

Integrated Energy Systems Office Solar Photovoltaic System Cost Benchmarks

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Image courtesy of Michael Slider

Overview

Each year, the U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) and its national laboratory partners analyze cost data for U.S. solar photovoltaic (PV) systems to develop cost benchmarks. These benchmarks help measure progress toward goals for reducing solar electricity costs and guide SETO research and development programs. Read more to find out how these cost benchmarks are modeled and download the data and cost modeling program below.

Purpose and Scope

Market analysts routinely monitor and report the average cost of PV systems and components, but more detail is needed to understand the impact of recent and future technology developments on cost. Consequently, benchmark systems in the utility-scale, commercial, and residential PV market sectors are evaluated each year. Each benchmark system is representative of what is currently being installed in the United States and is defined in sufficient detail to assess the impact of system size, module efficiency, overhead, and many other factors on cost.

Unlike most PV cost studies that report values solely in dollars per watt, SETO's PV system cost benchmark reports values using intrinsic units for each component. For example, the cost of a mounting structure is given in dollars per square meter of modules supported by that structure. This measure is independent of how much power is produced by those modules, making it possible to assess the benefit of improving PV module efficiency (the structure's cost per module area is divided by the module's power output per module area to obtain the cost per watt for that structure when used with those modules). This approach is intended to allow any input parameter in the model to be varied by up to a factor of two (up or down) to assess its impact on cost.

All costs reported are represented two ways: Minimum Sustainable Price (MSP) and Modeled Market Price (MMP). MSP is the minimum price (with inflation adjustment) that a company can charge for its product or service in a balanced, competitive market and remain financially solvent for the long term, assuming that each of the company's input costs also represent the MSP for that cost element. MMP is the actual price in the current market, which may differ from MSP as a

result of temporary market distortions. MSP is the more useful metric for long-term planning, including R&D direction and predicting the future of the power grid. MMP is the more useful metric for short-term planning, including the impact of tax and trade policies.

Data Collection

Three DOE national laboratories—Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, and Sandia National Laboratories—collect cost data from PV industry stakeholders. Each stakeholder is contacted by only one lab to avoid overlap. The industry survey seeks to understand the cost structure for each stakeholder, including how their costs are affected by scale, overhead, and market distortions. Data collection focuses on transactions in the first quarter of the calendar year.

Each lab's data is analyzed by that lab and submitted to SETO along with a weighting factor that represents the number of independent data sources utilized for each cost element.

In addition to the cost of installing each benchmark system, the cost for operation and maintenance is also analyzed. The total cost over the service life of the system is amortized to give a levelized cost per year.

PV System Cost Model

In the PV System Cost Model (PVSCM), the owner's overnight capital expense (cash cost) for an installed PV system is divided into eight categories, which are the same for the utility-scale, commercial, and residential PV market segments:

1. **Module** – The cost to the installer of photovoltaic modules, as delivered.
2. **Inverter** – The cost to the installer of equipment for converting direct current (dc) to alternating current (ac), as delivered.
3. **Energy Storage System (ESS)** – The cost to the installer of adding an energy storage system, as delivered.

4. **Structural Balance of System (SBOS)** – The cost to the installer of structural balance of system components, as delivered.
5. **Electrical Balance of System (EBOS)** – The cost to the installer of electrical balance of system components, as delivered.
6. **Fieldwork** – The cost to the installer of work performed at the installation site.
7. **Office work** – The cost to the installer of work performed off-site.
8. **Other** – Costs incurred by the project developer not included elsewhere.

The first five categories are referred to as the **hardware cost** and the last three categories are referred to as the **soft cost**.

Each of the eight cost categories is divided into up to 12 cost elements. Each cost element is the sum of a fixed cost that is independent of size plus a variable cost that is proportional to size. The meaning of "size" depends on the category: the annual production rate of the manufacturing facility for Module, Inverter, and ESS; the rated capacity of the installed system for SBOS, EBOS, fieldwork, and office work; and the developer's annual system installation capacity for "Other." The variable cost is given in dollars per intrinsic unit, with the unit chosen that most directly scales with the size for that category.

