NREL Benchmarks the Installed Cost of Residential Solar Photovoltaics with Energy Storage for the First Time

Rooftop solar photovoltaic (PV) systems have proliferated in the United States in recent years—presenting many benefits, but also significant challenges. One challenge is the variable nature of PV generation: unlike electricity from conventional technologies, such as coal or nuclear power plants, electrical output from PV systems varies with changes in cloud cover and the daily rising and setting of the sun. As the amount of PV in the United States continues to grow, strategies will be needed to integrate this variable generation efficiently with the electrical grid while maximizing value to electricity providers and consumers. Energy storage technologies installed in conjunction with PV at individual homes are a promising approach—but cost and value barriers currently hinder the large-scale deployment of residential PV-plus-storage systems.

New National Renewable Energy Laboratory (NREL) research fills a gap in the existing knowledge about barriers to PV-plus-storage systems by providing detailed component- and system-level installed cost benchmarks for systems in the first quarter of 2016. The report is meant to help technology manufacturers, installers, and other stakeholders identify cost-reduction opportunities and inform decision makers about regulatory, policy, and market characteristics that impede PV-plus-storage deployment.

Research Methods

To analyze PV-plus-storage component costs and system prices, we adapt NREL's component- and system-level bottom-up cost-modeling approach for standalone PV. We account for all component and project-development costs incurred when installing residential systems, and we model the cash purchase price for such systems, excluding the federal investment tax credit. Costs are represented from the perspective of the installer; thus, all hardware benchmarks represent the price at which components are purchased by the installer. Importantly, we also apply a 17% fixed margin to all direct costs to model the sustainable sales price paid by the end user to the installer. This 17% fixed margin is referred to as "net profit" and is added to total installed costs as a separate category. We do not include any additional price gross-up or adders, which are common in the marketplace today. We use this approach because of the wide variation in installer profits[1] in the residential sector, where end-user pricing is highly dependent on region and project specifics such as local retail electricity rate structures, local rebate and incentive structures, competitive environment, and overall project or deal structures. In addition to our original analysis, model development, and review of the published literature, we derive inputs for our model and validate our results via interviews with industry and subject-matter experts.

One challenge to analyzing component costs and system prices for PV-plus-storage installations is choosing an appropriate metric. Unlike standalone PV, energy storage lacks a standard set of widely accepted benchmarking metrics, such as dollars-per-watt of installed capacity or levelized cost of energy. We address this issue by using the total installed price of a standard PV-plus-storage system as our primary metric, rather than using a metric normalized to system size.

Residential PV-Plus-Storage System Configurations

Here, system configuration refers to four characteristics that determine a PV-plus-storage system's functionality:

- PV system capacity (in kilowatts, kW)
- Battery energy capacity (in kilowatt-hours, kWh)
- Battery power capacity (in kW)
- Whether the battery is direct-current (DC) or alternating-current (AC) coupled.

1 Profit is one of the differentiators between "cost" (aggregated expenses incurred by an installer to build a system) and "price" (what the end user pays for a system).

