# U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2021

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November 2021

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# Introduction

**The National Renewable Energy Laboratory (NREL) has been modeling U.S. solar photovoltaic (PV) system costs since 2009. This year, our report benchmarks costs of U.S. PV for residential, commercial, and utility-scale systems, with and without storage, built in the first quarter of 2021 (Q1 2021).**

Our benchmarking method includes bottom-up accounting for all necessary system and project-development costs incurred when installing residential, commercial, and utility-scale systems, and it models the Q1 2021 costs for such systems, excluding any previous supply agreements or contracts. In general, we attempt to model the typical installation techniques and business operations from an installed-cost perspective, and our benchmarks are national averages. The residential PV-only benchmark and the commercial rooftop PV-only benchmark average costs by inverter type (string inverters, string inverters with direct current [DC] optimizers, and microinverters), weighted by inverter market share. The residential PV-only benchmark is further averaged across small installer and national integrator business models, weighted by market share. All benchmarks include variations—accounting for the differences in size, equipment, and operational use (particularly for storage)—that are currently available in the marketplace. All benchmarks assume nonunionized construction labor; residential and commercial PV systems predominantly use nonunionized labor, and the type of labor required for utility-scale PV systems depends heavily on the development process. All benchmarks assume the use of monofacial monocrystalline silicon PV modules. Benchmarks using cadmium telluride or bifacial modules could result in significantly different results. The data in this annual benchmark report inform the formulation of and track progress toward the U.S. Department of Energy (DOE) Solar Energy Technologies Office's Government Performance and Reporting Act cost targets.

# Introduction

**The benchmark report builds on several previous publications from NREL and Lawrence Berkeley National Laboratory:**

- Barbose, Galen, Naïm Darghouth, Eric O'Shaughnessy, and Sydney Forrester. 2020. *Distributed Solar 2020 Data Update.* Berkeley, CA: Lawrence Berkeley National Laboratory. https://doi.org/10.2172/1735556.
- Bolinger, Mark, Joachim Seel, Dana Robson, and Cody Warner. November 2020. *Utility-Scale Solar Data Update: 2020 Edition.* Berkeley, CA: Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/default/files/2020_utility-scale_solar_data_update.pdf.
- Feldman, David, Vignesh Ramasamy, Ran Fu, Ashwin Ramdas, Jal Desai, and Robert Margolis. 2021. *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2020*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77324. https://www.nrel.gov/docs/fy21osti/77324.pdf.
- Fu, Ran, Timothy Remo, and Robert Margolis. 2018. *2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71714. https://www.nrel.gov/docs/fy19osti/71714.pdf.
- Ardani, Kristen, Eric O'Shaughnessy, Ran Fu, Chris McClurg, Joshua Huneycutt, and Robert Margolis. 2017. *Installed Cost Benchmarks and Deployment Barriers for Residential Solar Photovoltaics with Energy Storage: Q1 2016*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A20- 67474. https://www.nrel.gov/docs/fy17osti/67474.pdf.
- Feldman, David, Galen Barbose, Robert Margolis, Mark Bolinger, Donald Chung, Ran Fu, Joachim Seel, Carolyn Davidson, Naïm Darghouth, and Ryan Wiser. 2015. *Photovoltaic System Pricing Trends, Historical, Recent, and Near-Term Projections*. Golden, CO: National Renewable Energy Laboratory. NREL/PR-6A20-64898. https://www.nrel.gov/docs/fy15osti/64898.pdf.

# Introduction

**(1) Download the full technical report, summary presentation, and the data file:**

- Download the full report: https://www.nrel.gov/docs/fy22osti/80694.pdf
- Download the data file: https://doi.org/10.7799/1829310

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# Key Definitions

| Unit | Description |
|---|---|
| Value | 2020 U.S. dollar (USD) |
| System Size | PV systems are quoted in DC terms; inverter prices are converted by DC to alternating current (AC) ratios; storage systems are quoted in terms of kilowatt-hours or megawatt-hours (kWh or MWh) of storage or the number of hours of storage at peak capacity. |

| Sector Category | Description | Size Range |
|---|---|---|
| Residential PV | 22-panel Residential rooftop systems | 3 kW–11 kW |
| Commercial PV | Commercial rooftop systems ballasted racking & ground-mount fixed tilt systems | 100 kW–2 MW |
| Utility-Scale PV | Ground-mounted systems, fixed-tilt and one-axis tracker | 5 MW–100 MW |

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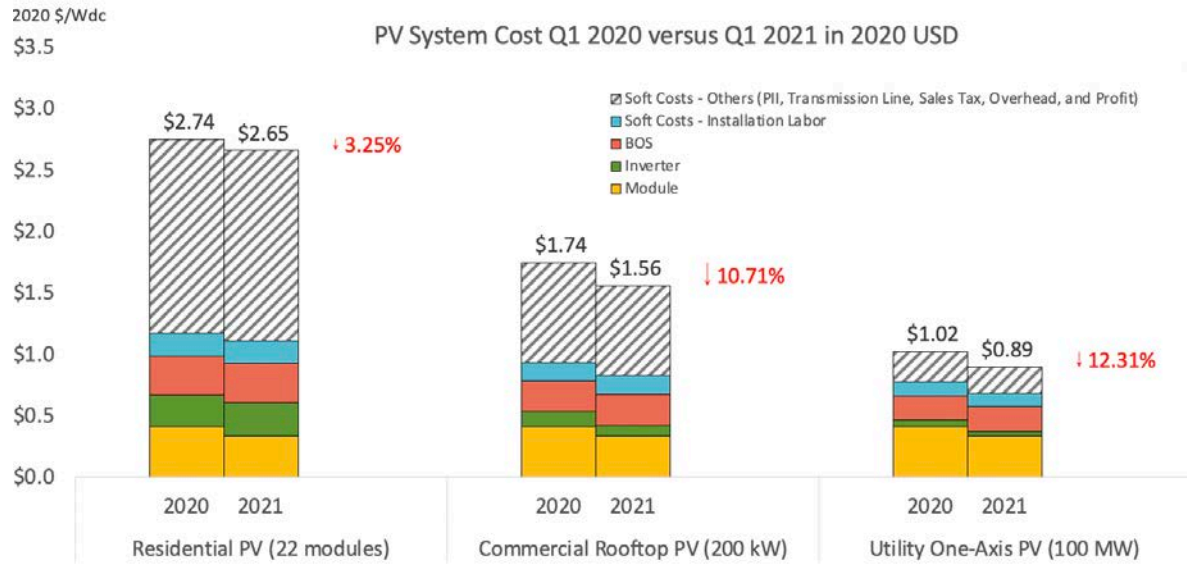
# Overall Stand-Alone PV Model Results (Total Installed Cost)

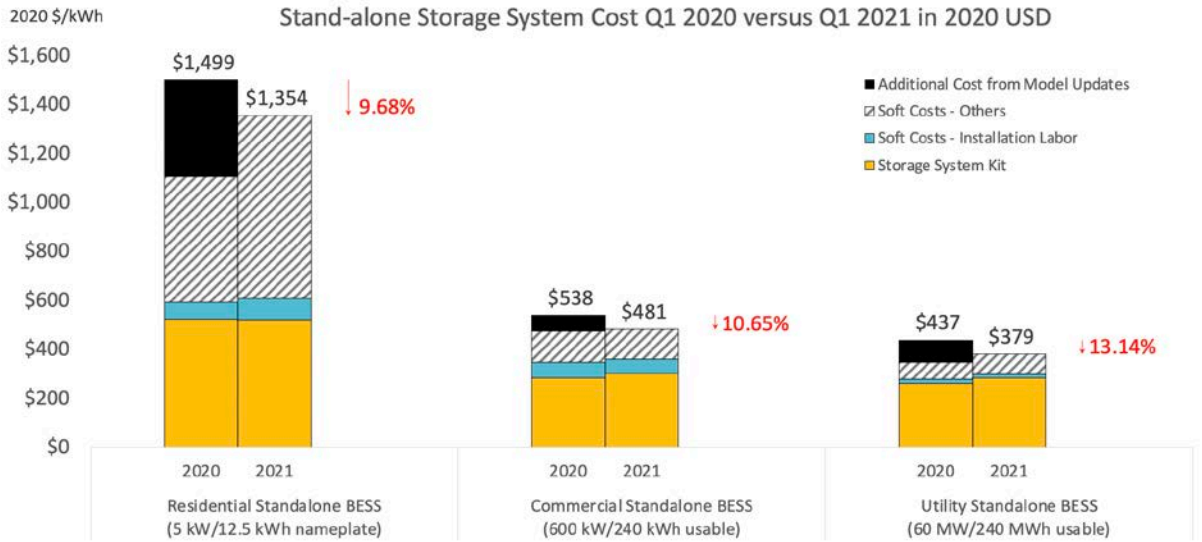



1. Values are inflation adjusted using the Consumer Price Index (2020). Thus, historical values from our models are adjusted and presented as real USD instead of nominal USD.
2. Cost categories are aggregated for comparison purposes. “Soft Costs—Others” represent permitting, inspection, and interconnection (PII); land acquisition; sales tax; and engineering, procurement, and construction (EPC)/developer overhead and net profit.
3. The current versions of our cost models make a few significant changes from the versions used in our Q1 2020 benchmark report (Feldman, Ramasamy, Desai, and Margolis 2021) and incorporate costs that had previously not been benchmarked in as much detail. The “Additional Costs from Model Updates” category represents the difference between modeled results.

# Overall Stand-Alone PV Model Results (Q1 2020 Versus Q1 2021)

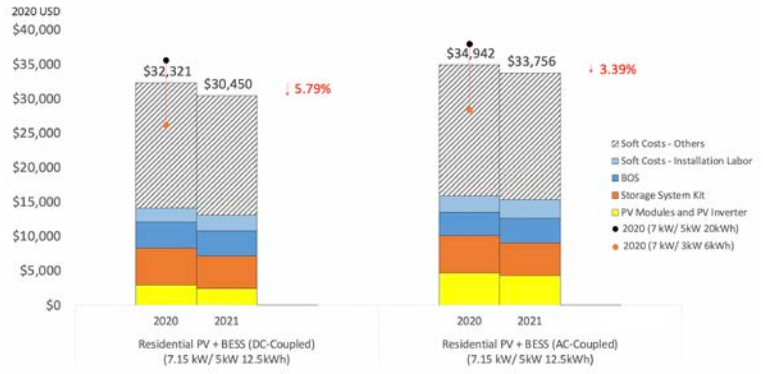
| Sector | Residential PV | Commercial Rooftop PV | Utility-Scale PV, One-Axis Tracking |
|---|---|---|---|
| Q1 2020 benchmarks in 2019 USD/$W_{DC}$ | $2.71 | $1.72 | $1.01 |
| Q1 2021 Benchmarks in 2020 USD/$W_{DC}$ | $2.65 | $1.56 | $0.89 |
| Drivers of cost reduction | • Higher module efficiency (from 19.5% to 19.9%)<br>• Lower module cost | • Higher module efficiency<br>• Lower module cost | • Higher module efficiency<br>• Lower module cost |
| Drivers of cost increment | • Higher Inverter price<br>• Higher labor wage<br>• Higher material and equipment cost | • Higher labor wage<br>• Higher material and equipment cost | • Higher labor wage<br>• Higher steel price<br>• Higher material and equipment cost |

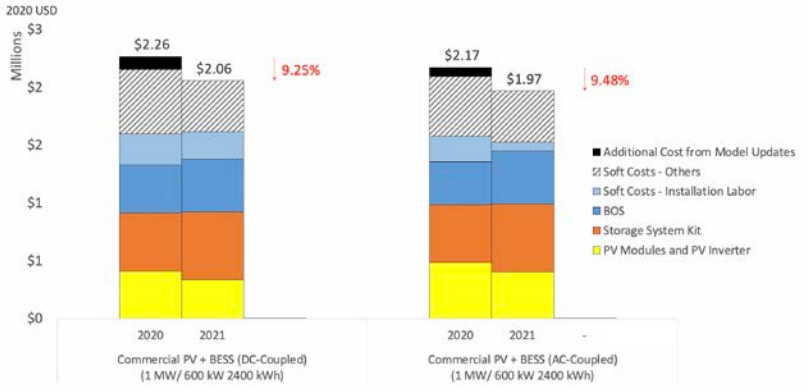
# Overall Stand-Alone Storage Model Results (Total Installed Cost)



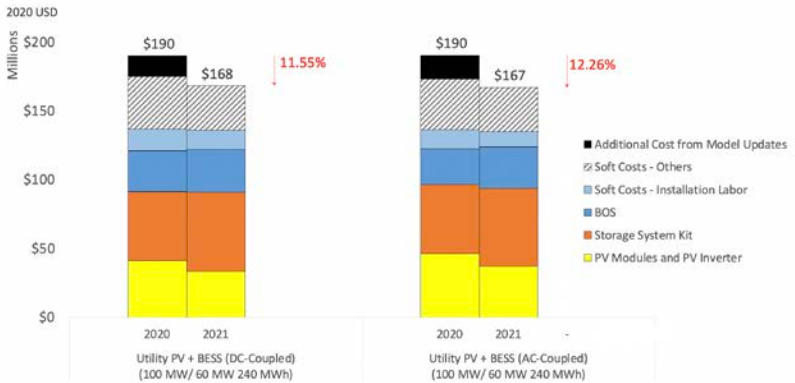

1. There were 9.68%, 10.65%, and 13.14% reductions in residential, commercial, and utility-scale stand-alone storage benchmarks between 2020 and 2021.
2. In previous benchmarking reports, across all sectors, storage system costs were represented in nameplate capacity but this year only the residential storage system cost is represented in nameplate capacity; commercial and utility scale storage system costs are represented in usable capacity.
3. The Q1 2020 residential storage capacity was also adjusted from previously benchmarked sizes of 5 kW/20 kWh and 3 kW/6 kWh to the Q1 2021 benchmarked size of 5 kW/12.5 kWh.
4. In addition to changing the dollar year from 2019 to 2020, we adjusted Q1 2020 values to have the same size storage capacity as the current Q1 2021 sizes to better demonstrate cost changes between years.