The PVSCM system cost is the price paid by the system owner to the system developer. Any tax credit realized by the owner is excluded and must be considered separately. Tariffs paid on imported hardware are treated as temporary market distortions that increase MMP but not MSP. Subsidies for domestically produced hardware are also treated as temporary market distortions, which may decrease MMP but not MSP. Tariffs and subsidies are noted in the spreadsheet's comments column.

Working with PVSCM Data

PVSCM is implemented using an Excel spreadsheet. It collects the cost elements for each category, then sums the categories to obtain the system cost, for both MSP and MMP. Unit conversion multipliers are listed on a separate sheet labeled

"Factors." An additional sheet is used to calculate the cost of operation and maintenance (O&M).

[Download the PVSCM Excel Program and Cost Data \(Zip file\)](#)

Utility-Scale PV System (UPV)

Figure 1 presents the UPV benchmark system cost components by cost category for both MSP and MMP, without ESS. These values represent weighted average figures based on the data collected by all three participating national laboratories. Details, including ESS and O&M, are available in the [PVSCM model](#) using the UPV 2024Q1.txt parameter file.

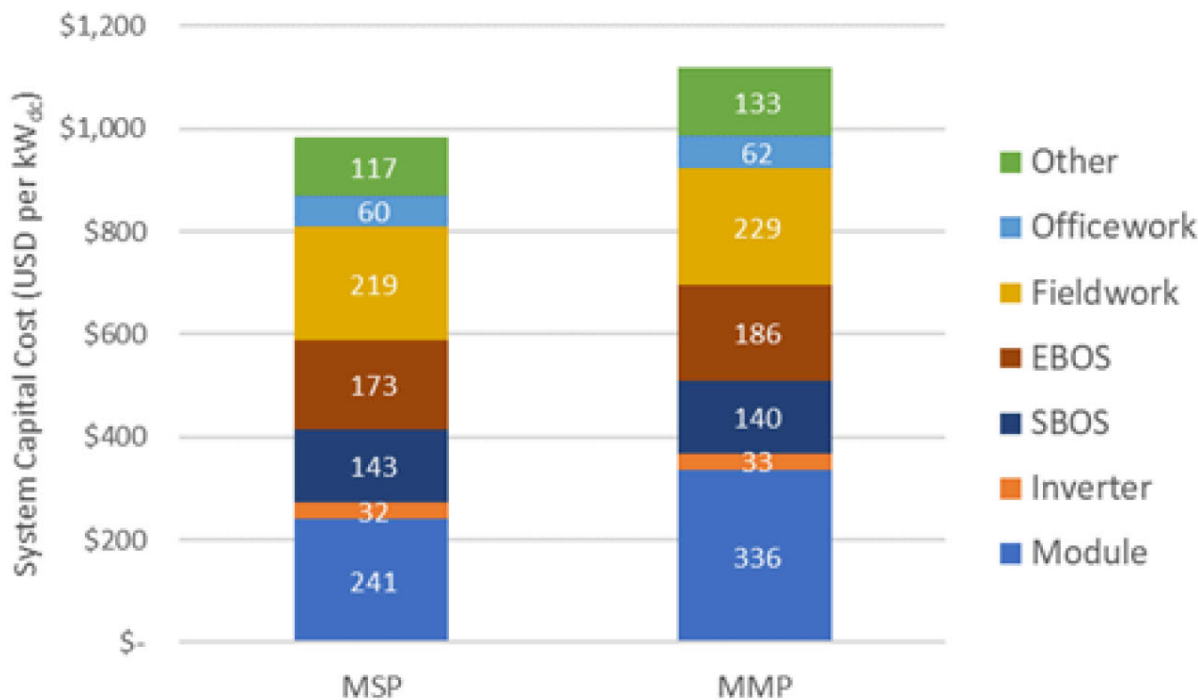


Figure 1: Benchmark Utility-Scale PV System Costs (No ESS).

