Resilient Solar Photovoltaics (PV) Systems

Introduction

The NYSolar Smart Distributed Generation (DG) Hub is a comprehensive effort to develop a strategic pathway to a more resilient distributed energy system in New York that is supported by the U.S. Department of Energy and the State of New York. This DG Hub fact sheet provides information to installers, utilities, policy makers, and consumers on resilient PV hardware and design. For information on other aspects of the resilient PV market, please see the companion factsheets on solar+storage economics, policy, and a glossary of solar+storage terms at: www.cuny.edu/DGHub.

What is Resilient PV?

Resilient PV is solar energy that is coupled with technology that allows it to continue to provide power during grid outages. Currently, traditional PV systems are configured to shut down during grid interruptions. This configuration protects the safety of utility workers. However, solar can continue to function and provide power during grid outages if configured for resiliency.

There are three standard ways to make PV resilient:

1. Pairing the solar modules with batteries to store energy for later use, known as PV with battery back-up.
2. Pairing solar with auxiliary generation like a diesel generator.
3. Utilizing an inverter with an emergency power outlet that provides limited power when the sun is shining.

This fact sheet will focus on PV with battery back-up, providing details on the key components of the system, including solar arrays, batteries, charge controllers, and inverters. It also presents key hardware barriers for PV with battery back-up and offers a few case studies to demonstrate the importance of resilient PV.

PV with Battery Back-up

PV with battery back-up can function as both a stand-alone or grid-connected system, providing emergency power when the grid is down, and economic benefits when grid-connected.

System Design

Design of PV with battery back-up is described in terms of how the battery back-up is integrated into the system. Solar modules and batteries typically generate and use direct current (DC) electricity. However, most appliances and the grid typically use alternating current (AC) electricity. DC energy must therefore go through an inverter to be converted into AC energy for use by appliances and the grid. Battery back-up can be integrated into the system on either the DC (DC-coupling) or AC (AC-coupling) side of the system. The majority of new resilient PV systems use a DC-coupled configuration when solar is not already in place. Figure 1 on page 2 illustrates a typical DC-coupled, grid–tied configuration. Existing systems that are retrofitted with battery back-up tend to use an AC-coupled design. Figure 2 on page 4 shows a typical AC-coupled, grid-tied configuration).

System Components

This section focuses on the various components of PV and battery back up storage systems.

Solar Array

Solar PV arrays generate on-site DC energy. Traditional solar cells are made from mono- or poly-crystalline silicon, and generally are the most efficient. Thin-film solar cells are made from amorphous silicon or non-silicon materials such as cadmium telluride, and are less efficient yet often less expensive (NREL June 2015).

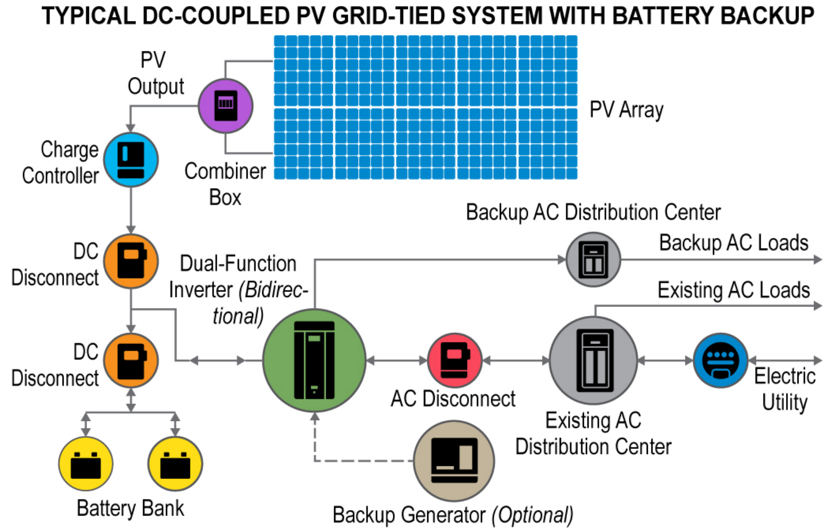

Figure 1. Typical components of a PV+ storage system (DC-coupled)

Batteries

Batteries store energy in DC form. Their life span is dependent on battery type, the percent of discharge, and the number of charge and discharge cycles it performs.