# Overall PV Plus Storage Model Results (Total Installed Cost)

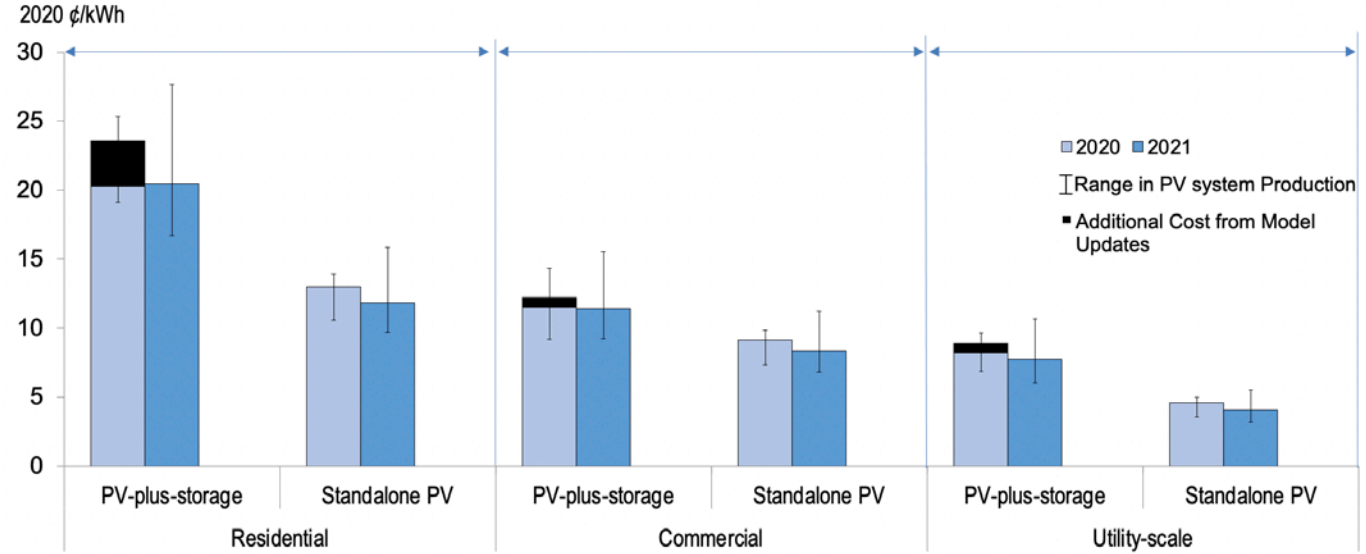



1. Approximately 6% and 3% reductions in residential PV-plus-storage benchmark between 2020 and 2021 for DC-coupled and AC-coupled cases, respectively.
2. 9.3% and 9.5% reductions in commercial PV-plus-storage benchmark between 2020 and 2021 for DC-coupled and AC-coupled cases, respectively. 11.6% and 12.3% reductions in utility-scale PV-plus-storage benchmark between 2020 and 2021 for DC-coupled and AC-coupled cases, respectively.
3. Most of the cost reduction of PV-plus-storage systems can be attributed to reductions in the cost of PV modules and battery packs.
4. The cost reductions occurred despite the rated capacity of the 22-module system increasing from 5.6 kW to 7.0 kW between 2016 and 2020.
5. Higher DC-DC converter cost in 2021 is another cost driver of DC-coupled systems.



# Overall LCOE for PV Standalone and PV-Plus-Storage Model Results




From 2020 to 2021, residential PV-plus-storage levelized cost of energy (LCOE) fell 13%, and residential stand-alone PV LCOE fell 9%; there were 7% and 13% reductions in levelized electricity costs for commercial and utility-scale PV-plus-storage systems. At the same time, LCOE of commercial and utility-scale stand-alone PV systems fell by 9% and 12% respectively. Reported 2021 residential PV-plus-storage LCOE values are initially 17% higher than 2020 values because the 2021 report models a larger battery system (5 kW; 12.5 kWh) than the 2020 benchmark report (3 kW/6 kWh). In this year's report, we updated residential financial assumption from a third-party-ownership model to one in which homeowners finance the cost of a system through their mortgage.

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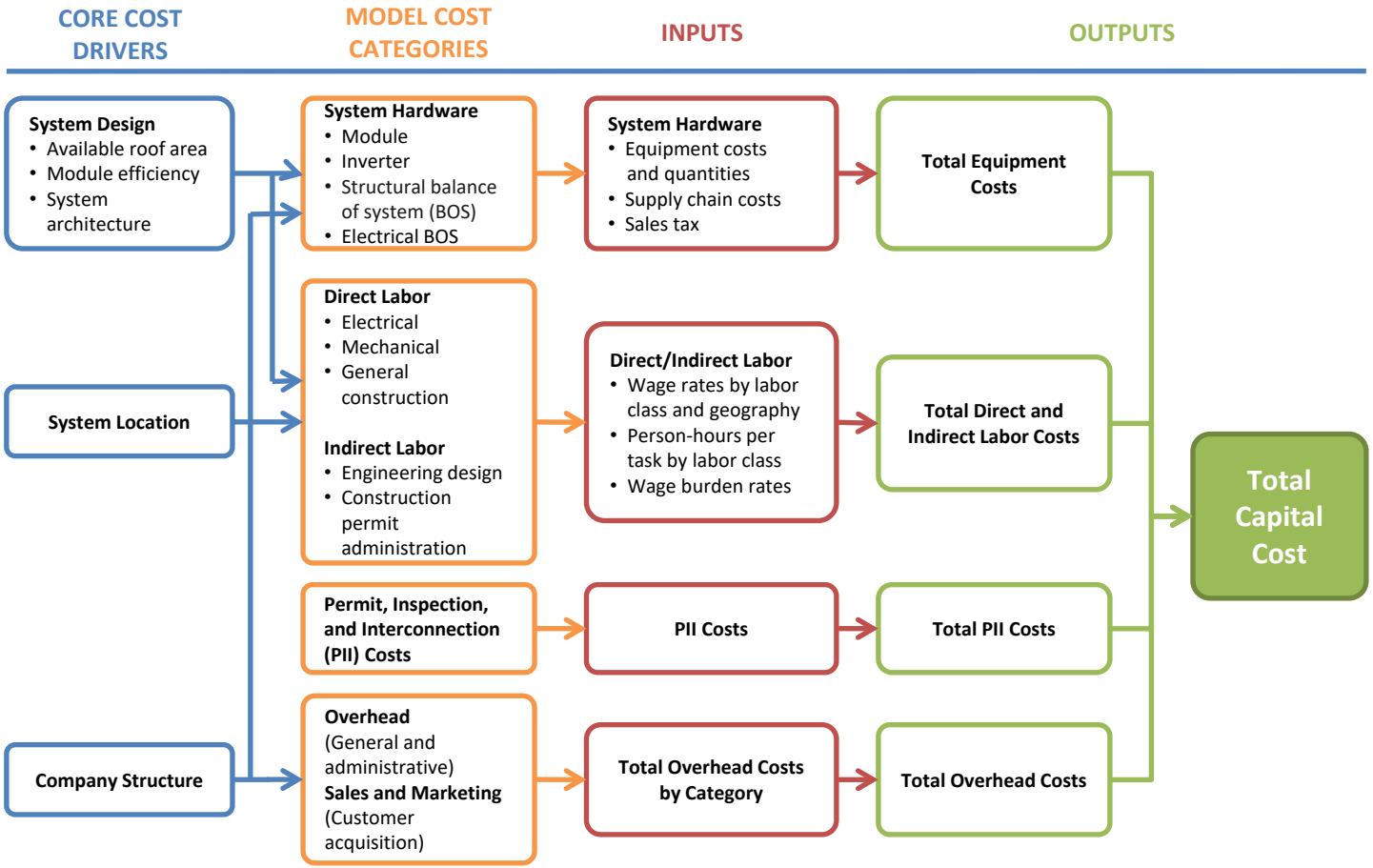
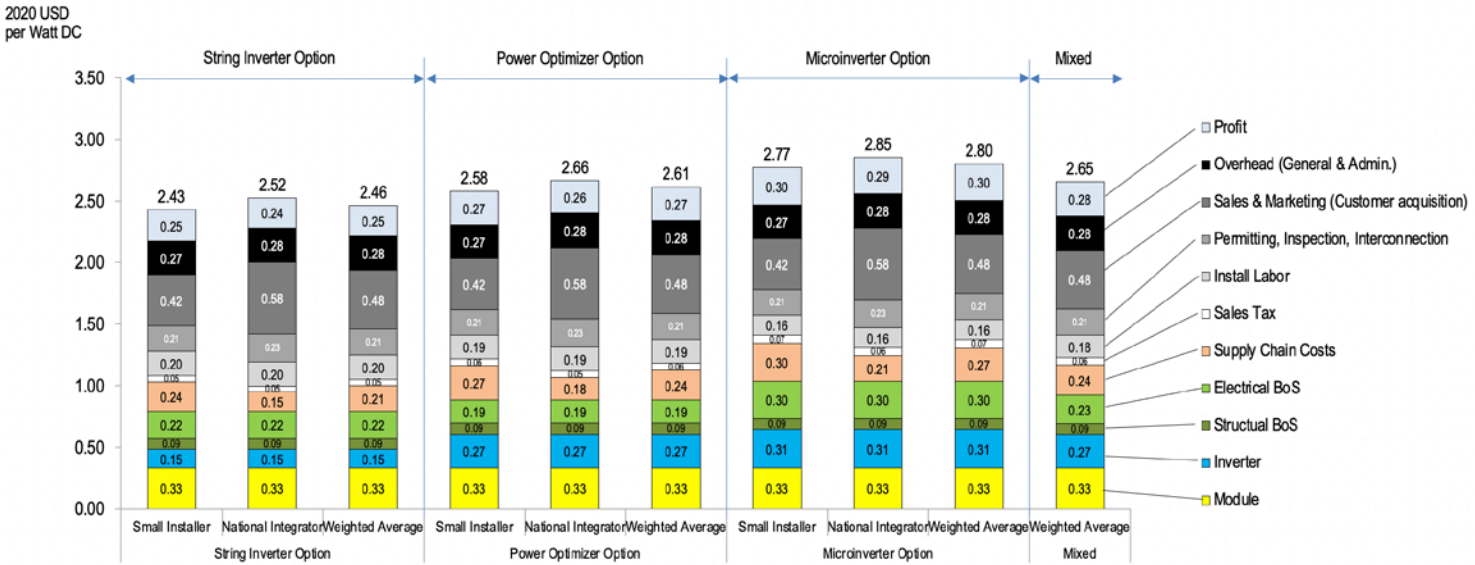
# Residential PV: Model Structure



# Residential PV: Modeling Inputs and Assumptions

| Category | Modeled Value | Description | Sources |
|---|---|---|---|
| System size | 7.15 kW | Average installed size per system | Barbose et al. 2020; CA NEM 2021 |
| Module efficiency | 19.9% | Average module efficiency | CA NEM 2021 |
| Module price | $0.34/$W_{DC}$ | Ex-factory gate (first buyer) price, Tier 1 monocrystalline modules | Wood Mackenzie and SEIA 2021 |
| Inverter price | Single-phase string inverter: $0.15/$W_{DC}$<br>DC power optimizer single-phase string inverter: $0.28/$W_{DC}$<br>Microinverter: $0.31/$W_{DC}$ | Ex-factory gate (first buyer) prices, Tier 1 inverters | Wood Mackenzie 2021; Wood Mackenzie and SEIA 2021 |
| Structural BOS (racking) | $0.09/$W_{DC}$ | Includes flashing for roof penetrations and all rails and clamps | NREL 2021 |
| Electrical BOS | $0.19–$0.30/$W_{DC}$<br>Varies by inverter option | Conductors, switches, combiners, and transition boxes, as well as conduit, grounding equipment, monitoring system or production meters, fuses, and breakers | Model assumptions, NREL 2021 |
| Supply chain costs (percentage of equipment costs) | Varies by installer type and location | 15% costs and fees associated with shipping and handling of equipment<br>Additional 6% cost for historical inventory<br>Additional 20% small-scale procurement for module-related supply chain costs for small installers<br>Additional 20% for inverter-related supply chain costs for small installers and 10% for national integrators | NREL 2021; model assumptions |
| Sales tax | National average: 5.1% | Sales tax on material and equipment | RSMeans 2021 |
| Direct installation labor | Electrician: $27.36/hour<br>Laborer: $18.22/hour<br>Hours vary by inverter option | Modeled national average labor rates | BLS 2020; NREL 2021 |
| Burden rates (percentage of direct labor) | Total nationwide average: 31.7% | Workers' compensation, federal and state unemployment insurance, Federal Insurance Contributions Act, builder's risk, and public liability | RSMeans 2021 |
| PII | $0.21/$W_{DC}$ for small installers<br>$0.23/$W_{DC}$ for national integrators<br>Varies by location | Completed and submitted applications, fees, design changes, and field inspection | NREL 2021; Cook et al. 2021 |
| Sales and marketing (customer acquisition) | $0.42/$W_{DC}$ (small installer)<br>$0.58/$W_{DC}$ (national integrator)<br>Varies by location | Initial and final drawing plans, advertising, lead generation, sales pitch, contract negotiation, and customer interfacing | NREL 2021 |
| Overhead (general and administrative) | $0.27/$W_{DC}$ (small installer)<br>$0.28/$W_{DC}$ (national integrator)<br>Varies by location | Rent, building, equipment, staff expenses not directly tied to PII, customer acquisition, or direct installation labor | NREL 2021 |
| Profit (%) | 17% | Fixed percentage margin applied to all direct costs including hardware, installation labor, direct sales and marketing, design, installation, and permitting fees | Fu et al. 2017 |

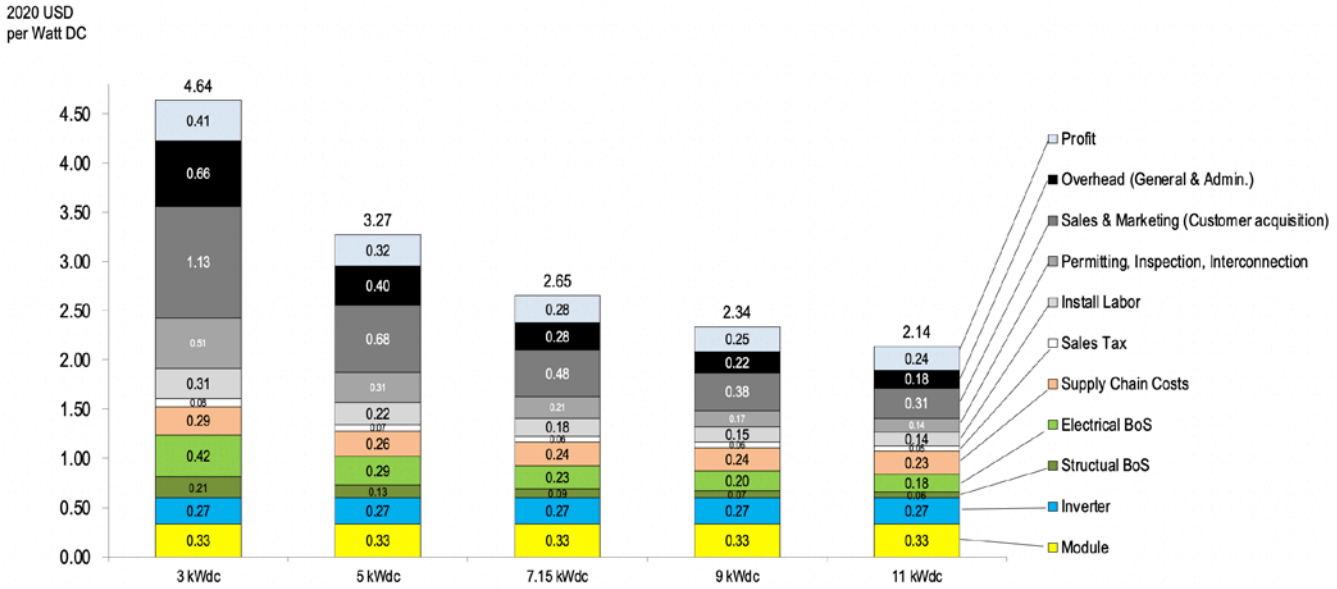
# Residential PV: Model Outputs




**Q1 2021 U.S. benchmark: 7.15-kW residential system cost (2020 USD/$W_{DC}$)**

This figure presents the U.S. national benchmark from our residential model. Market shares of 63% for installers and 37% for integrators are used to compute the national weighted average. String inverter, power optimizer, and microinverter options are each modeled individually, and the “mixed” case applies their market shares (13%, 54%, and 33%) as weightings.

