Energy Storage for PV Power

Photovoltaic (PV) power is one of the fastest growing renewable energy tech¬nologies today. Because of the intermittent nature of PV electrical output, energy storage will be an important enabler for its continued growth. Of the candidate storage technologies, electrochemical batteries hold the most promise for widespread deployment. Development of economical, scalable PV energy storage systems is being actively pursued across a range of battery technologies, from lead-acid to lithium-ion to redox flow batteries.

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PV is unique among electricity generation technolo¬gies. It requires no consumable fuel and often involves no moving parts, generating emissions-free electricity with relatively low operation and maintenance costs, even in remote locations. In addition, PV is highly mod¬ular and scalable, with installations ranging from watt-scale solar-powered garden lights up to megawatt-scale solar farms producing wholesale electricity. However, PV is inherently variable and intermittent: the power output varies throughout the day as the angle of inci¬dence changes, decreases rapidly if a cloud passes over¬head, and drops to zero at night.

PV systems can be divided into two categories: stand-alone and grid-connected (also known as utility-inter¬active). Stand-alone systems are used where a utility connection would be uneconomical or inconvenient; examples include buildings or groups of buildings in remote locations, as well as single-device systems such as solar-powered highway displays, outdoor lights, com¬munication relay towers, and irrigation pumps. Grid-connected PV includes systems both "behind the meter" (on the customer side) and "in front of the meter" (on the utility side). Residential PV systems, for example, are behind the meter; large solar farms are in front of the meter.

In all of these applications, there are essentially three approaches to handling the uncontrollable variation in electricity produced by PV. These three approaches are routinely used in combination with one another.

The first approach is to modulate the electrical load to match the variation in produced electricity. In the case of a stand-alone PV system powering an irrigation pump, for example, it may be acceptable for the pump to run only when there is sufficient sunlight. For a util¬ity-scale solar farm, the analogous solution is demand response (DR), where certain utility customers are incentivized to cut load in response to temporary elec¬tricity scarcity. Customers using thermal energy storage, discussed in previous Emerging Technologies columns [1] are particularly well-suited to participate in DR.

The second approach to intermittency is to use an alternative generation source to make up the difference between PV generation and total load. A stand-alone sys¬tem powering a remote research facility, for example, might use a conventional diesel generator in conjunc¬tion with a PV installation. At the utility scale, a natural gas combustion turbine power plant (capable of ramping generation up and down relatively quickly) could be dis¬patched to make up for a drop in the output of a solar farm.

The third approach is to use energy storage to absorb excess electricity and release it when needed, thereby smoothing out the variations in the PV sys¬tem output. In general, storage is less inconvenient to the end user than DR, and cleaner than supplemental conventional generation. Most stand-alone PV systems incorporate storage, and implementing grid-connected storage economically is a develop¬ment challenge currently being aggressively funded by by both the govern-ment and private sector.

As grid penetration of variable energy resources (wind and solar) approaches 20% to 30%, grid-scale storage will become a necessity [2]. As of this writing, the U.S. DOE is work¬ing on a commercialization roadmap for energy storage technologies, due to be released in October 2013, with the intent to enable higher penetra¬tions of wind and PV [3].

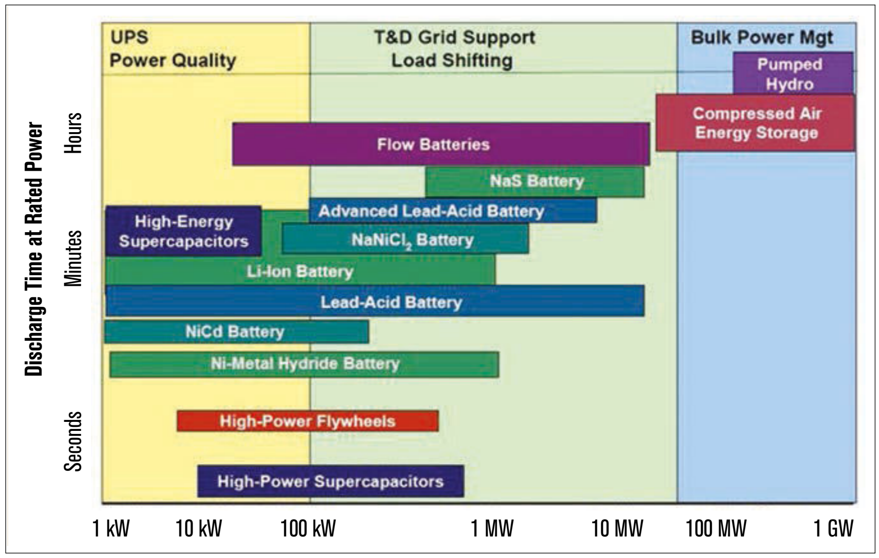
As shown in Figure 1, a number of candidate technologies can be used for energy storage [4] At the utility scale, pumped hydro and compressed air energy storage (CAES) are mature and economically attractive technolo-gies for bulk stor¬age. Pumped hydro uses excess electricity to transfer water from one reservoir to a higher elevation reservoir. During system discharge, the water flows back down to the lower reservoir through a hydroelectric turbine, regenerating the electricity.