While there are many different battery types and chemical compositions, this section will focus on the two main, commercialized types of batteries used in resilient PV systems: **lead-acid** and **lithium-ion** batteries. **Flow** batteries, though less common for this application, will also be addressed.

Choosing a battery that is both economical and provides sufficient emergency power can be challenging and depends on a number of factors, including:

- cost
- energy density (size)
- cycle life
- thermal stability/safety

Batteries Commonly Used for PV with Battery Back-up

Lead Acid: Lead-acid batteries have been commercially available since the 1800's. There are two main types of lead-acid batteries: vented lead-acid (VLA) batteries and valve regulated (VRLA). VLA, or flooded, batteries require that water be routinely added to the batteries to maintain the system. The VRLA, or sealed batteries, require less maintenance than the VLA and eliminate the threat of an acid spill due to their sealed design (Sandia 2013). Deep-discharge VRLA are specially designed for stationary solar electric systems. A deep-cycle battery can be discharged down to 45%-75% of its rated capacity. Carbon-enhanced VRLA, currently in development, provide increased efficiency and offer a potential low-cost high-performance energy storage solution for grid scale applications.

Lithium Ion (Li-ion): Li-ion batteries are a much newer technology, commonly used in the electric vehicle and stationary storage markets. Li-ion is used where light weight and high energy density are of prime importance, such as a building with space constraints. There are different types of Li-ion systems that are generally defined by various cathode chemistries that affect performance, longevity, safety, and cost (Battery University, 2015). The characteristics of the following five types of Li-ion batteries will be compared in the table on page 3:

- lithium iron phosphate (LFP)
- lithium nickel manganese cobalt oxide (NMC)
- lithium nickel cobalt aluminum oxide (NCA)
- lithium manganese oxide (LMO)
- lithium titanate (LTO)

Of the five Li-ion battery candidates, none show a significant advantage over the others. Focusing on one strong attribute like energy density may compromise another, like safety (which is the case with NCA). LTO is generally considered the

Battery Comparison Table

Specifications	Battery Chemistries						
	Lead Acid	Lithium-Ion					Flow Batteries
	VRLA (Deep-Cycle)	LFP	NMC	NCA	LTO	LMO	Redox
Usage[1]	Resiliency, Grid Support, Peak load shifting, Intermittent energy smoothing, UPS	Resiliency, Grid Support, Peak load shifting, Intermittent energy smoothing, UPS					Resiliency, Grid Support, Peak load shifting, Intermittent energy smoothing, UPS, Bulk power management
Energy density (Wh/kg)	30-50	90-120	150-220	200-260	70-80	100-150	10-20
Lifetime cycles (80% depth of discharge)	50-100[7]	1000-2000	1000-2000	500	3000-7000	300-700	10,000+
Efficiency (%)	85-90[2]	90-95	90-95	90-95	90-95	90-95	65-85
Charge rate	8-16 hrs[1]	2-4 hrs	2-4 hrs	2-4 hrs	1-2 hrs	1-2 hrs	Depends on size of tanks & cell stack[5]
Cost	$150-300/kWh[4, 7]	$400/kWh[7]	$428-750/kWh[3, 6]	$240-$380/kWh[3, 6]	$2,000/kWh[7]	$250-300/kWh[7]	$680-800/kWh[6, 7]
Advantages	Well-known and reliable technology, able to withstand deep discharges, relatively low cost, and ease of manufacturing.	High energy density, able to withstand deep discharges, and long cycle lives.					Relatively safe, well suited for bulk storage, long cycle life (claim 10,000-20,000 cycles), and easy to scale up the amount of energy stored by simply making the tanks larger.
Disadvantages	Relatively low number of life cycles (must be replaced more often) and lower energy density (larger size for less energy storage).	More expensive than lead acid systems and may become thermally unstable. Overheating or short circuits in Li-ion cells may cause thermal run-away—a phenomenon where the internal heat generation in a battery increases faster than it can dissipate. This heat can damage or destroy the cells and is a potential source for fires. Electronic protection circuits are added to the battery pack to prevent thermal run-away.					Relatively high cost, low efficiency (less than 70%) and low energy density; high maintenance with pumps that often leak and precipitate out.
Safety (Thermal Run-away)[8]	Considered thermally safe	High thermal stability	Increased thermal stability	Thermal instability	Highest thermal stability	Increased thermal stability	Very safe since storage of electrolyte is separate from power generation unit

Sources: All information from Battery University unless otherwise noted.