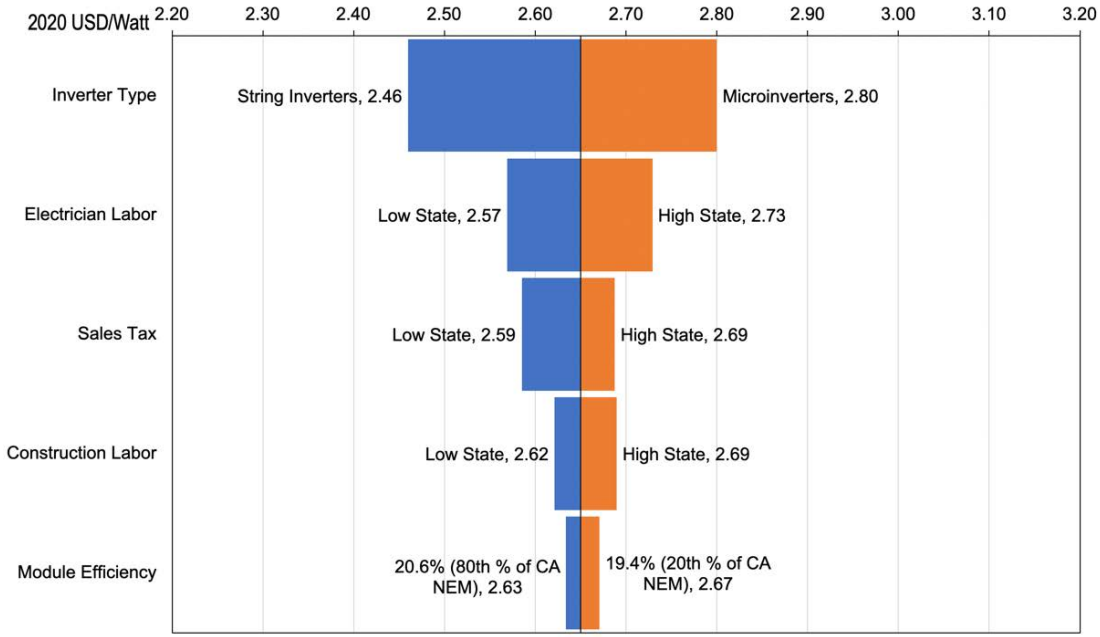
# Residential PV: Model Outputs




**Q1 2021 U.S. residential benchmark, by PV system size (2020 USD/WDC)**

We model different system sizes because of (1) the variety in residential PV system sizes in the marketplace and (2) the strong relationship between size and cost, on a per-watt basis. Economies of scale—driven by hardware, labor, and related markups—are evident here, as is the impact of costs spread over a larger number of watts. Soft cost is reduced by 62% between a 3-kW and an 11-kW system.

# Residential PV: Model Outputs




**Sensitivity analysis for Q1 2021 benchmark: Mixed 7.15-kW residential system cost (2020 USD/W$_{DC}$)**

This figure presents a sensitivity analysis of the benchmark for the mixed case, with cost categories that vary by location and hardware specification. Inverter type has the largest impact on installed system cost, with the use of string inverters resulting in \$2.46/$W_{DC}$ and the use of microinverters resulting in \$2.80/$W_{DC}$.

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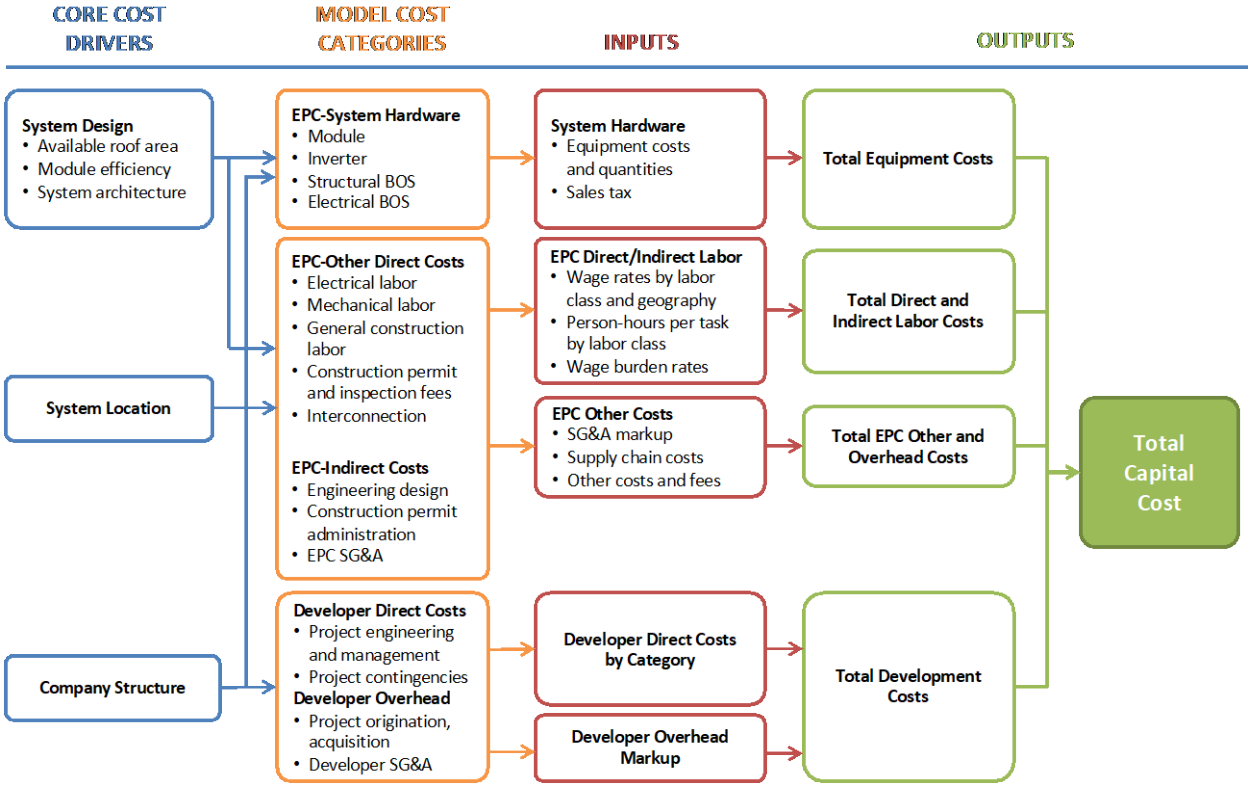
# Commercial PV: Model Structure

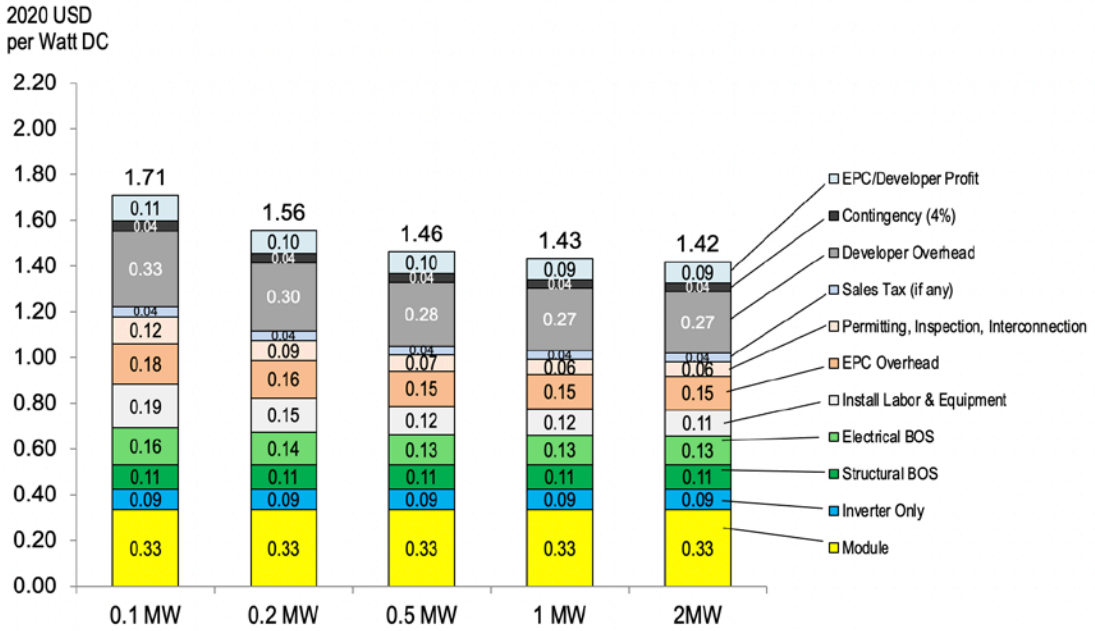


# Commercial PV: Modeling Inputs and Assumptions

| Category | Modeled Value | Description | Sources |
|---|---|---|---|
| System size | 200 kW (rooftop) and 500 kW (ground-mount); range (100 kW–2 MW) | Average installed size per system | Barbose et al. 2020 |
| Module efficiency | 19.9% | Average monocrystalline module efficiency | CA NEM 2021 |
| Module price | $0.34/$W_{DC}$ | Ex-factory gate (first buyer) average selling price, Tier 1 monocrystalline modules | Wood Mackenzie and SEIA 2021 |
| Inverter price | Three-phase string inverter: $0.08/$W_{DC}$<br>DC power optimizer three-phase string inverter: $0.16/$W_{DC}$ (rooftop only)<br>Microinverter: $0.31/$W_{DC}$ (rooftop only) | Ex-factory gate prices (first buyer) average selling price, Tier 1 inverters | Wood Mackenzie 2021; Wood Mackenzie and SEIA 2021 |
| Structural components (racking) | $0.11–$0.18/$W_{DC}$; assumes national average wind and snow loading[a]; varies by racking type (ground-mounted versus rooftop-ballasted) | Ex-factory gate prices; flat-roof ballasted racking system or fixed-tilt ground-mounted racking system | MEPS 2019; model assumptions; NREL 2021 |
| Electrical components | $0.13–$0.45/$W_{DC}$ | Conductors, conduit and fittings, transition boxes, switchgear, panel boards, and other parts | Model assumptions; NREL 2021; RSMeans 2021 |
| EPC overhead (percentage of equipment costs) | 13% | Costs and fees associated with EPC overhead, inventory, shipping, and handling | NREL 2021 |
| Sales tax | National average: 5.1% | Sales tax on equipment costs | RSMeans 2021 |
| Direct installation labor | Electrician: $27.36/hour<br>Laborer: $18.22/hour | Modeled labor rate assumes national average nonunionized labor rates | BLS 2020; NREL 2021 |
| Burden rates (percentage of direct labor) | Total nationwide average: 31.7% | Workers' compensation, federal and state unemployment insurance, Federal Insurance Contributions Act, builders' risk, public liability | RSMeans 2021 |
| PII | $0.03-$0.12/$W_{DC}$ | For construction permits fee, interconnection study fees for existing substation, testing, and commissioning | NREL 2021 |
| Developer overhead | $0.27–$0.47/W<br>Varies by system size (30% developer overhead) | Includes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions | Model assumptions; NREL 2021 |
| Contingency | 4% | Estimated as markup on EPC cost; value represents actual cost overruns above estimated cost | NREL 2021 |
| Profit | 7% | Applies a fixed percentage margin to all costs, including hardware, installation labor, EPC overhead, and developer overhead | NREL 2021 |

[a] Racking companies currently meet the national standard, so there is not as much differentiation by state in the market within rooftop systems. The ground-mount racking system requires more material, equipment, and labor compared than the ballasted racking system. However, installation of ground-mount PV systems at utility scale helps reduce the BOS cost of these systems owing to economies of scale.

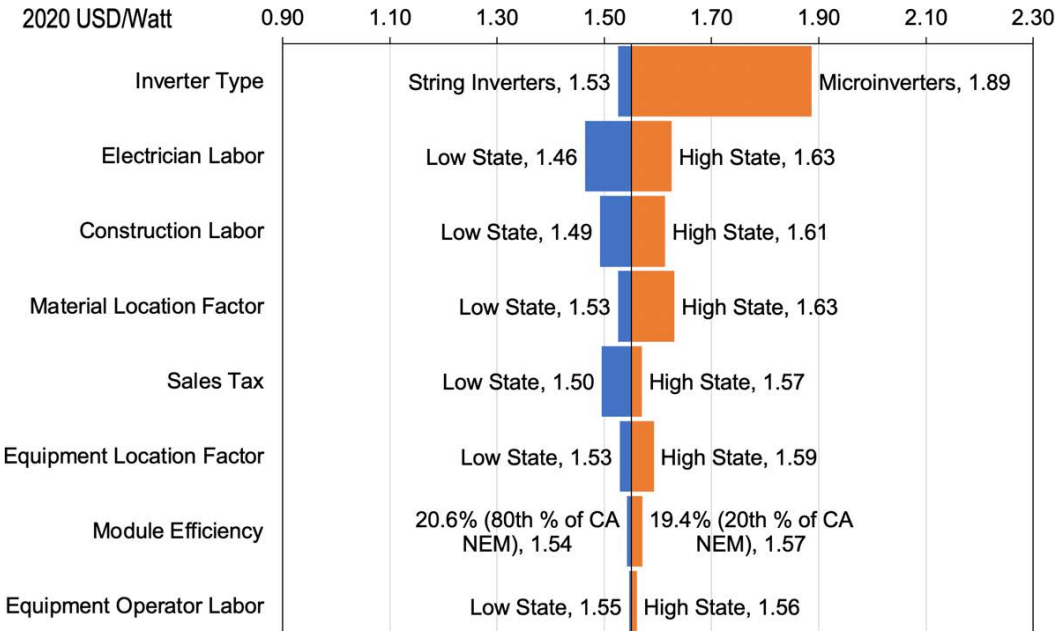
# Commercial PV: Rooftop Model Outputs




**Q1 2021 U.S. benchmark: Commercial rooftop PV system cost (2020 USD/W$_{DC}$)**

We model different system sizes because of the wide scope of the "commercial" sector, which comprises a diverse customer base occupying a variety of building sizes. Also, economies of scale—driven by hardware, labor, and related markups—are evident here. That is, as system sizes increase, the per-watt cost to build them decreases. Owing to the adoption of the 2017 and 2020 National Electrical Code in many states, three-phase string inverter, power optimizer, and microinverter options are each modeled individually for the commercial rooftop model, and the "mixed" case applies their market shares (76%, 20%, and 4% respectively) as weightings.

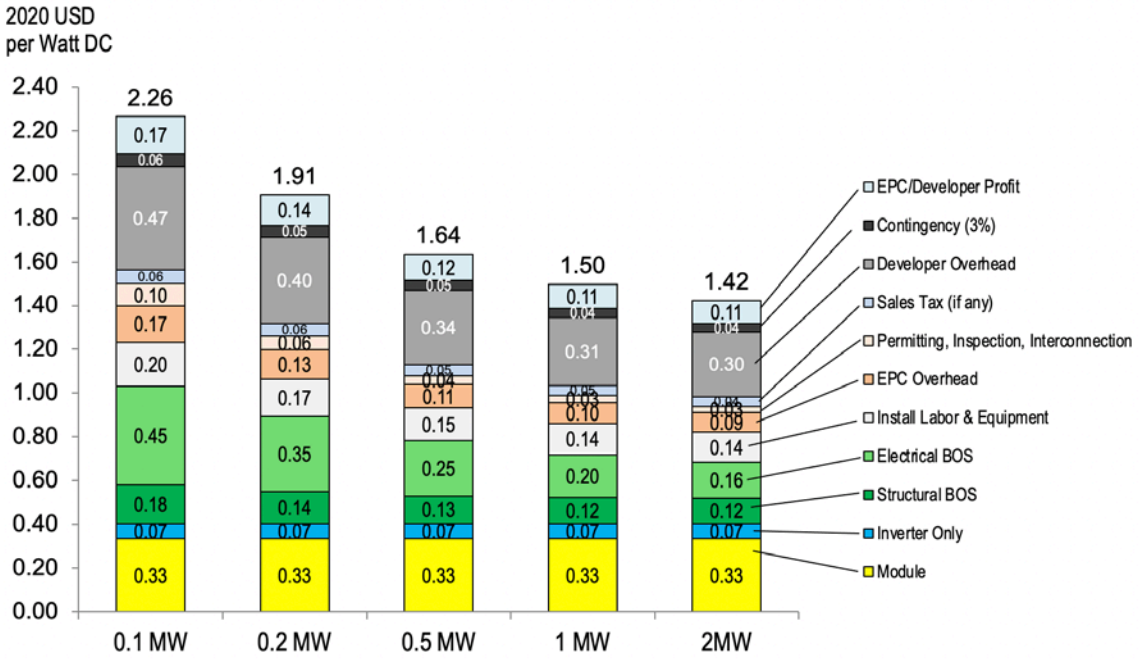
# Commercial PV: Rooftop Model Outputs




**Sensitivity analysis for Q1 2021 benchmark : 200-kW commercial rooftop system cost (2020 USD/$W_{DC}$)**

This figure presents a sensitivity analysis of the benchmark for the mixed case, with cost categories that vary by location and hardware specification. Inverter type has the largest impact on installed system cost, with use of string inverters resulting in \$1.53/$W_{DC}$ and use of microinverters resulting in \$1.89/$W_{DC}$.