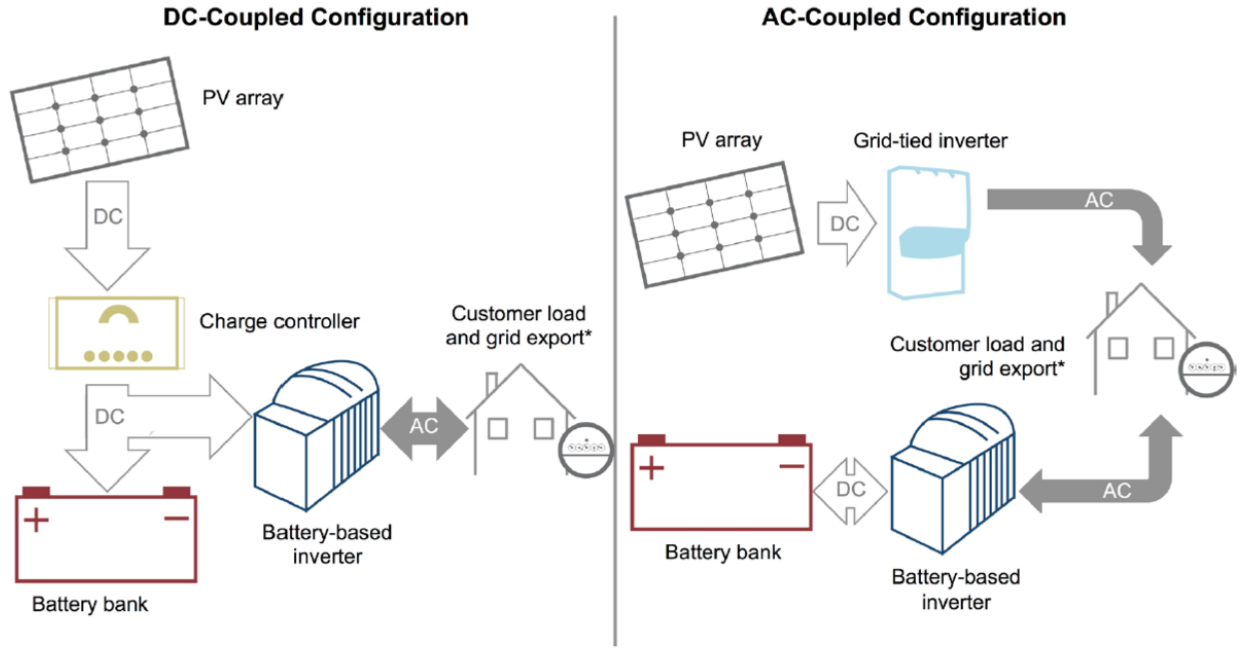

Figure 1: Modeled DC- and AC-coupled system configurations (simplified for illustrative purposes)

Customer preference for specific characteristics is based on several factors, including cost, load profile, and planned use of the system for load shifting (storing energy in one period for use in a later period). In general, customers who have loads with high peaks of short duration may desire a high-power (kW) battery capable of meeting the high peak. Customers who have flatter loads with lower peaks of longer duration may prefer a high-energy (kWh) battery capable of longer-duration energy discharge.

A PV array, a battery, and a battery-based inverter are the fundamental components of all PV-plus-storage systems. Additional component requirements are determined by whether the system is DC or AC coupled[2]: a DC-coupled system often requires a charge controller to step down the PV output voltage to a level that is safe for the battery, whereas an AC-coupled system requires a grid-tied inverter to feed PV output directly to the customer's load or the grid **(Figure 1)**. Importantly, our modeled DC-coupled system includes a bi-directional, battery-based inverter, because interviewees indicated that most DC-coupled systems today are installed with bi-directional inverters. However, a DC-coupled system does not necessarily require a bi-directional inverter unless the battery will charge from an AC power source such as a backup generator or grid electricity.

Each step in the energy paths illustrated in Figure 1 is associated with a power conversion and an associated efficiency loss. In other words, efficiency declines as the number of power conversions increases. The number of steps in the energy paths of DC- and AC-coupled systems varies depending on the primary use of the system. Based on the current state of technology, AC-coupled systems are generally more efficient in applications where PV energy is mostly consumed at the time of generation, and DC-coupled systems are more efficient in applications where PV energy is mostly stored for use at a later time. Technological improvements to eliminate the need for the charge controller or increase the efficiency of battery-based inverters could reduce the efficiency gap between DC- and AC-coupled systems in PV consumption applications.

2 Our discussion is simplified to explain the basic technical differences between AC- and DC-coupled systems. However, the decision to use AC or DC coupling might also be driven by non-technical factors such as policy, contractual obligations, and economics.