CAES, which is much less common, uses a roughly analogous process, forcing air into an enclosed cavern during system charge, and releasing it through a com¬bustion turbine during discharge. Neither pumped hydro nor CAES is practical at smaller scales, and both require sites with specific geological and topographical characteristics. Pumped hydro requires a steep elevation gradient and suitable reservoir sites at both high and low elevations, while CAES requires a large natu-rally occur-ring cavern, or a salt formation into which a cavern can be easily mined.

Flywheels, which store energy in high-speed rotat¬ing masses, and supercapacitors, which are electrical charge-storage devices, are able to absorb and release comparatively large amounts of energy over very short timescales. These technologies are useful to utilities for smoothing momentary mismatches between electricity supply and demand, but they are not well suited to lon¬ger-term storage. That leaves the electrochemical storage tech-nologies—batteries—as generally the best suited to handling intermittent PV output. Their response times are fast, they have good scalability, and they have no unusual siting constraints.

As Figure 1 shows, there are many battery architec¬tures and chemistries, but three fami-lies are particu¬larly appropriate for stationary PV storage: lead-acid, rechargeable lithium-ion, and redox flow batteries.

Lead-acid batteries currently predominate in residen¬tial-scale PV battery systems. They have the advantages of low cost (~$150/kWh) and well-established manufactur-



-Figure 1- Summary of energy storage technologies. Comparisons are very approximate, intended for conceptual purposes only—many of these technologies cover broader areas than shown on chart [4]

ing, distribution and recycling networks. The envi¬ronmental footprint of lead-acid manufacturing is high, however, and the cycle life (the number of times the bat¬tery can be charged and discharged) is limited, especially when used at high ambient temperatures or with deep charge/discharge cycles [5]. Depending on the lifetime of the system in question, lead-acid batteries may have to be replaced periodically.

Despite their long heritage, lead-acid bat-teries are still the subject of R&D to lower costs, increase cycle life, and improve power characteristics. One important set of lead-acid innovations involves the addition of carbon-based materials to enhance performance [6].

Rechargeable lithium-ion batteries, widely used in portable devices, are beginning to be used for stationary storage applications as well. There are many different Li-ion chem-istries, each with specific power vs. energy characteristics. Compared to lead-acid, the energy density of Li-ion batteries is several times higher (by both weight and volume), and the cycle life is longer as well; this means smaller footprints, lower transport and instal-lation costs, and less system maintenance. Particularly for systems sited in remote areas, these can be compel¬ling advantages.

The cost of Li-ion is still sig¬nificantly higher than lead-acid (~$500/kWh), but substantial R&D funding, from both DOE and the private sector, is being devoted to lowering that cost. One recent example of a large-scale Li-ion storage facility is the 5 MW system con-structed in South Salem, Ore., as part of a DOE microgrid demonstration project [7].

Redox flow batteries resemble rechargeable fuel cells. The electrodes are inert, while the active chemicals remain in liquid electrolytes that are stored in tanks external to the cell itself. During charge or discharge, the electro-lytes are pumped continuously through the cell, maintaining a fresh supply of the required chemicals. The energy density of flow batteries is low compared to Li-ion, and the technology is less mature, having so far been pro¬duced commercially on only a small scale. System reliability, performance and cost are areas of active research [8].

Flow batteries are promising for stationary power applications in that both power and energy are highly—and independently—scal-able. Increasing the number of cells in the battery increases power capacity, while simply increasing the size of the electrolyte storage tanks increases the energy capacity. A num¬ber of start-up companies are pursu-ing commercialization of flow batteries with various chemistries, including vana¬dium, iron-chromium, and zinc-bromine.