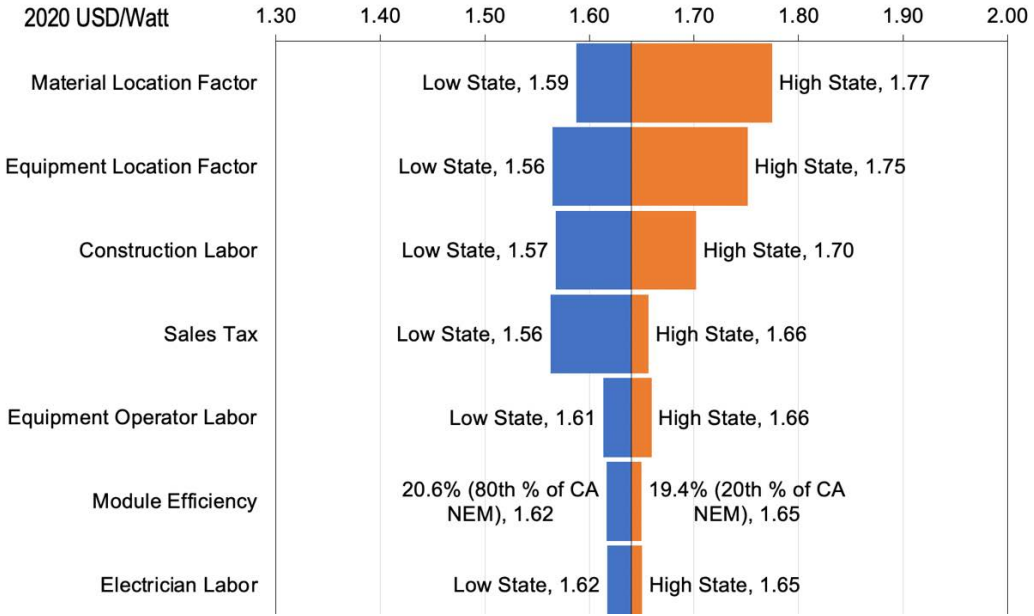
# Commercial PV: Ground-Mounted Model Outputs




**Q1 2021 U.S. benchmark: Commercial ground-mounted PV system cost (2020 USD/$W_{DC}$)**

We model different system sizes because of the wide scope of the "commercial" sector, which comprises a diverse customer base occupying a variety of building sizes. Also, economies of scale—driven by hardware, labor, and related markups—are evident here. That is, as system sizes increase, the per-watt cost to build them decreases. Compared with rooftop systems, ground-mounted applications have higher material, equipment, and labor costs associated with pile-driven mounting. As PV system size increases, the per-watt cost of pile-driven mounting is significantly reduced through economies of scale. Ground-mounted commercial PV systems also benefit from lower inverter costs owing to the rapid shutdown requirements for commercial rooftop systems.

# Commercial PV: Ground-Mounted Rooftop Model Outputs




**Sensitivity analysis for Q1 2021 benchmark: 500-kW commercial ground-mounted system cost (2020 USD/$W_{DC}$)**

This figure presents a sensitivity analysis of the benchmark for the mixed case, with cost categories that vary by location and hardware specification. Material location factor has the largest impact on installed system cost, with the lowest cost state resulting in \$1.59/$W_{DC}$ and the highest cost state resulting in \$1.77/$W_{DC}$.

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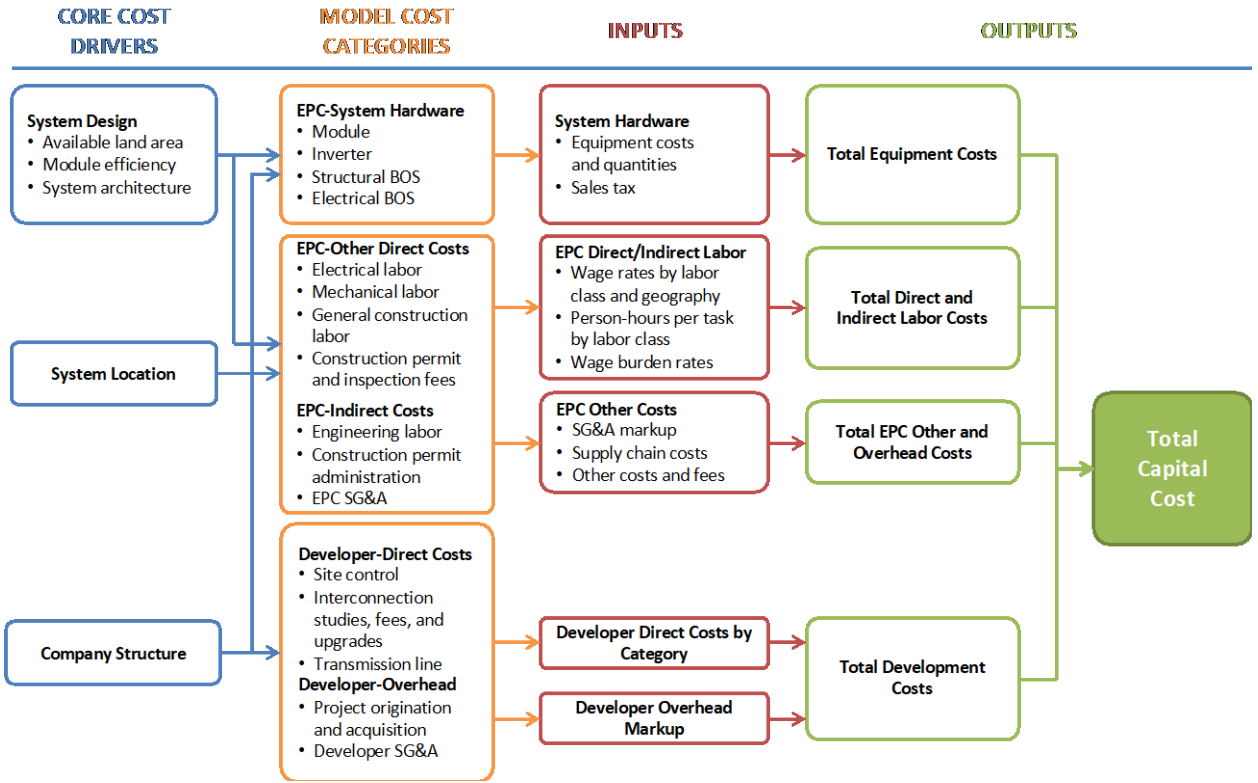
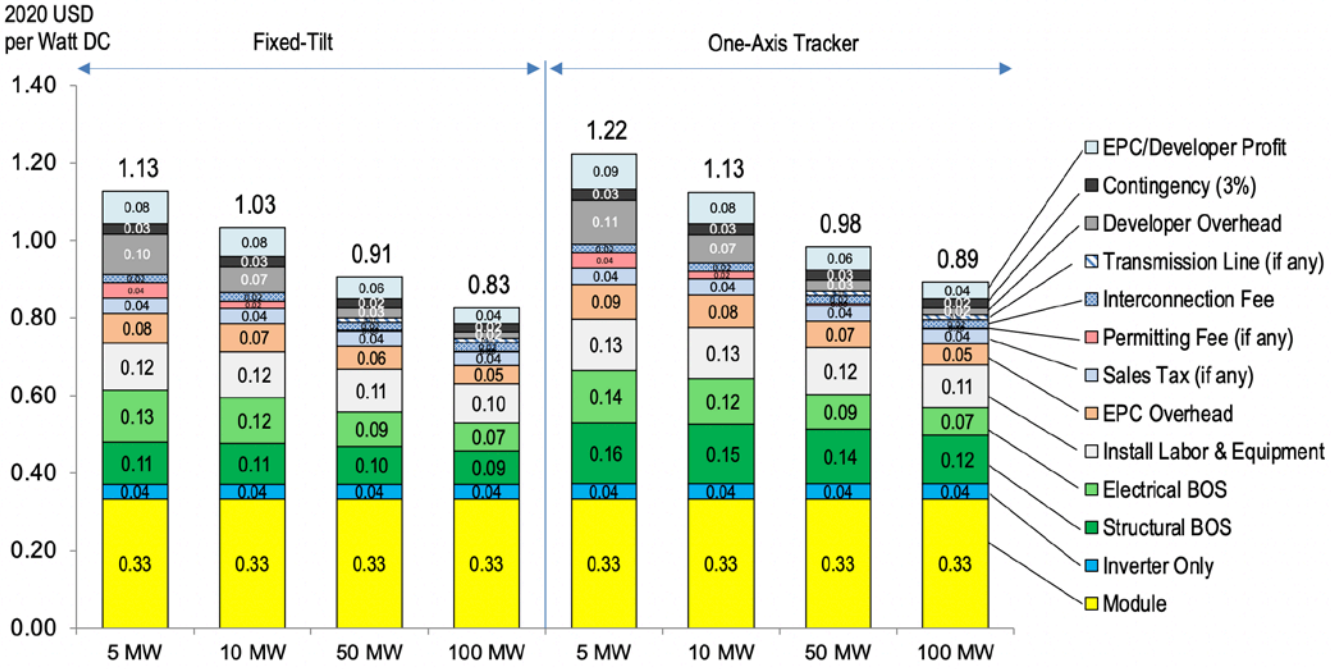
# Utility-Scale PV: Model Structure



# Utility-Scale PV: Modeling Inputs and Assumptions

| Category | Modeled Value | Description | Sources |
|---|---|---|---|
| System size | 100 MW; range: 5 MW–100 MW | A large utility-scale system capacity | Model assumption |
| Module efficiency | 19.9% | Average monocrystalline module efficiency | CA NEM 2021 |
| Module price | $0.34/$W_{DC}$ | Ex-factory gate (first buyer) price, Tier 1 monocrystalline modules | Wood Mackenzie and SEIA 2021; NREL 2021 |
| Inverter price | $0.05/$W_{AC}$ (fixed-tilt)<br>$0.05/$W_{AC}$ (one-axis tracker) | Ex-factory gate (first buyer) price, Tier 1 inverters<br>DC to AC ratio = 1.31 for fixed-tilt and 1.28 for one-axis tracker | Wood Mackenzie and SEIA 2021; Bolinger et al. 2020 |
| Structural components (racking) | $0.09-$0.12/$W_{DC}$ for a 100-MW system | Fixed-tilt racking or one-axis tracking system | MEPS 2019; model assumptions; NREL 2021 |
| Electrical components | $0.07–$0.14/$W_{DC}$ Varies by system size | Model upgraded to a 1,500-$V_{DC}$ system that includes conductors, conduit and fittings, transition boxes, switchgear, panel boards, onsite transmission, and other electrical connections | Model assumptions; NREL 2021; RSMeans 2021 |
| EPC overhead (percentage of equipment costs) | 8.67%–13% for equipment and material (except for transmission line costs); 23%–69% for labor costs; varies by system size and labor activity | Costs associated with EPC selling, general, and administrative (SG&A), warehousing; shipping; and logistics | NREL 2021 |
| Sales tax | National average: 5.1% | Sales tax on equipment costs | RSMeans 2021 |
| Direct installation labor | Electrician: $27.36/hour<br>Laborer: $18.22/hour | Modeled labor rate assumes national average nonunionized labor | BLS 2020; NREL 2021 |
| Burden rates (percentage of direct labor) | Total nationwide average: 31.7% | Workers' compensation, federal and state unemployment insurance, Federal Insurance Contributions Act, builders' risk, public liability | RSMeans 2021 |
| PII | $0.02–$0.06/$W_{DC}$<br>Varies by system size | For construction permits fee, interconnection, testing, and commissioning | NREL 2021 |
| Transmission line (gen-tie line) | $0.00–$0.01/$W_{DC}$<br>Varies by system size | System size < 10 MW uses 0 miles for gen-tie line, thus no transmission cost<br>System size > 200 MW uses five miles for gen-tie line<br>System size = 10–200 MW uses linear interpolation | Model assumptions; NREL 2021 |
| Developer overhead | 2%–12%<br>Varies by system size (100 MW uses 2%; 5 MW uses 12%) | Includes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions | Model assumptions; NREL 2021 |
| Contingency | 3% | Estimated as markup on EPC cost | NREL 2021 |
| Profit | 5%–8%<br>Varies by system size (100 MW uses 5%; 5 MW uses 8%) | Applies a percentage margin to all costs including hardware, installation labor, EPC overhead, and developer overhead | NREL 2021 |

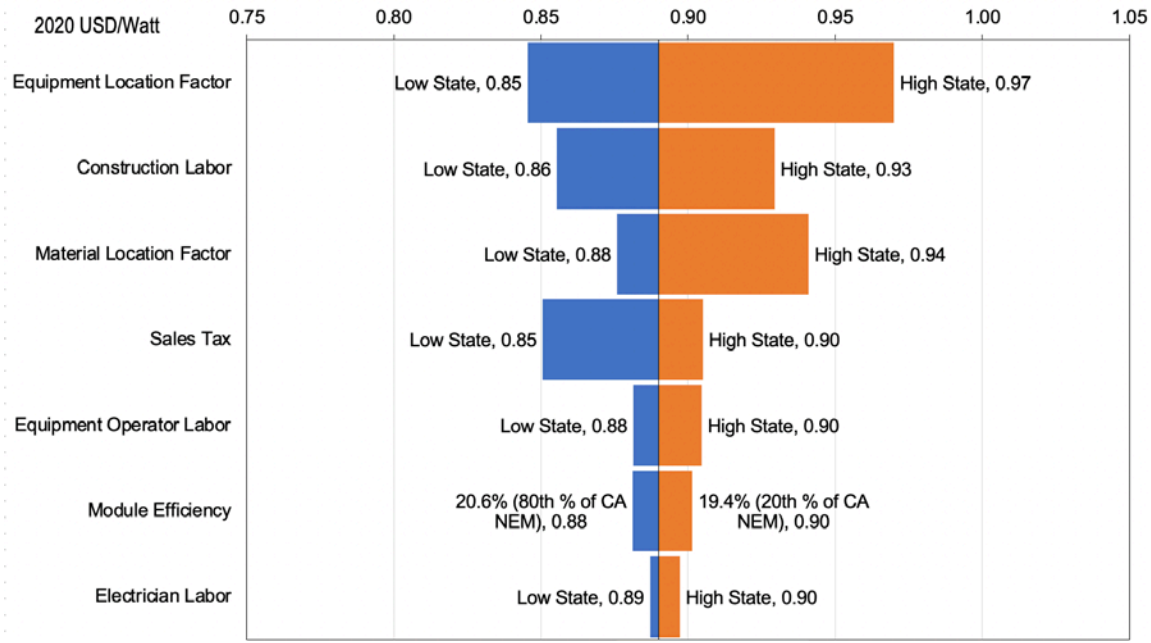
# Utility-Scale PV: Model Outputs




**Q1 2021 U.S. benchmark: Utility-scale PV total cost (EPC + developer) 2020 USD/$W_{DC}$**

(1) Nonunion labor is used.
(2) Economies of scale—driven by BOS, labor, related markups, and development cost—are demonstrated.