Representative UPV System Description

Commercial (Agrivoltaics) PV System (APV)

Figure 2 presents the APV benchmark system cost components by cost category for both MSP and MMP, without ESS. These values represent weighted average figures based on the data collected by all three participating national laboratories. Details, including ESS and O&M, are available in the [PVSCM model](#) using the APV 2024Q1.txt parameter file.

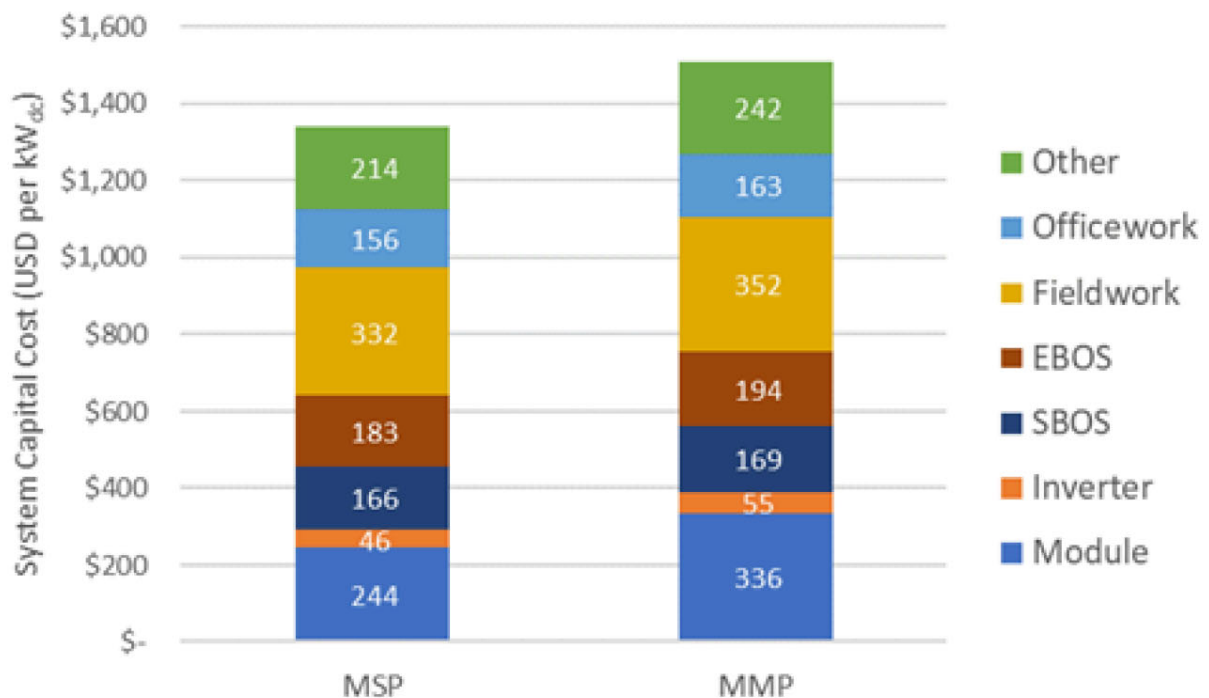


Figure 2: Benchmark Agrivoltaics System Costs (no ESS).

Representative APV System Description

Residential Rooftop PV System (RPV)

Figure 3 presents the RPV benchmark system cost components by cost category for both MSP and MMP, without ESS. These values represent weighted average figures based on the data collected by all three participating national laboratories. Details, including ESS and O&M, are available in the [PVSCM model](#) using the RPV 2024Q1.txt parameter file.