ENERGY SAVINGS

Electrochemical energy storage is a critical component of widespread PV deployment, and wind deployment as well. As such, it has the potential to indirectly enable conven-tional primary energy savings on the order of quads. In a more literal sense, though, storage actually outputs less electrical energy than originally used to charge the system. This round-trip efficiency (the ratio of the electric-ity out to the electricity in) is an important metric for any storage technology; Table 1 shows approximate ranges for the technolo-gies discussed previously.

MARKET POTENTIAL

PV is growing fast, and is projected to play a major role in global electricity production in the future. Policy incentives such as feed-in tariffs and tax breaks helped drive the global installed PV capacity from less than 2 GW in 2000 to more than 65 GW at the end of 2011, a growth rate of 44% per year [9] The growth of PV has also been helped by the decreasing price of PV panels, which has dropped from about $10/W in 2001 to a current average of $3.37/W [10].

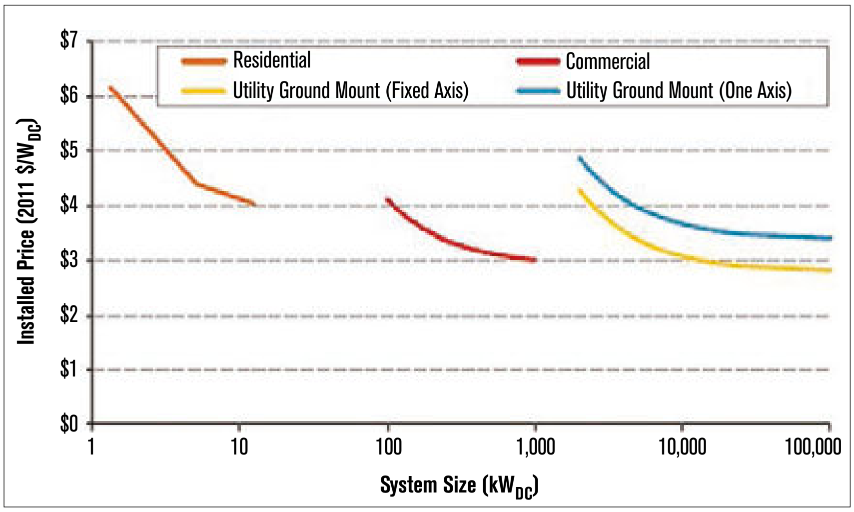
While large PV installations ben¬efit from economies of scale due to lower per-watt proj¬ect overhead costs and greater purchasing power (Figure 2), residential installations remain popular. According to the Solar Energy Industries Association, 164 MW of residential PV was installed in Q1 of 2013, vs. 318 MW of utility PV [10]. Currently, most grid-connected residential PV systems operate without on-site energy storage.

Under "net-metering" schemes for behind-the-meter PV, the customer gets credit for any excess power fed back to the grid, which offsets the cost of power drawn from the grid when the PV output is insufficient for the building load. This essentially reimburses the customer at the retail price of electricity, so apart from the benefits of emergency power backup and the psychological satisfaction of self suf¬ficiency, there is no motivation to install on-site storage.

Under "hourly netting" behind-the-meter schemes, however, the customer is reimbursed at the hourly wholesale price of electricity. This creates an economic incentive for on-site storage: electricity stored and used later is replacing electricity that would have been pur¬chased at the retail price [11]

In Germany, such decreasing feed-in tariffs, combined with rising electricity prices and a recently introduced subsidy for residential storage, are expected to kick start demand for small-scale storage systems, according to a recent report by IHS, a provider of global market and economic information [13].

The report predicts a global cumulative installed resi¬dential PV storage capacity of 2,500 MW by 2017, up from only 12 MW in 2012. The same report also forecasts an uptick in utility-scale PV storage installations, resulting in a total annual market for grid-connected PV storage of nearly 6000 MW by 2017.



-Figure 2- Economy-of-scale benefits: residential and commercial rooftop, ground-mount utility-scale

TECHNOLOGY	ROUND-TRIP EFFICIENCY
Pumped Hydro	~80%
Compressed Air Energy Storage	45% – 80%
Flywheels	~85%
Lead-Acid Batteries	85% – 90%
Lithium-Ion Batteries	80% – 90%
Flow Batteries	60% – 75%

-Table 1- Approximate round trip efficiencies for advanced energy storage technologies [4]

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