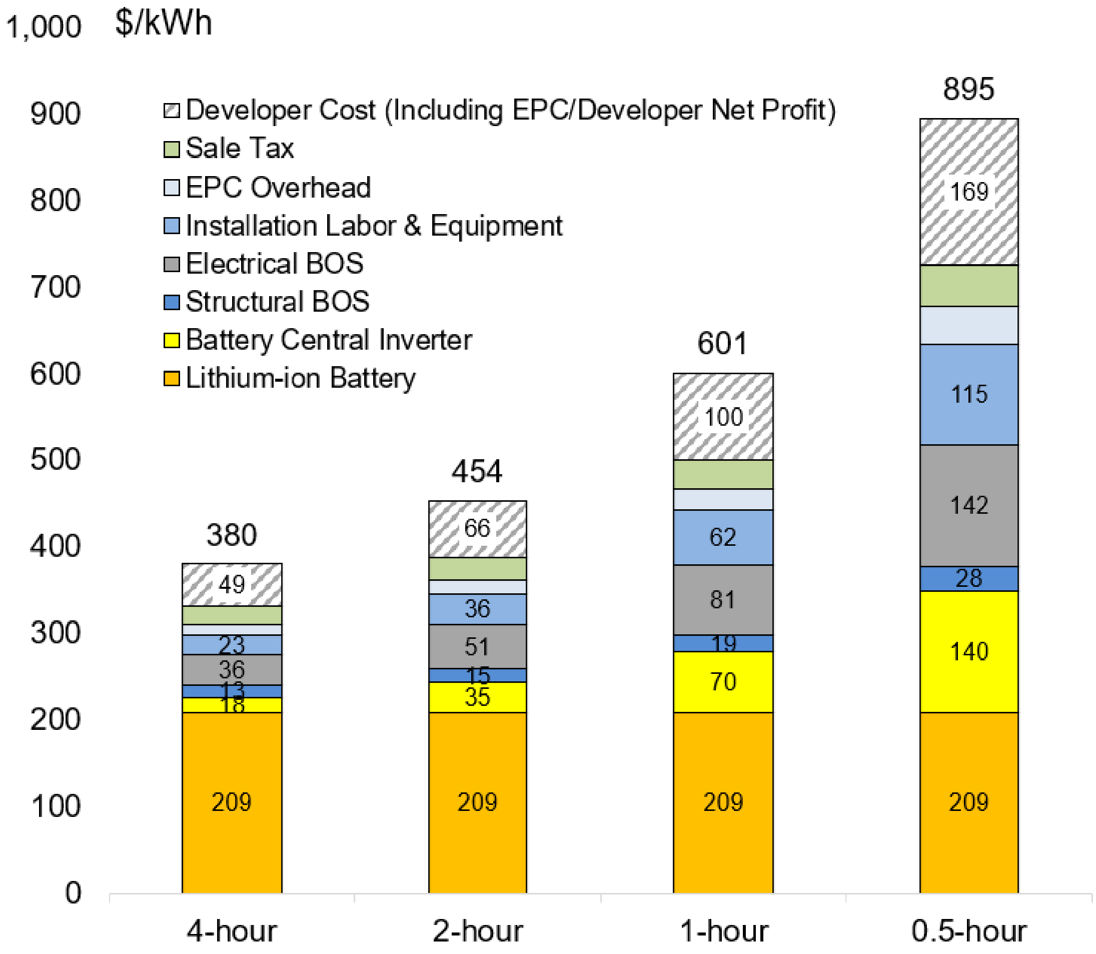


Fig. U.S. utility-scale lithium-ion battery storage cost (60 MWdc)

Energy storage cost ($/kWh) = battery cost ($/kWh) + other cost components ($) ÷ storage system size (kW) ÷ duration (hours).

Energy Storage Cost Model Results

	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**
Lithium-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
Sale 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**

Table. Detailed Cost Breakdown for a 60-MW U.S. Li-Ion Storage System

Energy Storage Cost Model Results

There are three types of costs when duration varies:

1) For **battery itself**, because its cost remains constant at $209/kWh in the model regardless of the system's duration or energy size (MWh), both "total cost" and "$/W" metric have the linear relationship with the MWh size.

2) For **battery central inverter**, because its cost remains constant at $0.7/W in the model regardless of the system's duration or energy size (MWh), "total cost" metric remains constant for the constant power size (60-MW). However, the "$/kWh" metric has the linear relationship with the MWh size.

3) For **other cost components**, their costs in terms of energy metric ($/kWh) and power metric ($/W) do not have a linear relationship with the system's duration. This result is because on one hand, the number of storage containers is driven by energy size (5 MWh per container in the model) instead of power size; on the other hand, some other cost items such as site preparation and number of transformers remain constant for the constant power size (60-MW). Thus, the mixed cost items do not present the linear relationship that can be found in 1) and 2).