[1] GridMarket. (2012). Technology Matrix. http://www.gridmarket.com/intelligence-2/technology-matrix/.

[2] Sandia National Laboratories. A Study of Lead-Acid Battery Efficiency Near Top-of-Charge and the Impact on the PV System Design. http://www.otherpower.com/images/scimages/7427/Lead_Acid_Battery_Efficiency.pdf.

[3] Fortune. (May 2015). Why Tesla's Grid Batteries Will Use Two Different Chemistries. http://fortune.com/2015/05/18/tesla-grid-batteries-chemistry/.

[4] ESJ. (2015). Lead Acid and Grid Storage. http://www.energystoragejournal.com/lead-acid-and-grid-storage/.

[5] Pacific Northwest National Laboratory. (2012). Vanadium Redox Flow Batteries. http://www.kigeit.org.pl/FTP/PRCIP/Literatura/081_Vanadium_Redox_Battieries.pdf.

[6] Navigant Consulting. (2014). Advanced Batteries for Utility-Scale Energy Storage. http://www.navigantresearch.com/research/advanced-batteries-for-utility-scale-energy-storage.

[7] Email exchanges with Sam Jaffe, Cairn ERA

[8] Thermal run-away refers to the internal heat generation in a battery that increases faster than it can dissipate, which can lead to fire.

safest chemistry system, but has the lowest energy density of the group.

Flow Batteries: Liquid electrolyte flow batteries are basically rechargeable fuel cells. All reactants and products of the electro-active chemicals are stored externally to the fuel cell. To create a current, the liquids are pumped from large tanks into a cell stack where an electrochemical reaction occurs across a membrane. The electrolytes are pumped in the reverse direction to charge the battery. Flow batteries are generally considered safer than traditional batteries because storage of electrolyte is separate from the power generation unit. The electrode reactants are typically acids that undergo reduction/oxidation (redox) reactions. Various redox systems have been explored; vanadium redox battery (VRB) systems are considered among the most attractive. (MIT Technology Review, 2013)

Charge Controllers

In DC-coupled PV with battery back-up systems, the charge controller regulates the DC power and prevents overcharging of the batteries which can result in damage to the battery or create a safety hazard. The battery charge controller is connected between the solar array and the battery bank on the DC circuits.

Inverters

Inverters convert DC from the solar array or batteries to AC, which powers homes and buildings. Battery-based inverters can also convert AC power from the grid or generators to DC to charge batteries. Batteries are integrated with the solar array through the inverter.

There are three types of solar energy inverters: 1) stand-alone inverters, 2) dual inverters, and 3) grid-tied inverters.

1. Stand alone inverters are used for off-grid solar systems.
2. Dual inverters (also called bi-directional or inverter-charger) are used for solar systems that function both on and off grid. Dual inverters that assist with regulation of both voltage and frequency during an islanded or microgrid scenario are referred to as grid forming inverters (GFI).
3. Grid-tied inverters (GTI) or micro-inverters are unidirectional inverters that are used for grid-tied solar systems; they cannot function off-grid.

Dual inverters use software to automatically select between charging the batteries, providing electricity to the on-site load, and/or feeding electricity onto the grid. The function that is selected at any moment depends on electricity demand from the on-site load, the grid status, storage status, and available generation from solar. When the grid goes down, the dual inverter isolates the PV from the grid, while continuing to supply the on-site back-up AC loads with electricity from the solar array and batteries.

GFI allow for more elaborate monitoring and communication of the grid status, the ability to control the system from a centralized location, and the capability to make autonomous decisions to improve grid stability, support power quality, and provide ancillary services (NREL May 2015). Some of the inverters currently deployed with PV systems can already provide this advanced functionality, needing only software upgrades or adjustments to operation parameters.