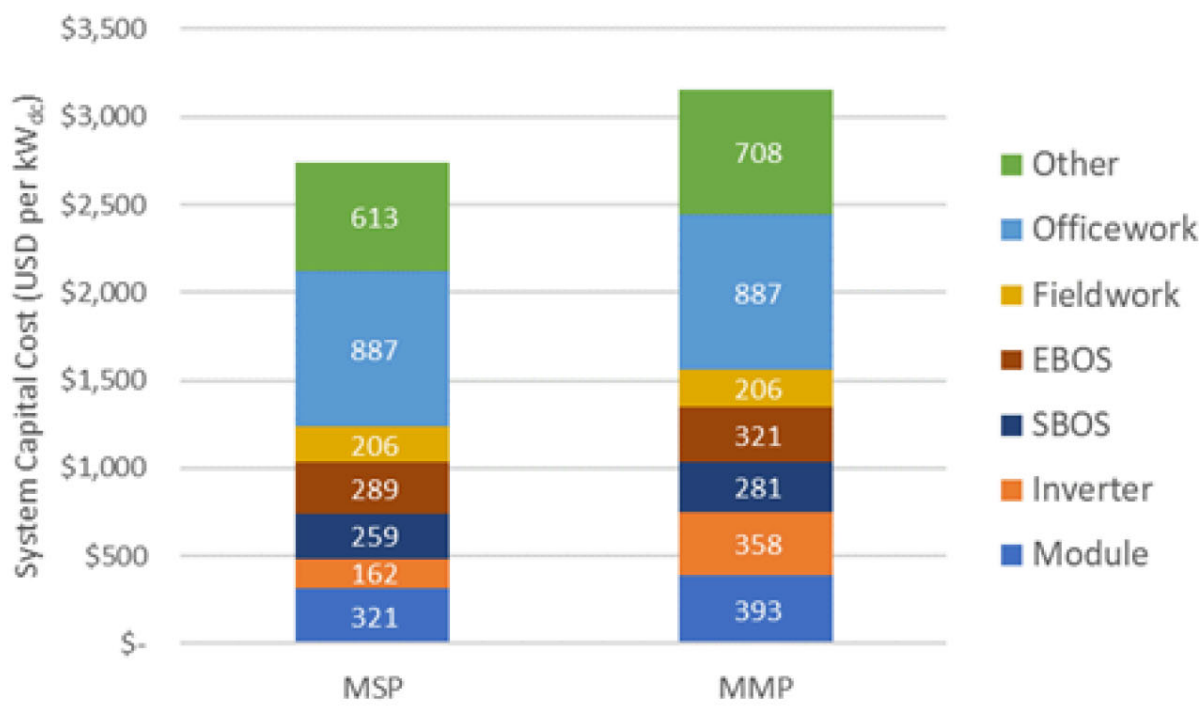


Figure 3: Benchmark Residential System Costs (no ESS).

Representative RPV System Description

Levelized Cost of Electricity (LCOE)

LCOE Calculation Details

The following tables summarize this year’s cost benchmarks and resulting LCOE values, for PV-only systems and for PV+ESS. All dollar values are inflation-adjusted to 2023 U.S. dollars (CPI-U=304.7).

These benchmark LCOE values do not reflect any system-level subsidies, which reduce the effective LCOE in proportion to the subsidy percentage. LCOE is lower than the value listed in these tables in locations with more annual sunshine (30% less in the desert southwest), and higher in regions with less annual sunshine (30% more in the Pacific northwest).

Table 1. 2024Q1 PV Cost and LCOE Benchmarks

Type	PV System	MSP	MMP	O&M	LCOE
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	Size				
UPV	100 MW _{dc}	\$0.98/W _{dc}	\$1.12/W _{dc}	\$19/kW _{dc} - yr	\$47/MWh
APV	3 MW _{dc}	\$1.34/W _{dc}	\$1.51/W _{dc}	\$22/kW _{dc} - yr	\$75/MWh
RPV	8 kW _{dc}	\$2.74/W _{dc}	\$3.15/W _{dc}	\$30/kW _{dc} - yr	\$142/MWh

Table 2. 2024Q1 PV+ESS Cost and LCOE Benchmarks

Type	PV System Size	ESS Size	MSP	MMP	O&M	LCOE
UPV	100 MW _{dc}	240 MWh	\$1.73/W _{dc}	\$1.99/W _{dc}	\$48/kW _{dc} - yr	\$94/MWh

APV	3 MW _{dc}	6 MWh	\$1.99/W _{dc}	\$2.28/W _{dc}	\$43/kW _{dc} -yr	\$126/MWh
RPV	8 kW _{dc}	13.5 kWh	\$4.50/W _{dc}	\$5.19/W _{dc}	\$70/kW _{dc} -yr	\$264/MWh

Figure 4 illustrates this year's benchmark LCOE values for both PV and PV+ESS. For comparison, the corresponding LCOE value for each type of system in 2020 and 2023 are shown. Note the benchmark commercial system in 2023 was a community-solar system, whereas in 2024 it was an agrivoltaics system.