# Utility-Scale PV: Model Outputs

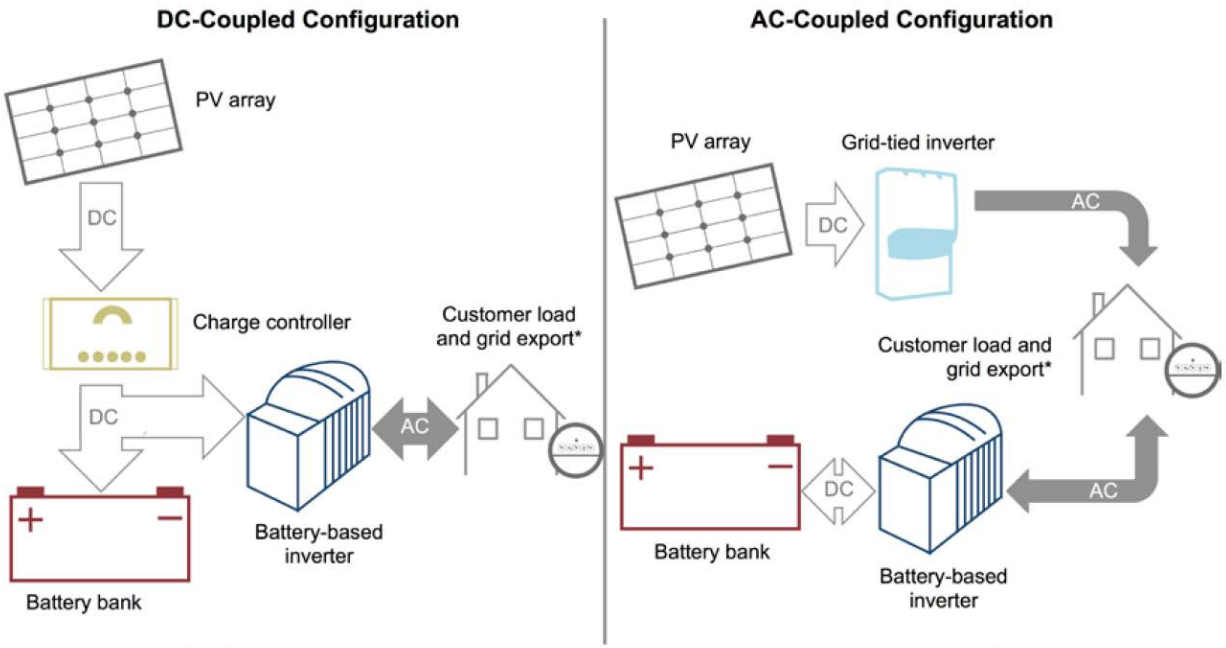



**Sensitivity analysis for Q1 2021 benchmark: 100-MW one-axis utility-scale PV system cost (2020 USD/$W_{DC}$)**

This figure presents a sensitivity analysis of the benchmark for the mixed case, with cost categories that vary by location and hardware specification. Equipment location factor has the largest impact on installed system cost, with the lowest cost state resulting in \$0.85/$W_{DC}$ and the highest cost state resulting in \$0.97/$W_{DC}$.

# Contents

# Residential PV-Plus-Storage: System Configurations

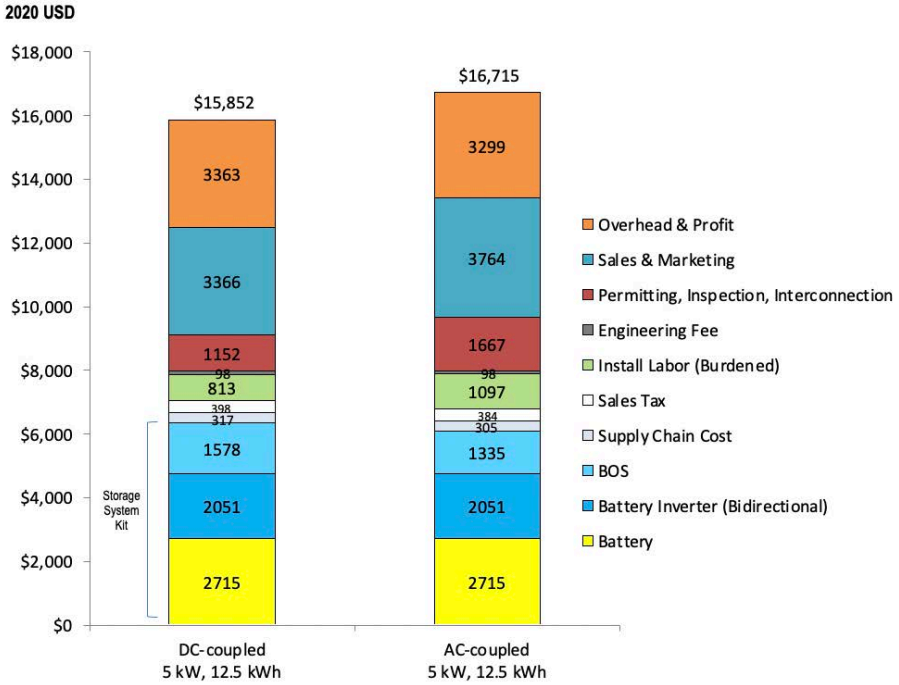



*Grid-connected PV plus storage systems are used to first meet a customer's load and then export excess PV generation to the grid. When wired for back-up power, it is common to install a critical loads sub-panel and use PV plus storage systems to provide power to essential loads (e.g. refrigeration, essential lighting, well pumps) in the case of a grid-outage event.

# Residential Storage-Only: Modeling Inputs and Assumptions

| Category | Modeled Value | Description |
|---|---|---|
| System size | 5 kW/12.5 kWh storage | Typical U.S. residential battery system |
| Battery pack cost | $221/kWh nameplate | Battery pack only |
| Battery-based inverter cost | $167/kWh nameplate | 8-kW, 48-V bidirectional inverter (more resilient) |
| Electrical BOS cost | • $1,578 (DC-coupled)<br>• $1,335 (AC-coupled)<br>Assumes higher electrical BOS costs for DC-coupled systems because of the need for a charge controller | Revenue-grade meter, communications device, AC main panel, DC disconnect, maximum power point tracking, charge controller, subpanel (breaker box) for critical load, conduit, wiring, DC cable |
| Supply-chain costs | 5% of cost of equipment | Includes costs of inventory, shipping, and handling of equipment |
| Sales tax | 5.1% (national average) | Sales tax on the equipment |
| Installation labor cost | Electrician: $27.36/hour<br>Laborer: $18.22/hour<br>For AC systems, we assume extra labor hours of work due to an additional inverter and extra wiring. | Assumes national average pricing |
| Engineering fee | $98 | Engineering design and professional engineer-stamped calculations and drawings |
| PII | $295 permit fee<br>$1,133–$1639 in labor | 20–32 hours (DC-coupled/AC-coupled) of commissioning and interconnection labor, and permit fee |
| Sales and marketing (customer acquisition) | $0.54/$W_{DC}$ | 20 hours more time for DC system, and 32 hours more for AC system, per closed sale, associated with selling a storage system versus selling a PV system |
| Overhead (general and administrative) | $0.25/$W_{DC}$ | Rent, building, equipment, staff expenses not directly tied to PII, customer acquisition, or direct installation labor |
| Profit (%) | 17% | Fixed percentage margin applied to all direct costs, including hardware, installation labor, direct sales and marketing, design, installation, and permitting fees |

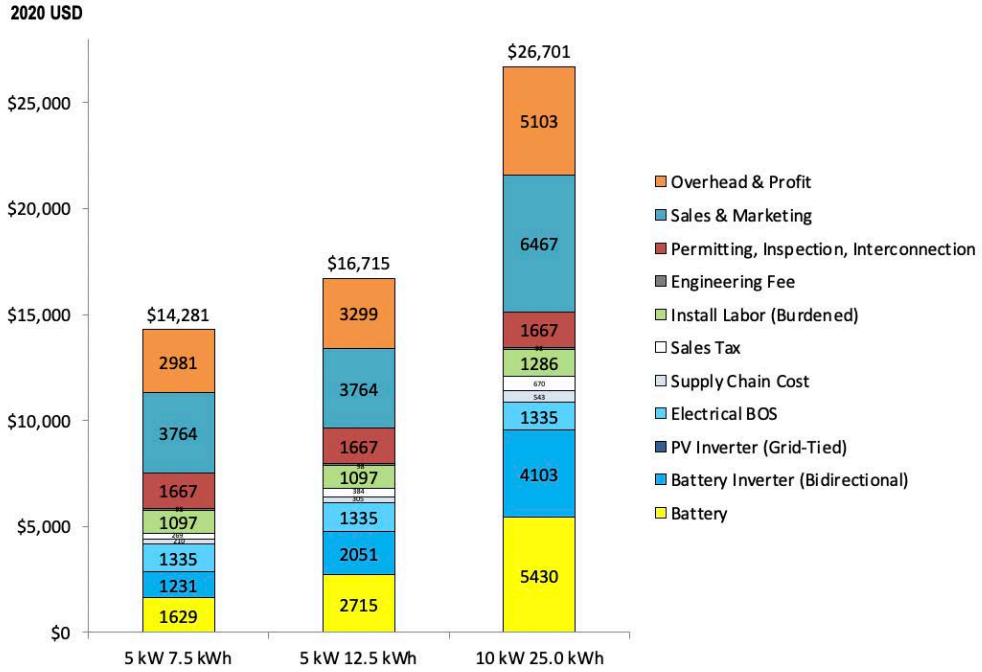
# Residential Storage-Only: Model Outputs




**Q1 2021 U.S. benchmark: Residential storage-only system cost (2020 USD/$W_{DC}$)**

As demonstrated, the kit for a 5-kW/12.5-kWh storage system costs approximately $6,406–$6,662 with a total installed cost of $15,852 (DC-coupled) to $16,715 (AC-coupled). We assume all batteries are installed inside the home. Installation of batteries outside would require additional BOS hardware, such as a concrete pad and associated container. Such additional BOS hardware would add to the benchmarked price of our modeled systems.

# Residential Storage-Only: Model Outputs



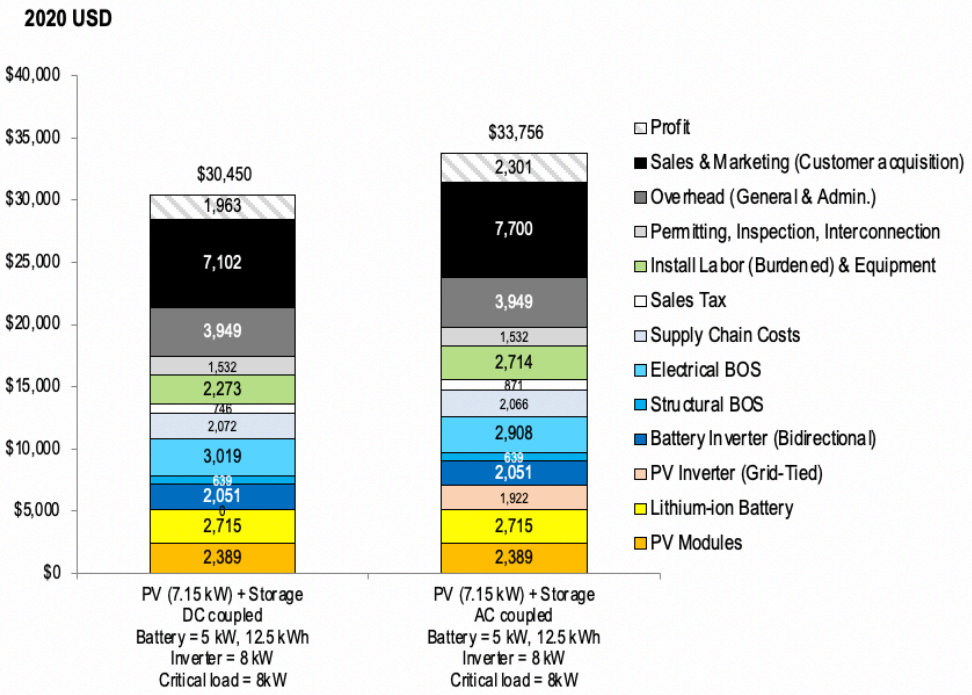

**Q1 2021 U.S. benchmark: Installed cost of stand-alone residential storage system by size (2020 USD/$W_{DC}$)**

Figure above shows the range in cost of typical stand-alone storage system sizes currently in the marketplace. Though we assume no economies of scale in our residential storage cost model, as demonstrated in the figure, certain costs are fixed regardless of the system size, reducing the cost per unit of capacity as the system size increases.

# Changes to Residential PV and Storage Models When They Are Combined

| Category | Modeled Value | Description |
|---|---|---|
| Electrical BOS | 90% of the combined BOS costs for PV and battery stand-alone systems | Duplicative parts are removed |
| Installation labor | 90% of the combined BOS costs for PV and battery stand-alone systems | Duplicative work is removed |
| Sales and marketing | 20 hours more time for DC system, and 32 hours more for AC system, per closed sale, associated with selling a PV system with storage | Additional explanation, calculations, and a lower close rate, and the AC system requires more customer site assessment |

# Residential PV-Plus-Storage: Model Outputs

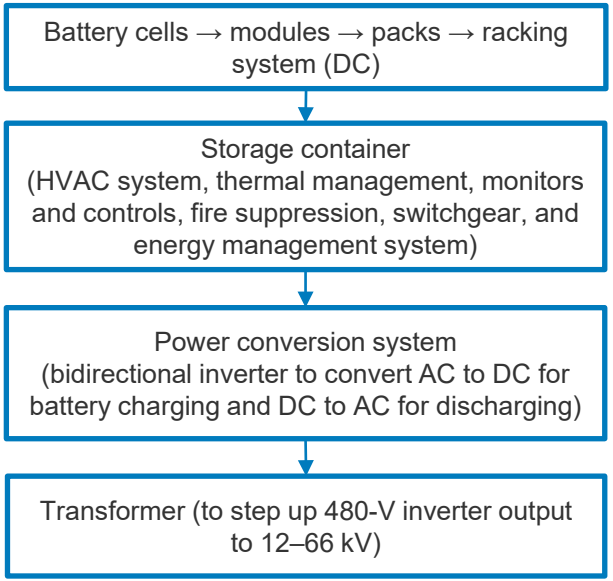



**Q1 2021 U.S. benchmark: Residential PV-plus-storage system cost (2020 USD/$W_{DC}$)**

With AC-coupling, the price of the system is $33,756, which is $3,306 (10.9%) more than the price of the DC-coupled system ($30,450).