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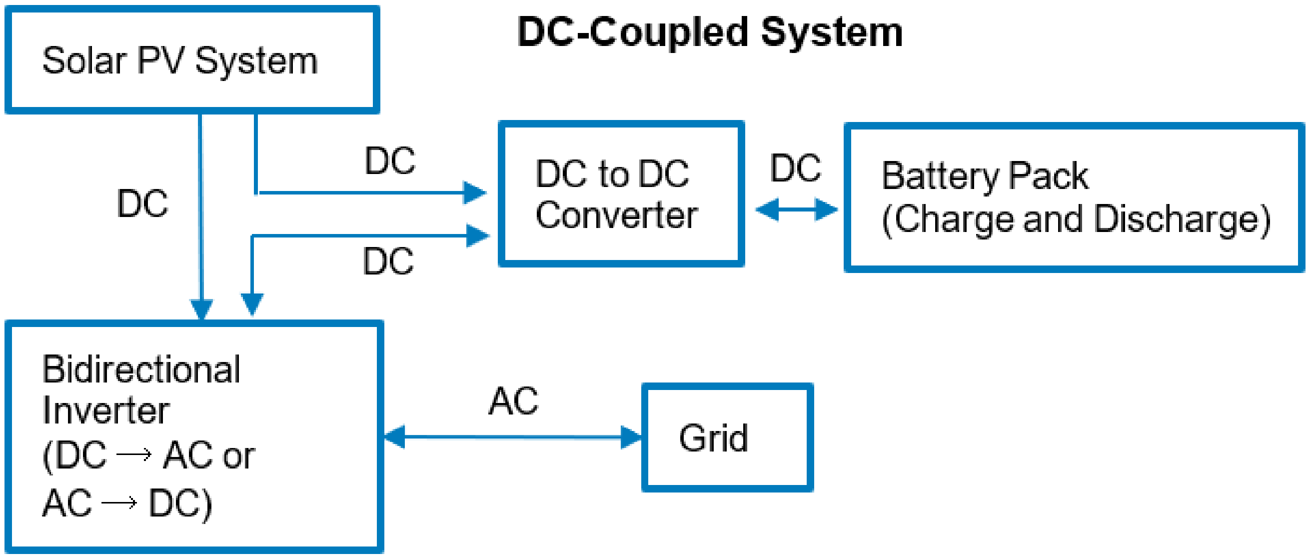
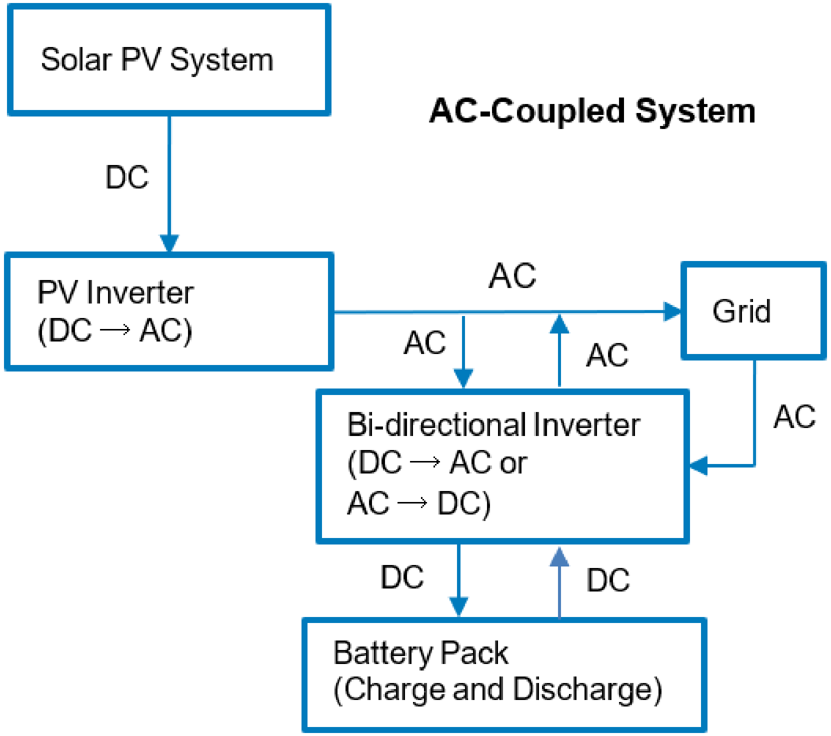
PV Plus Energy Storage Cost Model



1) A DC-coupled system uses only one single bidirectional inverter, thus reducing the costs for 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.
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).