GTI monitor grid frequency and voltage and then synchronize its electrical output to match the grid's waveform. This allows the inverter to feed electricity from the solar system into the grid that

TYPICAL AC-COUPLED PV GRID-TIED SYSTEM WITH BATTERY BACKUP

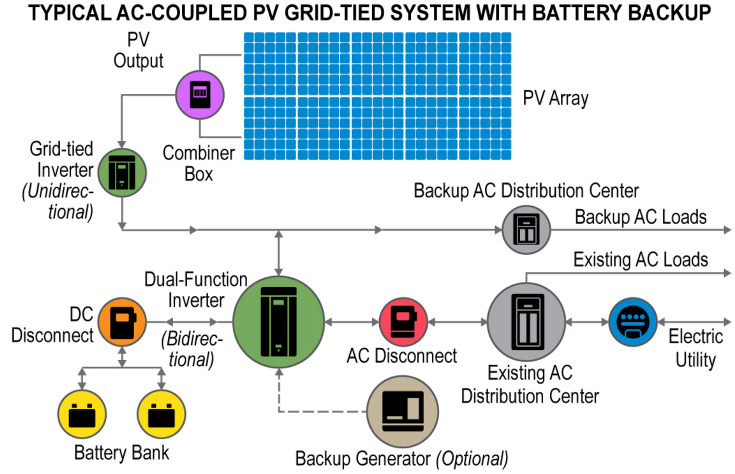

Figure 2. Typical components of a PV+ storage system (AC-coupled)

matches the electricity being delivered from the utility. GTI shut down if the grid goes down or if the voltage or frequency go outside the inverter's operating limits. GTI must use an AC coupled design (with an additional dual inverter) in order to provide emergency power from the solar array and batteries. Micro-inverters are also a type of GTI that convert solar energy from DC to AC at the module level through small inverters attached to the back of each PV module.

Inverter use in AC-coupled systems

AC coupled system designs are typically used to retrofit an existing solar system to add batteries. These systems use two separate inverters: one for the solar, and one for the batteries. They replace the charge controller in a DC-coupled system with a GTI (see Figure 2). Some GTIs are sensitive to AC supply and do not support an AC-coupled storage installation. It is important to research the existing inverter specifications prior to adding storage to a PV system. AC-coupled systems require additional conversions between AC and DC, which decreases the overall efficiency of the PV system. (Clean Energy Group March 2015)

Integrating PV with Battery Back-up with Other DG Assets

PV with Battery Back-up as Microgrid Assets

PV with battery back-up can also be integrated into a microgrid with other forms of distributed generation such as generators, combined heat and power (CHP), or other renewables like wind.

PV with Battery Back-up with Generators

Standalone diesel generators are commonly used for emergency power. Generators can also be paired with solar and/or batteries to reduce the consumption of fuel, extending emergency power during longer outages. When integrating PV and generators without storage, several considerations should be taken into account. To maintain generator reliability during a grid outage and to control system voltage and frequency, at least one generator must run at all times, at a minimum of 30% of its rated capacity. If there are additional generators, they can be ramped up or down in accordance with changes in load and PV output.

Complexity of controls in PV-diesel systems depend on the size of the PV system. If the PV is contributing 20% or less of needed energy, controls are simpler. Diesel generators may automatically throttle back as solar energy becomes available. As solar penetration levels increase beyond 20%, demand for diesel generation decreases and extra generators may be shut off. This reduces system inertia and increases the likelihood of frequency fluctuations. Solar inverters in these systems must have advanced functionality to allow the system to operate in a stable manner over a larger frequency and voltage range.

An additional control unit is required to ensure compliance with a minimum 30% load. The controller reduces the power output of the solar inverters in order to maintain the load of the generators above the minimum capacity. The controller must also respond quickly in the case of a sudden load drop, to avoid damage to generators. The controller should work efficiently to limit starting and shutdown of the diesel generators. The controller also manages voltage, keeping the system within acceptable voltage tolerance levels (Gallego 2013).

When adding battery storage to a PV and diesel system, the battery management system can control system voltage and frequency so the diesel generator can be completely shut off when enough PV is available. This allows the generator to operate at its maximum efficiency and cycle on and off charging the batteries, resulting in fuel savings. PV+diesel+battery back-up systems are commercially available in the tens of kilowatts range, but larger systems in the hundreds of kilowatts are less established.

Sizing Resilient PV

Sizing for Emergency Power: Due to the size and cost of batteries, it is often not economical to provide enough battery back-up to cover all of a building's load. Resilient PV systems are therefore typically designed to cover only the building's **critical loads.** Critical loads vary based on facility type. A single family home might prioritize loads for lighting, refrigeration, and power to charge small electronics, while a multi-story commercial building might prioritize lighting, HVAC, water pumps, and elevators. For critical facilities (ex. hospital, shelter, or police station) that must remain powered during an emergency for an extended period of time, diesel generators can be paired with PV and batteries to help fuel supplies last longer. This table shows average solar and battery system sizes across sectors.