# Contents

# Commercial PV-Plus-Storage: Li-ion Battery Energy Storage Components



# Commercial PV-Plus-Storage: System Components

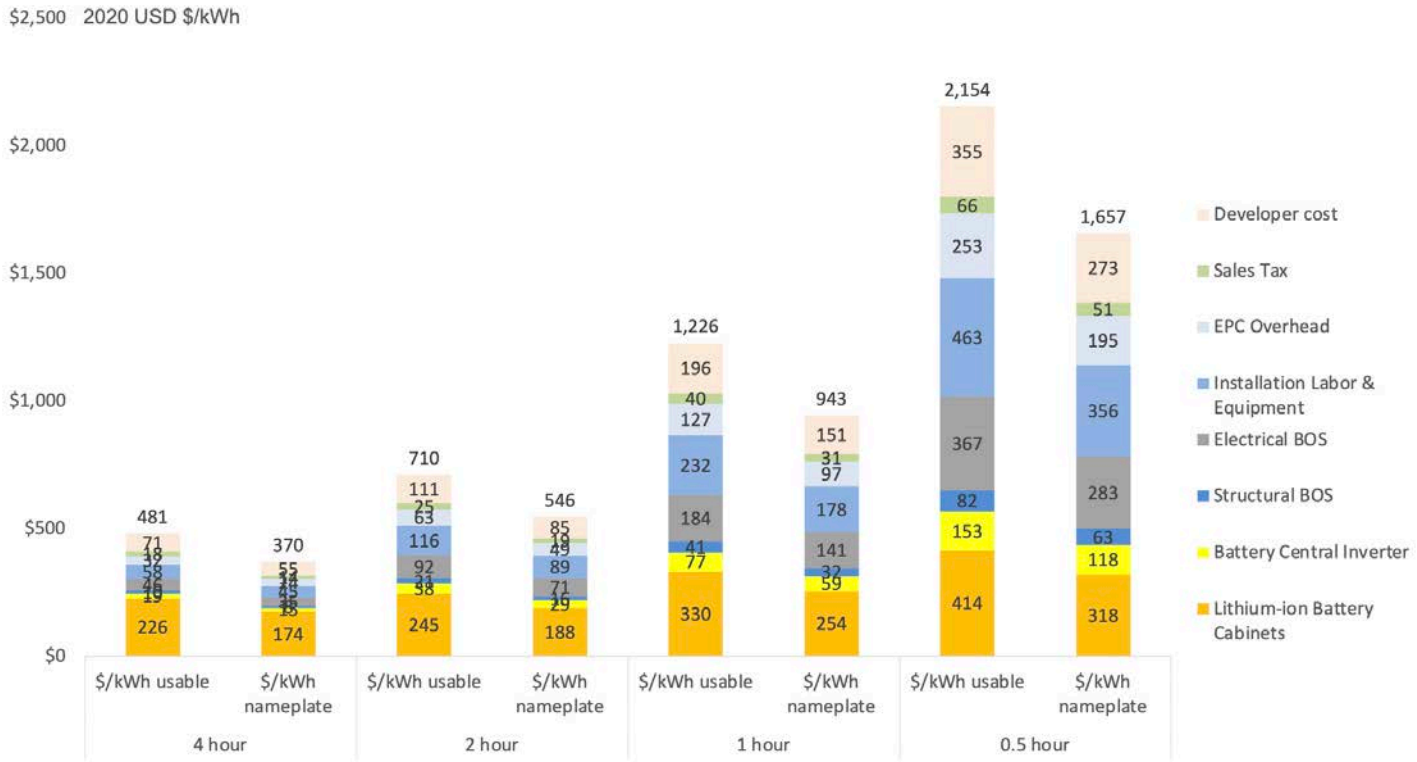
Battery Cell | Battery Module | Battery Racks | Battery Container

# Commercial Storage-Only: Modeling Inputs and Assumptions

| Model Component | Modeled Value | Description | Sources |
|---|---|---|---|
| Battery total size | 600 $kW_{DC}$<br>2.4 MWh usable | Baseline case to match a 1-MW PV system | NREL 2021 |
| Battery size per container | 5 MWh per 40-ft container | 1 container | NREL 2021 |
| Li-ion battery price ($/kWh usable) | 0.5 hours: \$229/$kWh_{usable}$<br>1 hour: \$211/$kWh_{usable}$<br>2 hours: \$168/$kWh_{usable}$<br>4 hours: \$165/$kWh_{usable}$ | Ex-factory gate (first buyer) prices | BNEF 2020 |
| Duration | 0.5–4.0 hours | Duration determines energy (MWh). | NREL 2021 |
| RTE | 90% | Round trip efficiency | NREL 2021 |
| Min. state of charge (SOC) and max. SOC | 10% and 90% | Minimum and maximum SOC | NREL 2021 |
| Battery central inverter price | \$0.06/W | Ex-factory gate (first buyer) prices | Wood Mackenzie 2019 |
| Battery cabinet | \$0.21–\$0.90 | Includes battery packs, containers, thermal management system and fire suppression system | NREL 2021 |
| Electrical BOS | \$0.18/W | Includes conduit, wiring, DC cable, energy management system, switchgear, transformer, and monitor and controls for each container; costs impacted by number of containers, number of transformers, and row spacing | NREL 2021 |
| Structural BOS | \$0.04/W | Includes foundation and inverter house; costs impacted by numbers of inverters and transformers | NREL 2021 |
| Installation labor | Electrician: \$27.36/hour<br>Laborer: \$18.22/hour | National average modeled labor rate assumes nonunionized labor. | BLS 2020 |
| Sales tax | 5.1% (national average) | Sales tax on the equipment | RSMeans 2021 |
| 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 | NREL 2021 |
| Developer cost: developer overhead | 6% of total installation cost | Includes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions | NREL 2021 |
| Developer cost: PII | \$0.03/W | Construction permits fee, interconnection study, interconnection inspection, and interconnection fee | NREL 2021 |
| Developer cost: contingency | 4% | Estimated as markup on the total EPC cost | NREL 2021 |
| Developer cost: EPC/developer net profit | 5% | Applies a percentage margin to all costs including hardware, installation labor, EPC overhead, and developer overhead | NREL 2021 |

We determine the battery size (600 $kW_{DC}$) using an inverter loading ratio of 1.3 and an inverter/storage size ratio of 1.67, based on Denholm, Eichman, and Margolis (2017). For a 1-MW PV system with an inverter loading ratio of 1.3 and inverter/storage size ratio of 1.67, maximum deliverable power at point of interconnection is 1.37 megawatts alternating current ($MW_{AC}$) (1-MW/1.3 + 1 MW/1.67) for AC-coupled systems and 770 $kW_{AC}$ (1 MW/1.3) for DC-coupled systems.

# Commercial Storage-Only: Model Outputs



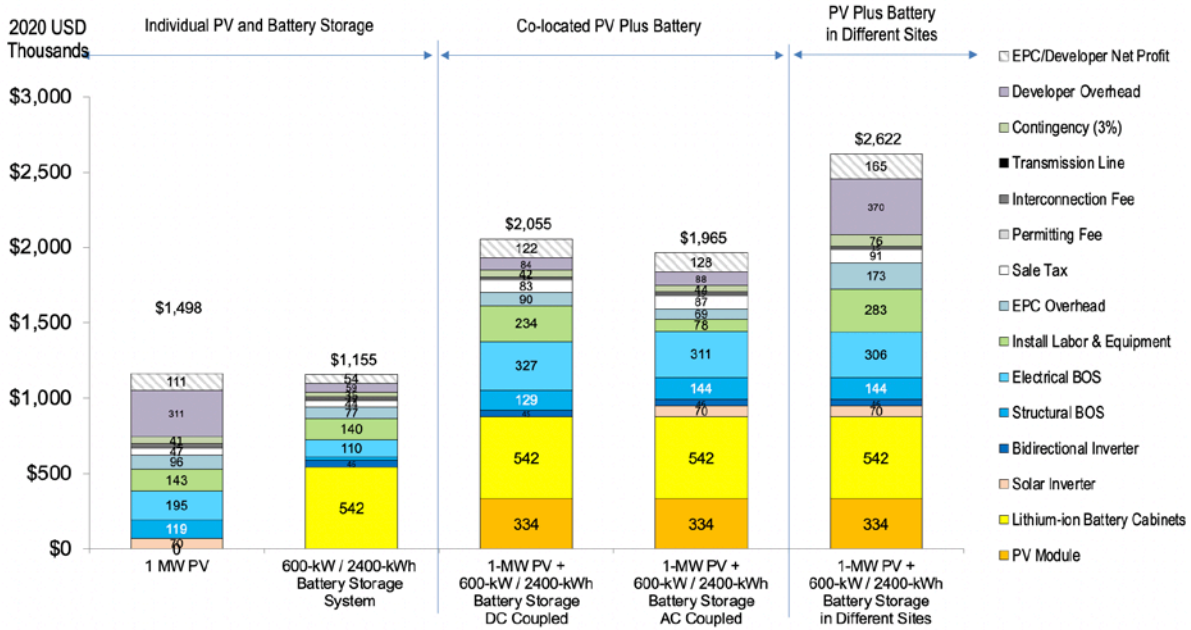

**Q1 2021 U.S. benchmark: Commercial storage-only system cost (2020 USD/$W_{DC}$)**

Above figure shows the resulting costs in nameplate and usable capacity ($/kWh ) for 600-kW Li-ion energy storage systems, which vary from $481/kWh-usable (4-hour duration) to $2,154/kWh-usable (0.5-hour duration). The battery cabinet cost accounts for 47% of total system cost in the 4-hour system but only 19% in the 0.5-hour system. At the same time, non-battery cost categories account for an increasing proportion of the system cost as duration declines.

# Changes to Commercial PV and Storage Models When They Are Combined

| Category | Modeled Value | Description |
|---|---|---|
| Electrical BOS | 90% of the combined BOS costs for PV and battery stand-alone systems | Duplicative parts are removed |
| Installation labor | 90% of the combined BOS costs for PV and battery stand-alone systems | Duplicative work is removed |
| Sales and marketing | 20 hours more time for DC system, and 32 hours more for AC system, per closed sale, associated with selling a PV system with storage | Additional explanation, calculations, and a lower close rate; also, the AC system requires more customer site assessment |

# Commercial PV-Plus-Storage: Model Outputs



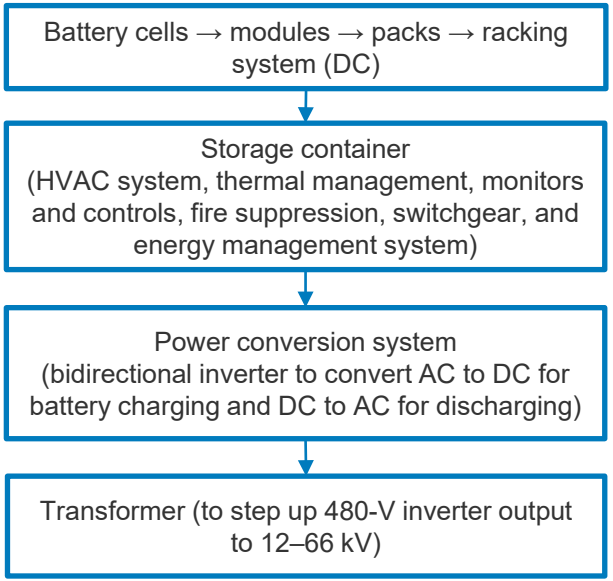

**Q1 2021 U.S. benchmark: Commercial PV-plus-storage system cost (2020 USD/$W_{DC}$)**

Colocating the PV and storage subsystems produces cost savings by reducing costs related to site preparation, permitting, interconnection, installation labor, hardware (via sharing of hardware such as switchgears, transformers, and controls), overhead, and profit. The cost of the colocated AC-coupled system is 25% lower than the cost of the system with PV and storage sited separately.

Using DC-coupling rather than AC-coupling results in a 4.5% higher 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 (O&M)—should be considered.