Installed Cost Benchmark Results

We present results for two grid-tied system applications, which we refer to as the "small-battery case" and "large-battery case," in addition to several typical system configurations. The small-battery case—which uses a 5.6-kW PV array and a 3-kW/6-kWh lithium-ion battery system—is designed to provide backup power for a limited number of critical loads in the event of a grid outage and enable a typical customer to optimize self-consumption of PV electricity, including peak-demand shaving and time-of-use shifting.[3]

Figure 2 shows our benchmarking results for the small-battery case, including new DC- and AC-coupled systems (when PV and storage are installed simultaneously) and AC-coupled systems with the storage system retrofitted after the PV array. **The benchmarked price of each of these battery-coupled systems is about twice as high as the price of a standalone 5.6-kW PV system.** The DC-coupled system price ($27,703) is $1,865 lower than the AC-coupled system price ($29,568) for a new PV-plus-storage installation. The price premium for AC-coupled systems is mainly due to higher hardware, labor, and sales and marketing costs associated with the additional grid-tied inverter and more complex system design and engineering requirements. The installed price is $32,786 for an AC-coupled system when the battery is retrofitted to an existing PV array, which is $3,218 higher than the price of installing the PV and storage simultaneously.[4] The simultaneous installation results in savings related to installation labor and electrical wiring as well as indirect costs (supply-chain costs, overhead, regulatory costs, and profit).

3 Generally, as net-metering rates decline, the economics of using residential PV-plus-storage systems for self-consumption improve. Although currently only a small number of residential demand charges and time-of-use tariffs exists, as states move away from full retail-rate net metering (e.g., in Hawaii and Nevada) and as utilities implement residential time-of-use pricing (e.g., in California and Illinois), we anticipate that the economics of PV-plus-storage for self-consumption will become increasingly competitive.

4 We do not model the costs of adding a DC-coupled battery to an existing PV system, because this configuration is not commonly deployed owing to required inverter and associated wiring replacement and potential for violation of ownership agreement terms for third-party-owned systems.