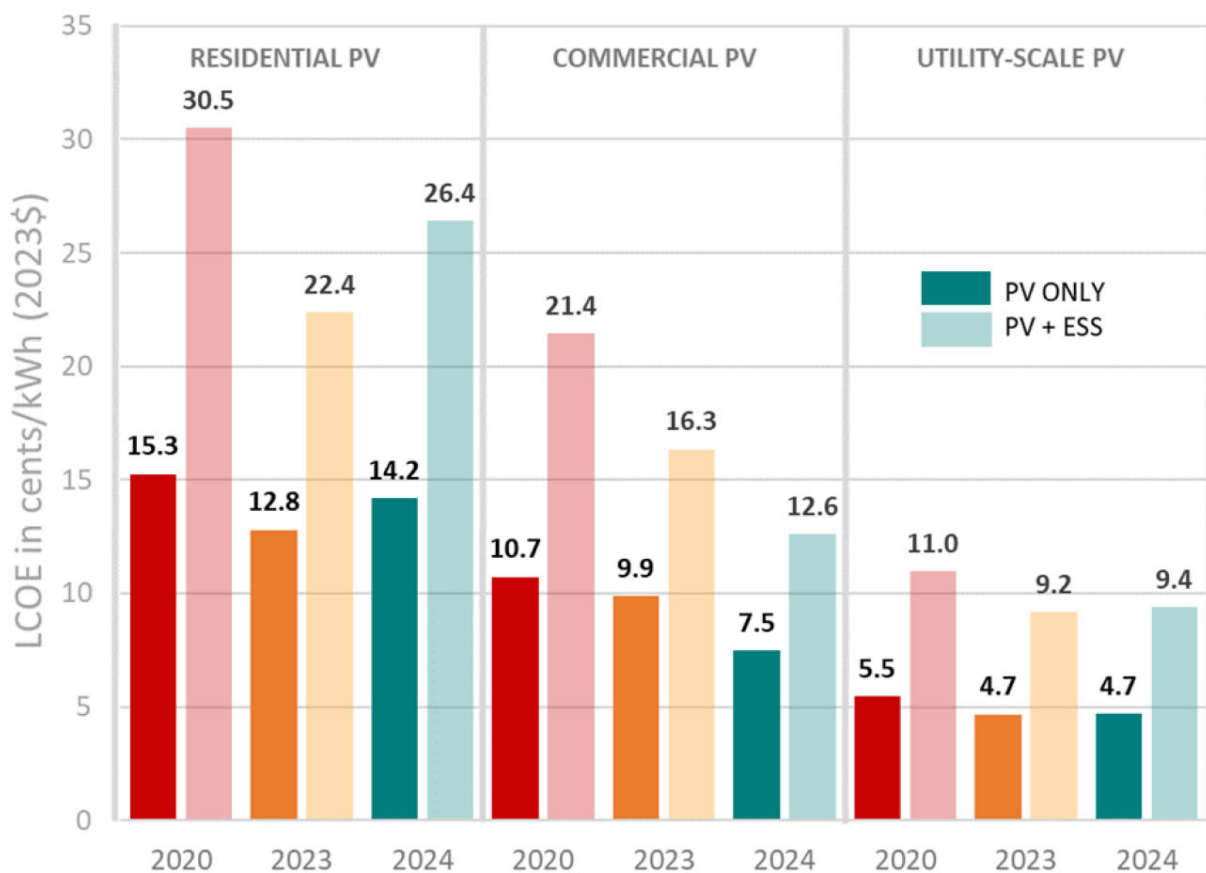


Figure 4. Levelized cost of electricity (LCOE) for representative systems installed in an average U.S. climate without deductions for federal,

state, or local incentives. All costs have been inflation-adjusted to 2023 U.S. dollars.

Contributors

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