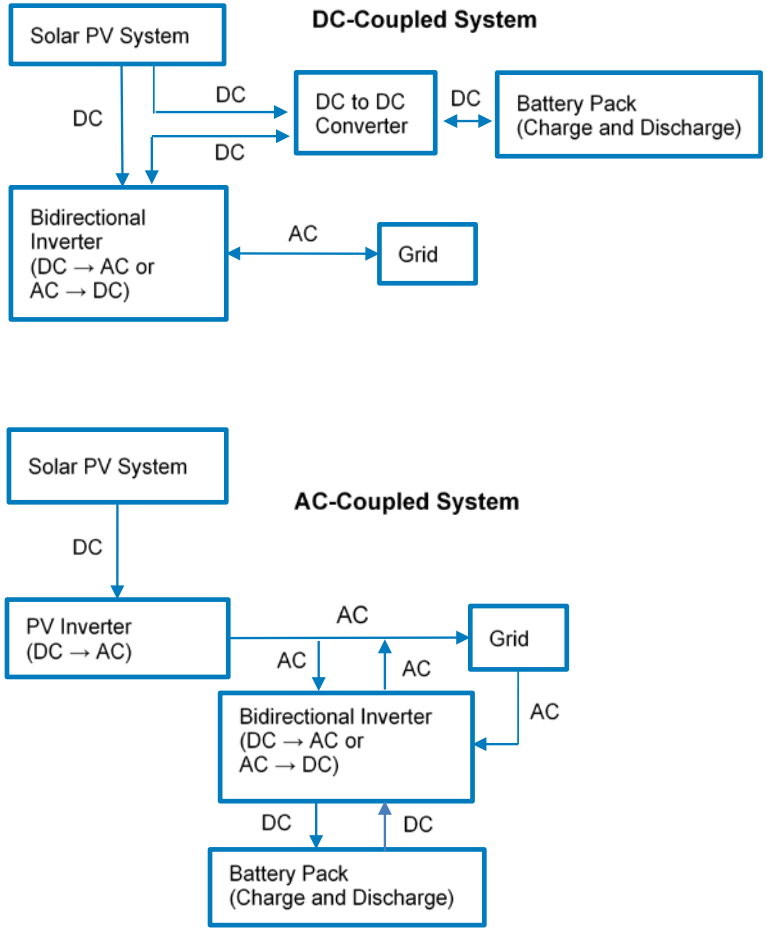
# Contents

# Utility-Scale PV-Plus-Storage: Li-ion Battery Energy Storage Components



# Utility-Scale PV-Plus-Storage: System Components

# Utility-Scale PV-Plus-Storage: System Configurations

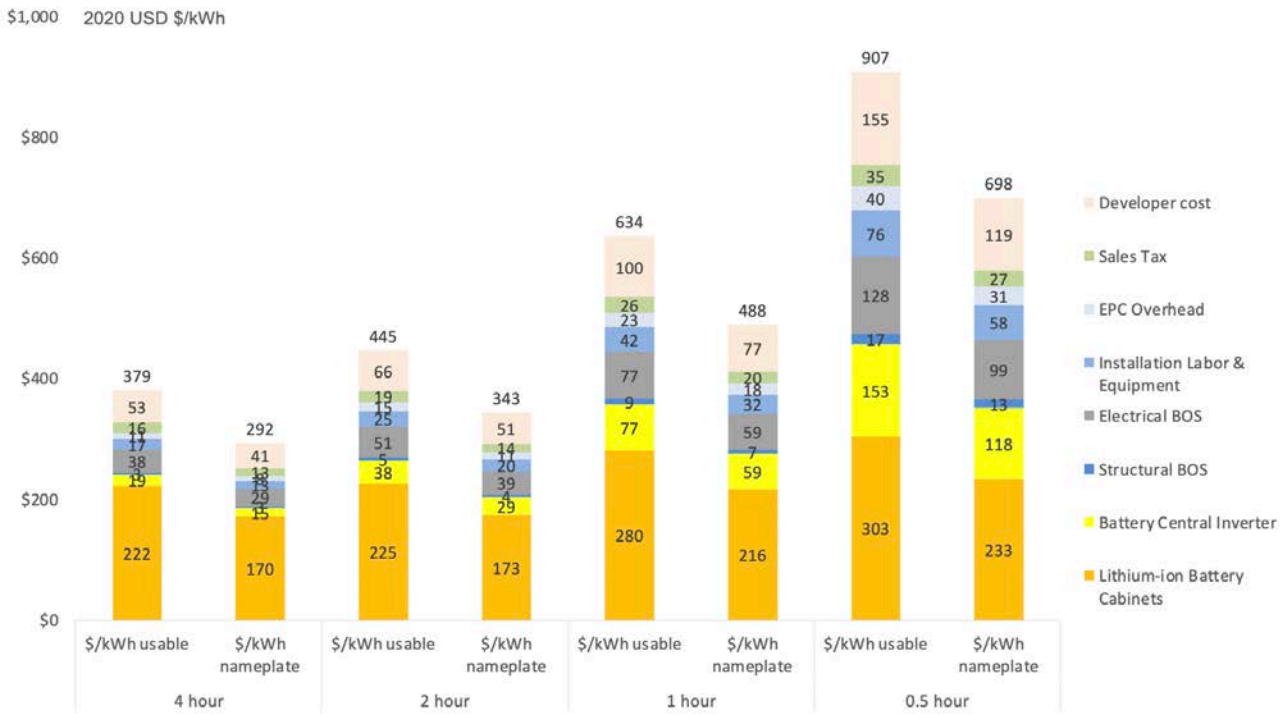


# Utility-Scale Storage-Only: Modeling Inputs and Assumptions

| Model Component | Modeled Value | Description | Source |
|---|---|---|---|
| Battery total size | 60 $MW_{DC}$<br><br>240 MWh usable | Baseline case to match a 100-MW PV system | NREL 2021 |
| Battery size per container | 5 MWh per 40-ft container | Assumption to compute the number of containers | NREL 2021 |
| Li-ion battery price ($/kWh usable) | 0.5 hours: $229/$kWh_{usable}$<br><br>1 hour: $211/$kWh_{usable}$<br><br>2 hours: $168/$kWh_{usable}$<br><br>4 hours: $165/$kWh_{usable}$ | Ex-factory gate (first buyer) prices | BNEF 2020 |
| Duration | 0.5–4.0 hours | Duration determines energy (MWh) | NREL 2021 |
| RTE | 90% | Round-trip efficiency | |
| Min. SOC and max. SOC | 10% and 90% | Minimum and maximum SOC | |
| Battery central inverter price | $0.06/$W_{AC}$ | Ex-factory gate (first buyer) prices | Wood Mackenzie 2019 |
| Battery cabinet | $0.15-$0.89/W | Includes battery packs, containers, thermal management system and fire suppression system. | NREL 2021 |
| Inverter size | 2.5 MW per inverter<br><br>(24 inverters) | Used to determine the number of battery inverters | NREL 2021 |
| Electrical BOS | $0.06–$0.15/W | Includes conduit, wiring, DC cable, energy management system, switchgear, transformer, and monitor and controls for each container; determined by number of containers, number of transformers, and row spacing | NREL 2021 |
| Structural BOS | $0.01/W | Includes foundation and inverter house; costs impacted by number of inverters, number of transformers, and the spacing between containers. | NREL 2021 |
| Installation labor | Electrician: $27.36/hour<br><br>Laborer: $18.22/hour | National average modeled labor rate assumes nonunionized labor | BLS 2020 |
| Sales tax | 5.1% (national average) | Sales tax on the equipment | RSMeans 2021 |
| EPC overhead and profit | 8.67% for equipment and material; 23%–69% for labor costs; varies by system size, and labor activity | Costs associated with EPC SG&A, warehousing, shipping, and logistics | NREL 2021 |
| Developer cost: 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 | NREL 2021 |
| Developer cost: PII | $0.02/W | Construction permits fee, interconnection study, interconnection inspection, and interconnection fee | NREL 2021 |
| Developer cost: contingency | 3% | Estimated as markup on the total EPC cost | NREL 2021 |
| Developer cost: EPC/developer net profit | 5% | Applies a percentage margin to all costs including hardware, installation labor, EPC overhead, and developer overhead | NREL 2021 |

We determine the battery size (60 megawatts direct current [$MW_{DC}$]) using an inverter loading ratio of 1.3 and an inverter/storage size ratio of 1.67, based on Denholm, Eichman, and Margolis (2017). For a 100-MW PV system with an inverter loading ratio of 1.3 and an inverter/storage size ratio of 1.67, and assuming battery inverter capacity is equal to battery DC capacity maximum deliverable power at point of interconnection is 137 $MW_{AC}$ (100 MW/1.3 + 100 MW/1.67) for AC-coupled systems and 77 $MW_{AC}$ (100 MW/1.3) for DC-coupled systems.

# Utility-Scale Storage-Only: Model Outputs




**Q1 2021 U.S. benchmark: Utility-scale storage-only system cost (2020 USD/$W_{DC}$)**

Figure above shows the resulting nameplate and usable costs for 60-MW Li-ion energy storage systems, which vary from \$379/$kWh_{usable}$ (4-hour duration) to \$907/$kWh_{usable}$ (0.5-hour duration). Though the per-energy-unit battery cost increases as system duration decreases, the total battery cost—and the proportion of the cost attributed to the battery—decreases as system duration decreases. For example, the battery cabinet cost accounts for 58% of total system cost in the 4-hour system but only 33% in the 0.5-hour system. At the same time, non-battery cost categories account for an increasing proportion of the system cost as duration declines.

# Cost Factors for Siting PV and Storage Together Versus Separately

| Model Component | Colocated PV-Plus-Storage | PV-Plus-Storage at Different Sites |
|---|---|---|
| Site preparation[a] | 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 |

[a] Site preparation is a subcategory of labor cost, so it is not shown in the cost breakdown chart.

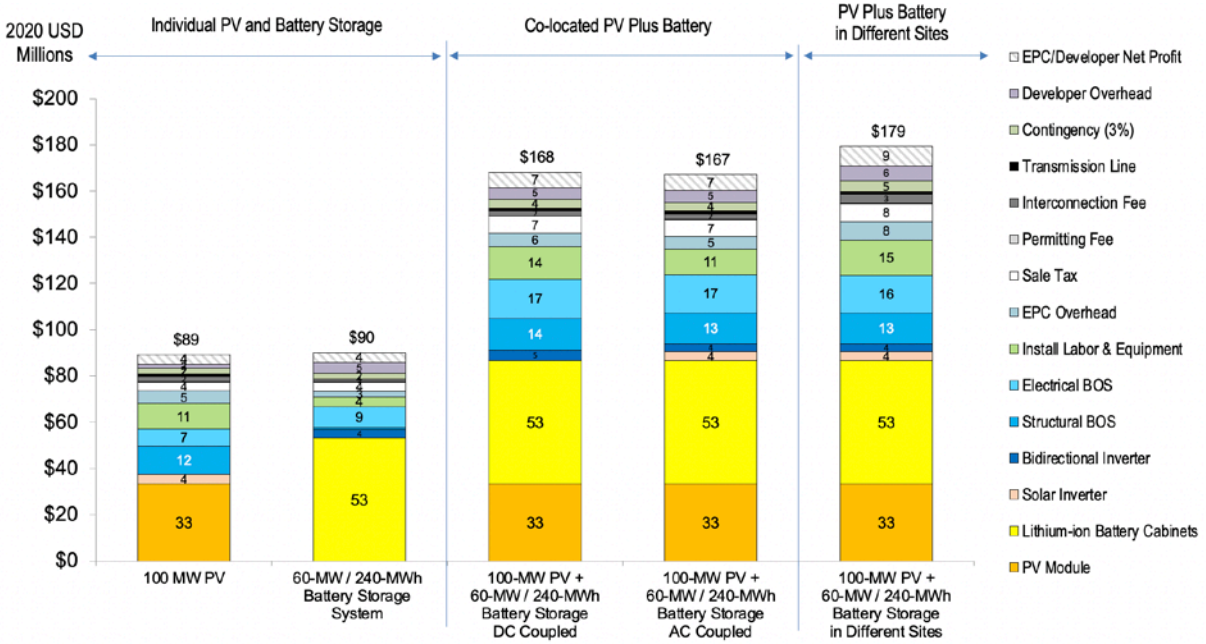
# Comparison of DC- and AC-Coupling for Utility-Scale PV-Plus-Storage Systems

| 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 |
| 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 (better labor mobilization) |
| 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) |

**Reasons an installer or a developer may pursue a DC-coupled system include:**

•Installing a DC-coupled system with a single bidirectional inverter reduces additional costs for the inverter, inverter wiring, and inverter housing.
•DC-coupled systems mitigate extra conversion of energy from DC to AC to DC, and so they have higher RTE than AC-coupled systems. However, as power electronics are becoming more efficient, the actual efficiency difference is becoming smaller (Enphase 2019).
•Because the battery is connected directly to the PV system via DC-DC converter, excess PV generation that falls outside the inverter limits can be sent directly to the battery and thus lead to an increase in overall output for the same interconnection capacity (DiOrio and Hobbs 2018).
•A DC-coupled system has only one point of interconnection, reducing interconnection complexity, time, and associated cost.
•DC-coupled systems could use a unidirectional inverter as well, but that configuration is not considered in our cost modeling. This configuration could lead to lower total system installed cost than a DC-coupled system using a bidirectional inverter but at the same time it prevents the system from grid charging.

# Utility-Scale PV-Plus-Storage: Model Outputs




**Q1 2021 U.S. benchmark: Utility-scale PV-plus-storage system cost (2020 USD/$W_{DC}$)**

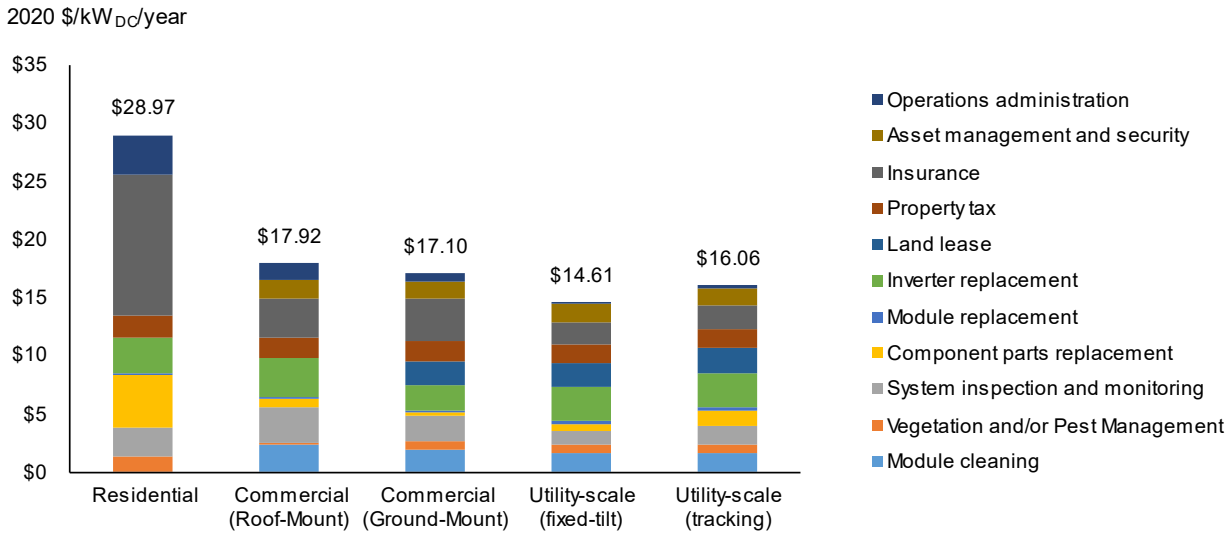
Colocating the PV and storage subsystems produces cost savings by reducing costs related to site preparation, land acquisition, permitting, interconnection, installation labor, hardware (via sharing of hardware such as switchgears, transformers, and controls), overhead, and profit. The cost of the colocated AC-coupled system is 6%–7% lower than the cost of the system with PV and storage sited separately.

Between DC-coupling and AC-coupling, total costs vary by a smaller percentage, as the 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 offset each other. 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 that is due to clipping), design flexibility, and O&M—should be considered.

# O&M and LCOE

- Introduction and Key Definitions
- Overall Model Outputs
- Market Study and Model Inputs
- Model Output: Residential PV
- Model Output: Commercial PV
- Model Output: Utility-Scale PV
- Residential PV-Plus-Storage
- Commercial PV-Plus-Storage
- Utility-Scale PV-Plus-Storage
- **O&M and LCOE**
- Conclusions

# Operations and Maintenance




In Fiscal Year 2018, a PV O&M working group that was convened under the sponsorship of DOE's Solar Energy Technologies Office developed a model to calculate the cost associated with PV system O&M (Walker et al. 2020). A total of 133 measures in the cost model are sorted into 9 O&M cost categories: inverter replacement, operations administration, module replacement, components parts replacement, system inspection and monitoring; module cleaning and/or vegetation and pest management; land lease; property tax; and insurance, asset management, and security. The current benchmarks are $28.97/kW$_{DC}$/yr (residential), $17.92/kW$_{DC}$/yr (commercial; roof-mounted), $17.10/kW$_{DC}$/yr (commercial; ground-mounted), $14.61/kW$_{DC}$/yr (utility-scale, fixed-tilt), and $16.06/kW$_{DC}$/yr (utility-scale, single-axis tracking).

# Stand-Alone PV LCOE Input Assumptions & Output

| | Residential | | Commercial Rooftop | | One-Axis Tracker | |
|---|---|---|---|---|---|---|
| | 2020 | 2021 | 2020 | 2021 | 2020 | 2021 |
| Installed cost ($/W) | 2.74 | 2.65 | 1.74 | 1.56 | 1.02 | 0.89 |
| Annual degradation (%) | 0.70 | 1.00 | 0.70 | 0.70 | 0.70 | 0.70 |
| Levelized O&M expenses over life of asset ($/kW-yr) | 29 | 29 | 19 | 18 | 18 | 16 |
| Preinverter derate (%) | 90.5 | 85.9 | 90.5 | 85.9 | 90.5 | 85.9 |
| Inverter efficiency (%) | 98.0 | 96.0 | 98.0 | 96.0 | 98.0 | 96.0 |
| Inverter loading ratio | 1.15 | 1.15 | 1.15 | 1.15 | 1.34 | 1.28 |
| Inflation rate (%) | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| Equity discount rate (real) (%) | 6.1 | 10.2 | 6.1 | 6.1 | 5.1 | 5.1 |
| Debt interest rate (%) | 5.0 | 4.5 | 5.0 | 5.0 | 5.0 | 5.0 |
| Debt fraction (%) | 71.8 | 100 | 71.8 | 71.8 | 71.8 | 71.8 |
| Debt term (years) | 18 | 25 | 18 | 18 | 18 | 18 |
| Entity | Corporation | Homeowner | Corporation | Corporation | Corporation | Corporation |
| Analysis period (years) | 30 | 25 | 30 | 30 | 30 | 30 |
| Initial energy yield (kWh/$kW_{DC}$) | 1,546 | 1,445 | 1,440 | 1397 | 1,721 | 1,694 |
| Real LCOE (2020 US$) | 13.0¢/kWh | 11.9¢/kWh | 9.1¢/kWh | 8.3¢/kWh | 4.6¢/kWh | 4.1¢/kWh |

**Other Key Assumptions**

(1) Corporation has a federal corporate tax rate of 21% and state corporate tax rate of 6% and uses the Modified Accelerated Cost Recovery System depreciation schedule.

(2) Homeowner uses a mortgage loan that is interest deductible, with a federal personal tax rate of 15% and a personal state tax rate of 6%.