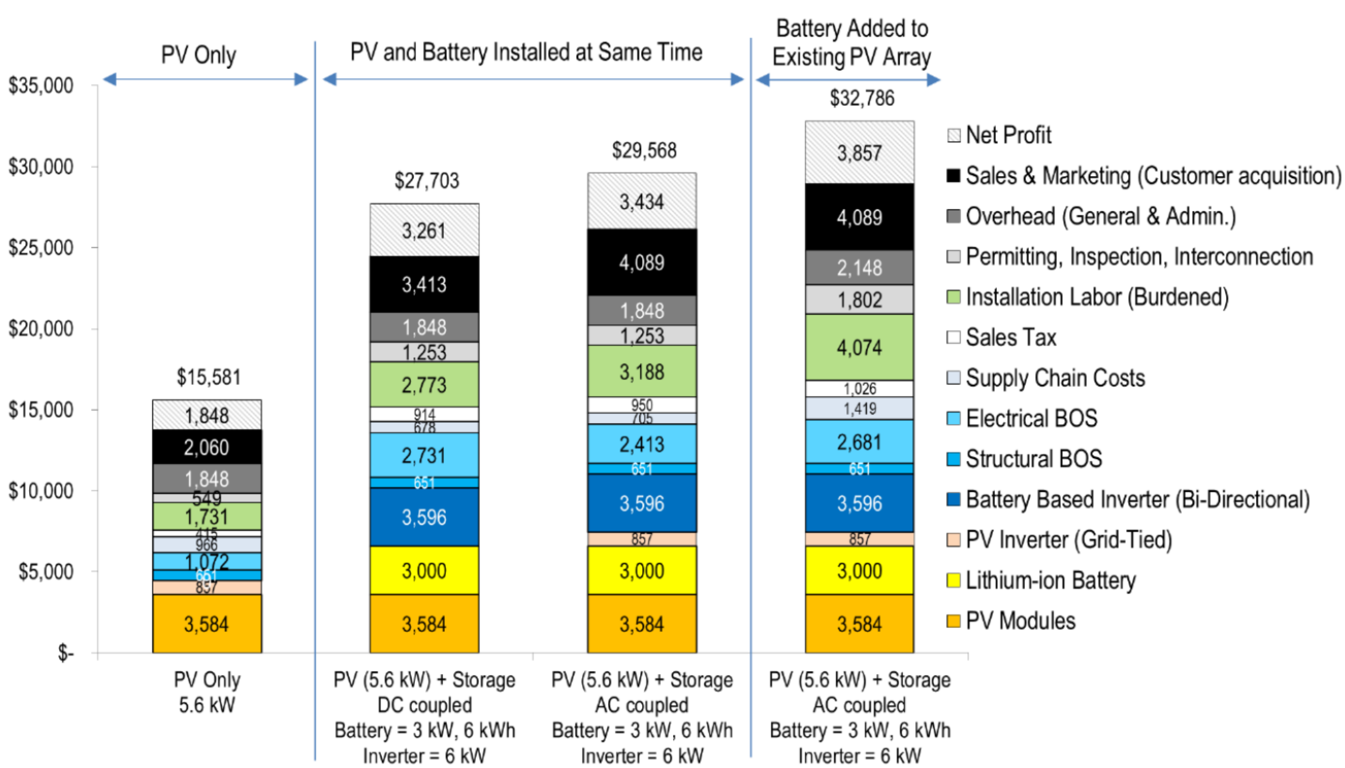

Figure 2. Modeled total installed cost and price components for residential PV-plus-storage systems, small-battery case (2016 U.S. dollars)

The large-battery case—which uses a 5.6-kW PV array and a 5-kW/20-kWh lithium-ion battery system—is designed to meet greater backup power (kW) and energy (kWh) requirements in the event of a grid outage and enable a typical customer to optimize self-consumption of PV electricity, including peak-demand shaving and time-of-use shifting **(Figure 3). With DC coupling, the price of the large-battery system is $45,237, which is $17,534 (63%) higher than the small-battery system price.** With AC coupling, the price of the large-battery system is $47,171, which is $17,603 (60%) higher than the small-battery system price. The premium is due to the larger systems' higher battery, inverter, balance of system (BOS), and labor costs, plus indirect costs (profit, sales tax, and supply-chain costs).

Hardware costs constitute about half the total price of our modeled small-battery systems. The largest single hardware cost for these systems is the 6-kW battery-based inverter ($3,596), followed by the PV array ($3,584) and the lithium-ion battery ($3,000). **For our large-battery systems, hardware costs constitute about 60% of the total price,** with the $10,000 battery dominating the hardware cost contribution, followed by electrical BOS ($4,826–$5,463) and the 8-kW battery-based inverter ($4,795). The ranking of soft cost contributions varies by system configuration/application, with major contributions for all systems from net profit, sales and marketing, and installation labor.