PV Plus Energy Storage Cost Model



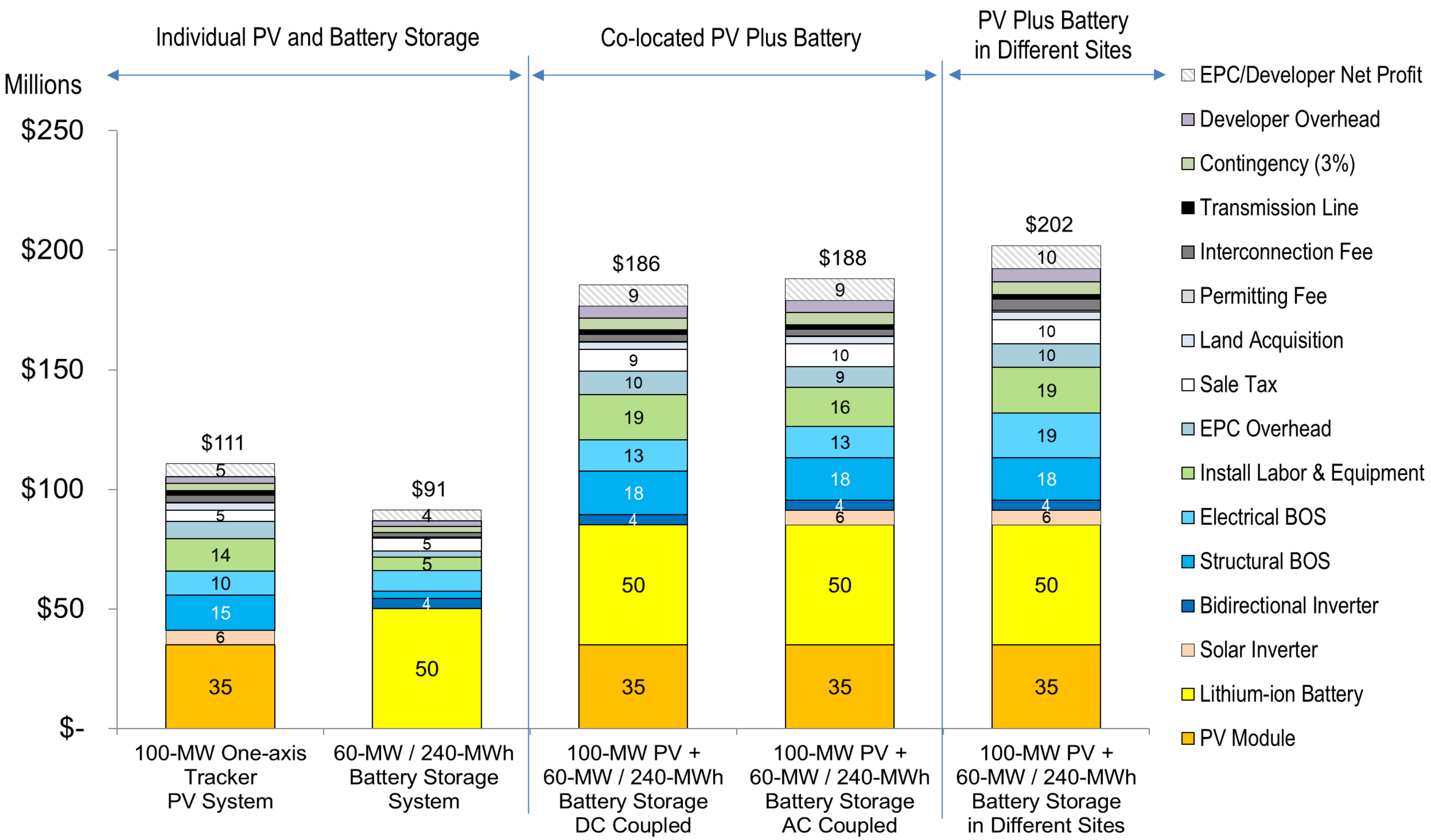
1) **Because battery racks are not directly connected to the PV system, AC-coupled system can use large size of battery racks and thus reduce the number of HVAC and fire suppression systems in the containers.**
2) **For a retrofit (adding battery storage to an existing PV array), an AC-coupled battery may be more practical than a DC-coupled battery, which requires installers to replace the existing PV inverter with a bidirectional inverter.**
3) **For AC-coupled systems, installers have more flexibility to adjust the location of batteries. This design flexibility makes the preventative and corrective maintenance easier since the crew does not have to go into the PV field.**

PV Plus Energy Storage Cost Model

Category	Colocated PV plus storage	PV plus storage in different sites
Site preparation	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

Category	DC coupled energy storage configuration	AC coupled energy storage configuration
Number of inverters	1 (bidirectional inverter for battery)	2 (bidirectional inverter for battery plus grid-tied inverter for PV). Thus, more costs for inverter, inverter wiring, and inverter housing.
Battery rack size	Smaller (since battery is directly connected to PV). Thus, requires more HVAC and fire suppression systems.	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)

PV Plus Energy Storage Cost Model Results



Co-located PV plus battery system can share several major electrical hardware components, such as the step-up transformer, switchgear, and controls. Also, co-location can reduce the "Soft Cost" including site preparation, land acquisition, installation labor, permitting, interconnection, and overhead and profit for both the EPC and the developer.

PV Plus Energy Storage Cost Model Results

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
Lithium-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
Sale 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**

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

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Summary

- US Utility-scale standalone energy and PV-plus-storage system cost models have been developed (based on lithium-ion batteries) to benchmark the installed system costs for co-located PV-plus-storage vs. PV and storage sited separately, and DC vs. AC coupling configurations for the co-location case.

- 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), and related 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.

- DC-coupling and AC-coupling have different cost categories due to number of inverters, battery rack size, DC-to-DC converters, labor costs, and related EPC overhead.

Q&A

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