(3) No state or local subsidies

(4) For corporations: a working capital and debt service reserve account for six months of operating costs and debt payments (earning an interest rate of 1.75%), a six-month construction loan, with an interest rate of 4% and a fee of 1% of the cost of the system, $1.1 million of upfront financial transaction costs for a $100 million third-party ownership transaction of a pool of commercial projects

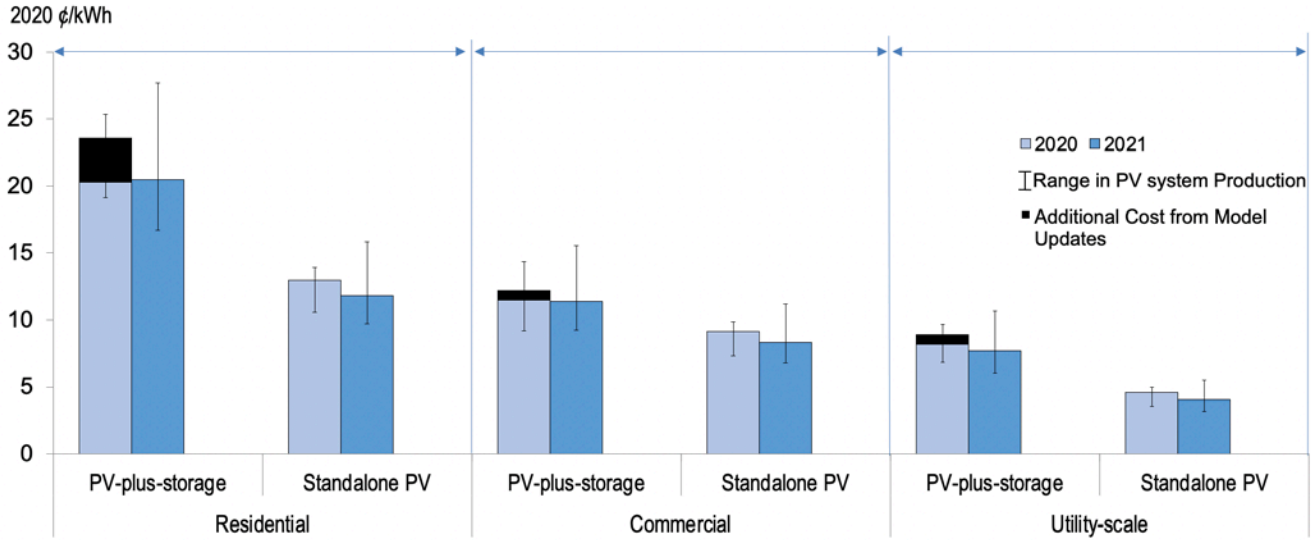
(5) 2020 capacity factors are based on Kansas City, Missouri, with a tilt/azimuth of 25/180 (residential), 10/180 (commercial rooftop), and tracking/180 (utility-scale). 2021 capacity factors are based on Fredonia, Kansas (which is near the geographic center of the 48 conterminous states and corresponds with the area-weighted capacity factor of the 48 conterminous states as outlined in the 2021 Annual Technology Baseline), with a tilt/azimuth of 20/214 (residential) (Barbose et al. 2020), 10/190 (commercial rooftop) (Barbose et al. 2020), and tracking/180 (utility-scale).

# PV-Plus-Storage LCOE Input Assumptions & Output

| | Residential<br>22-panel PV plus 5-kW/12.5-kWh storage system | | Commercial<br>1-MW fixed-tilt ground-mounted PV plus 600-kW/2.4-MWh storage system | | Utility-scale<br>100-MW one-axis tracker PV plus 60-MW (240-MWh) battery storage, AC-coupled | |
|---|---|---|---|---|---|---|
| | 2020 | 2021 | 2020 | 2021 | 2020 | 2021 |
| Installed cost ($) | $34,942 | $30,450 | $2,170,851 | $1,970,000 | $190 million | $167 million |
| Annual degradation (%) | 0.70 | 1.00 | 0.70 | 0.70 | 0.70 | 0.70 |
| Levelized O&M expenses over life of asset ($/kW-yr) | 39 | 39 | 29 | 28 | 28 | 26 |
| First follow-on investments (inverter, battery replacements) ($) | $865 | $763 | $80,439 | $63,360 | $8.0 million | $6.3 million |
| Second follow-on investments (inverter, battery replacements) ($) | $648 | $572 | $60,329 | $47,520 | $6.0 million | $4.8 million |
| Preinverter derate (%) | 90.5 | 85.9 | 90.5 | 85.9 | 90.5 | 85.9 |
| Inverter efficiency (%) | 98.0 | 96.0 | 98.0 | 96.0 | 98.0 | 96.0 |
| Inverter loading ratio | 1.15 | 1.15 | 1.15 | 1.15 | 1.34 | 1.28 |
| Inflation rate (%) | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| Equity discount rate (real) (%) | 6.1 | 10.2 | 6.1 | 6.1 | 5.1 | 5.1 |
| Debt interest rate (%) | 5.0 | 4.5 | 5.0 | 5.0 | 5.0 | 5.0 |
| Debt fraction (%) | 71.8 | 100 | 71.8 | 71.8 | 71.8 | 71.8 |
| Debt term (years) | 18 | 25 | 18 | 18 | 18 | 18 |
| Entity | Corporation | Homeowner | Corporation | Corporation | Corporation | Corporation |
| Analysis period (years) | 30 | 25 | 30 | 30 | 30 | 30 |
| Initial energy yield (kWh/$kW_{DC}$) | 1,546 | 1,445 | 1,440 | 1397 | 1,721 | 1,694 |
| Real LCOE (2020 US$) | 23.3¢/kWh | 20.5¢/kWh | 12.1¢/kWh | 11.4¢/kWh | 8.8¢/kWh | 7.7¢/kWh |

The current version of our residential PV-plus-storage model assumes a battery size of 5 kW/12.5 kWh; the Q1 2020 benchmark models a battery size of 3 kW(6 kWh) (Feldman et al. 2021). To better distinguish the historical cost trends from the changes to our cost models, we calculate the Q1 2020 residential PV-plus-storage using a battery size of 5 kWh (12.5 kWh). For this reason, capital expenditures (2020 USD 28,721) and LCOE (20.1 USD cents/kWh) differ from those reported in Table above, adjusting for dollar year.

# LCOE




From 2020 to 2021, residential PV-plus-storage LCOE fell 13%, and residential stand-alone PV LCOE fell 9%; there were 7% and 13% reductions in levelized electricity costs for commercial and utility-scale PV-plus-storage systems. At the same time, LCOE of commercial and utility scale stand-alone PV systems fell by 9% and 12%, respectively. Reported 2021 residential PV-plus-storage LCOE values are initially 17% higher than 2020 values because the 2021 report models a larger battery system (5 kW/12.5 kWh) than the 2020 benchmark report (3 kW/6 kWh). In this year's report, we updated residential financial assumption from a third-party-ownership model to one in which homeowners finance the cost of a system through their mortgage.

# Contents

# Conclusions

| Cost Benchmarks | PV/Battery Energy Storage System |
|---|---|
| **Residential Systems** | |
| $2.65/$W_{DC}$ (or $3.05/$W_{AC}$) | 7.15-$kW_{DC}$ rooftop PV |
| $4.24/$W_{DC}$ –$4.70/$W_{DC}$ | 7.15-$kW_{DC}$ rooftop PV with 5 $kW_{DC}$/12.5 $kWh_{nameplate}$ of storage |
| **Commercial Systems** | |
| $1.56/$W_{DC}$ (or $1.79/$W_{AC}$) | 200-$kW_{DC}$ rooftop PV |
| $1.64/$W_{DC}$ (or $1.88/$W_{AC}$) | 500-$kW_{DC}$ ground-mounted PV |
| $2.04/$W_{DC}$ – $2.10/$W_{DC}$ | 1-$MW_{DC}$ ground-mounted PV colocated with 600 $kW_{DC}$/2.4 $MWh_{usable}$ of storage |
| **Utility-Scale Systems** | |
| $0.83/$W_{DC}$ (or $1.09/$W_{AC}$) | 100-$MW_{DC}$ fixed-tilt utility-scale PV |
| $0.89/$W_{DC}$ (or $1.14/$W_{AC}$) | 100-$MW_{DC}$ one-axis-tracking utility-scale PV |
| $1.66/$W_{DC}$ – $1.67/$W_{DC}$ | 100-$MW_{DC}$ one-axis tracker PV colocated with 60 $MW_{DC}$/240 $MWh_{usable}$ of storage |

Between 2020 and 2021, there were 3.3% ($0.09/W), 10.7% ($0.19/W), and 12.3% ($0.13/W) reductions (in 2020 USD) in the residential, commercial rooftop, and utility-scale (one-axis) PV system cost benchmarks respectively. BOS costs have either increased or remained flat across sectors, year-on-year, unlike in previous benchmarking reports, which generally have reported declining BOS costs. The increase in BOS cost has been offset by a 17% reduction in module cost. Overall, modeled PV installed costs across the three sectors have declined compared to our Q1 2020 system costs. The table shows the benchmarked values for all three sectors and the drivers of cost decreases and increases.

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# Changes in Methodology Between Q1 2020 and Q1 2021 Reports

- Interconnection and Transmission Cost estimated based on $MW_{AC}$; defined point of interconnection capacity and assumed it is equal to the total AC capacity of the plant.
- Assumes DC overbuild accounting for RTE loss (10%) and SOC limitations (20%); assumes battery is shipped as a cabinet enclosure with all battery components preassembled; includes cost of battery pack, container, racks, HVAC, thermal management system, and battery management system; represented in both nameplate and usable capacity.
- Residential energy storage system size updated from 3 kW/6 kWh to 5 kW/12.5 kWh; adjustment made to conform with typical battery size currently available in marketplace (Barbose et al. 2021).
- Low and high resource locations were made to show a wider range in solar resources available in the United States. Medium solar resource was changed to better correspond with U.S. national averages. We also adjusted PV system loss assumptions to better correspond with default assumptions in other NREL modeling applications.
- The percentage of host-owned PV systems has increased substantially over the past 5 years (63% of residential PV systems in 2019), and these use a personal loan. Though mortgages are not currently the most prevalent source of funding, they represent a major opportunity for cost reductions for PV system costs, and therefore we view this as a reasonable long-term steady-state financing assumption. Because of host-ownership, we assume the homeowner does not spend as much time and effort on maintaining the PV system as a third party and therefore O&M cost are reduced, while degradation rate increases, and system lifetime decreases.

# Appendix: PV System LCOE Benchmarks in 2020 USD

| | Market Financing Rates | | | | | | | | | | | Steady- State Financing | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reporting Year (Benchmarking Date)** | 2010 (Q4 2009) | 2011 (Q4 2010) | 2012 (Q4 2011) | 2013 (Q4 2012) | 2014 (Q4 2013) | 2015 (Q1 2015) | 2016 (Q1 2016) | 2017 (Q1 2017) | 2018 (Q12018) | 2019 (Q1 2019) | 2020 (Q1 2020) | 2020 (Q1 2020) | 2021 (Q1 2021) | 2030 Goal |
| **Residential PV (22-panel)** | | | | | | | | | | | | | | |
| LCOE (High resource) | 42.1 | 35.4 | 24.4 | 20.5 | 17.2 | 15.2 | 13.9 | 13.1 | 12.2 | 11.3 | 11.1 | 10.6 | 9.7 | — |
| LCOE (Medium resource) | 51.6 | 43.4 | 29.9 | 25.0 | 21.0 | 18.6 | 17.1 | 16.0 | 14.9 | 13.8 | 13.7 | 13.0 | 11.9 | 5.4 |
| LCOE (Low resource) | 55.4 | 46.6 | 32.1 | 26.9 | 22.6 | 19.9 | 18.3 | 17.2 | 16.0 | 14.8 | 14.7 | 13.9 | 15.8 | — |
| **Residential PV-Plus-Storage** | | | | | | | | | | | | | | |
| LCOE (High resource) | — | — | — | — | — | — | — | — | — | — | 16.6 | 25.4 | 16.7 | — |
| LCOE (Medium resource) | — | — | — | — | — | — | — | — | — | — | 20.1 | 23.6 | 20.5 | — |
| LCOE (Low resource) | — | — | — | — | — | — | — | — | — | — | 22.0 | 19.1 | 27.7 | — |
| **Commercial Rooftop PV (200 kW)** | | | | | | | | | | | | | | |
| LCOE (High resource) | 32.3 | 28.8 | 19.5 | 15.3 | 14.5 | 11.6 | 10.8 | 9.4 | 9.0 | 8.0 | 7.8 | 7.4 | 6.8 | — |
| LCOE (Medium resource) | 40.2 | 35.8 | 24.2 | 19.1 | 18.0 | 14.4 | 13.5 | 11.6 | 11.2 | 9.6 | 9.4 | 9.1 | 8.3 | 4.3 |
| LCOE (Low resource) | 43.3 | 38.6 | 26.1 | 20.5 | 19.4 | 15.5 | 14.5 | 12.5 | 12.0 | 10.7 | 10.5 | 9.8 | 11.2 | — |
| **Commercial PV-Plus-Storage** | | | | | | | | | | | | | | |
| LCOE (High resource) | — | — | — | — | — | — | — | — | — | — | 9.3 | 9.2 | 9.2 | — |
| LCOE (Medium resource) | — | — | — | — | — | — | — | — | — | — | 11.5 | 12.2 | 11.4 | — |
| LCOE (Low resource) | — | — | — | — | — | — | — | — | — | — | 12.3 | 14.3 | 15.6 | — |
| **Utility-Scale PV (100 MW One-Axis Tracking)** | | | | | | | | | | | | | | |
| LCOE (High resource) | 22.8 | 18.8 | 12.9 | 9.8 | 8.6 | 7.7 | 6.1 | 4.7 | 4.4 | 3.7 | 3.7 | 3.6 | 3.2 | — |
| LCOE (Medium resource) | 29.3 | 24.2 | 16.6 | 12.5 | 11.0 | 9.9 | 7.8 | 6.0 | 5.7 | 4.8 | 4.8 | 4.6 | 4.1 | 2.0 |
| LCOE (Low resource) | 31.8 | 26.3 | 18.0 | 13.6 | 11.9 | 10.7 | 8.5 | 6.5 | 6.2 | 5.2 | 5.2 | 5.0 | 5.5 | — |
| **Utility-Scale PV-Plus-Storage** | | | | | | | | | | | | | | |
| LCOE (High resource) | — | — | — | — | — | — | — | — | — | — | 6.5 | 6.9 | 6.0 | — |
| LCOE (Medium resource) | — | — | — | — | — | — | — | — | — | — | 8.5 | 8.9 | 7.7 | — |
| LCOE (Low resource) | — | — | — | — | — | — | — | — | — | — | 9.2 | 9.7 | 10.7 | — |

# Acronyms and Abbreviations

| | |
|---|---|
| AC | alternating current |
| BESS | battery energy storage system |
| BLS | U.S. Bureau of Labor Statistics |
| BOS | balance of system |
| CAPEX | capital expenditures |
| DC | direct current |
| DOE | U.S. Department of Energy |
| EPC | engineering, procurement, and construction |
| HVAC | heating, ventilating, and air conditioning |
| LCOE | levelized cost of energy |
| LCOS | levelized cost of storage |
| LCOSS | levelized cost of solar-plus-storage |
| Li-ion | lithium-ion |
| $MW_{AC}$ | megawatts alternating current |
| $MW_{DC}$ | megawatts direct current |
| NREL | National Renewable Energy Laboratory |
| O&M | operations and maintenance |
| OPEX | operating expenditures |
| PII | permitting, inspection, and interconnection |
| PV | photovoltaic(s) |
| Q | quarter |
| RTE | round-trip efficiency |
| SG&A | selling, general, and administrative |
| SOC | state of charge |
| USD | U.S. dollars |
| $V_{DC}$ | volts direct current |
| $W_{AC}$ | watts alternating current |
| $W_{DC}$ | watts direct current |

# Thank You

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