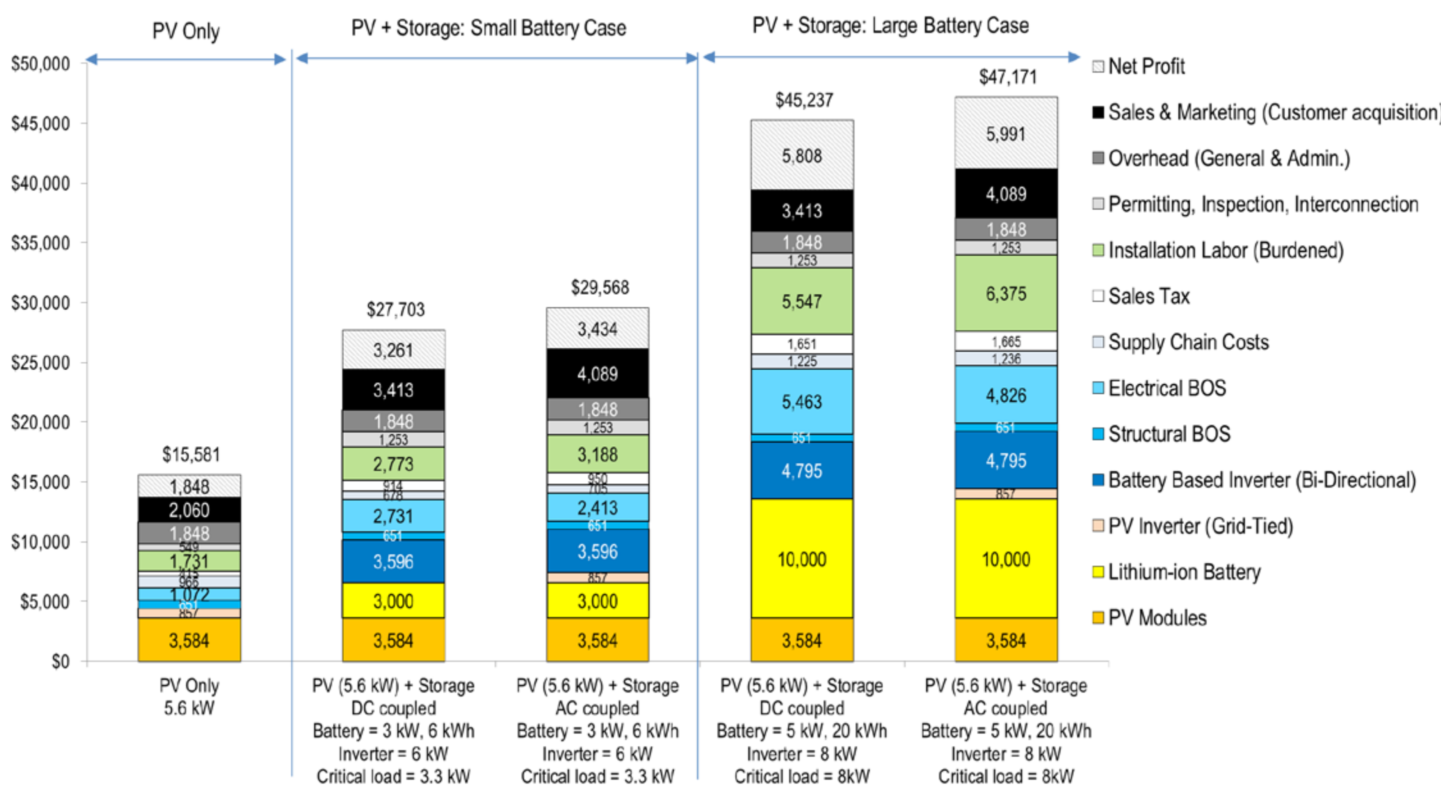

Figure 3. Modeled total installed cost and price components for residential PV-plus-storage systems, small-battery case vs. large-battery case (2016 U.S. dollars)

Conclusions and Future Work

Our modeling helps quantify the component cost and system price barriers to deployment of residential PV-plus-storage. NREL benchmarks represent the technologies most commonly deployed in the United States to date, on a national average basis. Likely future opportunities for cost reduction include the widespread adoption of new, lower-cost products and the streamlining of permitting and interconnection approval processes. In the full report, we also examine barriers beyond what we captured in the modeling described above, including those related to net-metering requirements, inadequate valuation of the benefits of storage, constrained government incentives, and flat utility rates. As we continue to benchmark PV-plus-storage component costs and system prices, we will incorporate insights into these barriers to refine our modeling while building a better understanding of the value barriers to deployment. Finally, future work will include a more comprehensive approach to analyzing the combination of PV and storage, moving beyond electrical battery storage alone to consider a wide range of options that enable energy storage and dispatch, such as controllable domestic water heaters and controllable heating, ventilation, and air-conditioning systems.

This work is supported by the U.S. Department of Energy's SunShot Initiative. The analysis is based on projections, estimates, or assumptions made on a best-effort basis, based upon present expectations.

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Ardani, K., E. O'Shaughnessy, R. Fu, C. McClurg, J. Huneycutt, and R. Margolis. 2016. *Installed Cost Benchmarks and Deployment Barriers for Residential Solar Photovoltaics with Energy Storage: Q1 2016*. NREL/TP-7A40-67474. Golden, CO: National Renewable Energy Laboratory. *www.nrel.gov/docs/fy17osti/67474.pdf*.

Questions

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NREL/BR-7A40-68282 • June 2017