Typical Solar and Storage System Sizes Across Sectors			
	Residential	Commercial	Utility
Solar	≤ 25 kW	25 kW-1 MW	≥ 1 MW
Battery	< 10 kWh (KW)	10 kWh (kW)–1MWh (MW)	> 1 MWh (MW)

Sizing for Energy Management: Solar+storage systems are generally grid-connected, therefore commercial resilient PV systems are typically sized to provide for energy management to ensure maximum economic benefit. The size of a solar+storage system designed for peak shaving, time-of-use shifting, or demand response depends on a building's daily and monthly use patterns. The building's monthly peak demand and the utility rate tariff structure are particularly important. Energy optimization modeling can be used to find the right balance between PV and battery size to provide maximum economic benefit given the specific site load, rate tariff, and incentives available.

Key Hardware Barriers for PV with Battery Back-up

While the market for PV with battery back-up is growing, several barriers remain that slow its growth. This section highlights a few of those key barriers.

Resilient PV used to reduce energy and demand charges have the potential to save commercial customers 20-30% on their energy bill (GTM 2014).

Cost: The largest barrier to the deployment of resilient PV is battery cost, however prices are declining. One study indicates the incremental cost of adding batteries to a residential PV system in California declined at an average rate of 11% per year between 2007 and 2013 (NYSERDA 2013). Another analysis suggests PV systems with storage will be cost-competitive with grid power in some locations within this decade (RMI 2014). There is also more focus on recouping high hardware costs through demand charge reduction, demand response and other revenue-generating opportunities.

Controls/Regulations: There are opportunities to improve cost-effectiveness with advanced communications and controls that allow resilient PV systems to take advantage of all value streams available. For example, current systems are often used to reduce peak demand, but may not participate in ancillary service markets which help balance the transmission system or demand response programs that could provide additional value and make systems more cost-effective. Simultaneously providing peak shaving, demand response, and ancillary services requires more complex controls as well as communication with the broader grid. While many of these inverter capabilities exist, these functions are typically turned off to meet certification requirements. Permitting the use of advanced inverter functions may allow resilient PV systems to capture additional value streams, further driving down costs.

Complex design: There is currently no standardization in resilient PV design, requiring each system to be custom designed. For example, a system that has been designed to use lead acid batteries cannot simply swap in a Li-ion battery without considering the charge control settings and other environmental requirements. To address this complex design, companies are designing new grid interactive and comprehensive off-grid inverter/chargers with the goal of making resilient PV system design and installation easier and faster.

Demonstration Projects & Case Studies

Midtown Community School: During Hurricane Sandy in 2012, fuel supplies for backup generators were limited, and fuel delivery was difficult due to the size and impact of the storm. Midtown Community School in Bayonne, New Jersey, had a constant supply of electricity throughout the storm and its aftermath as a result of its solar-diesel system. The school served as a community shelter, with 272 kW of PV and a diesel generator forming a microgrid to provide electricity while the local grid was out of service. The PV system significantly reduced the amount of diesel fuel required to maintain the electricity needs of the facility.

Princeton University: Princeton University's microgrid includes a natural gas combined heat and power (CHP) plant, a 5 MW diesel generator, 5.4 MW of solar PV and thermal energy storage. Under normal grid-tied operation, the microgrid is used for economic benefit, to reduce peak demand, and to sell frequency regulation services into the ancillary service market. During Hurricane Sandy, operators disconnected the microgrid and successfully supplied critical power to the campus for 1.5 days, providing services to the community and avoiding potentially millions of dollars of research-related losses.

Rutland, Vermont: The town of Rutland, Vermont experiences frequent storm-related power outages. The local utility, Green Mountain Power, is addressing these reliability issues by developing the country's first 100% solar-powered microgrid on a re-purposed landfill. The project will include 2.5 MW of solar capacity and 3.4 MWh (4 MW) of battery storage. This system will have the potential to supply 365 homes during normal grid-connected operation, or power the shelter during emergencies. In addition to backup power, the storage will provide quick-responding frequency regulation services for the grid.

If you are interested in contacting a vendor to assess the feasibility of a solar+storage project for your home or business, please visit the New York Battery and Energy Storage Technology Consortium's (NY-BEST) Supply Chain Database. Search for battery storage integrators to identify companies that provide energy storage systems.

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About

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