Will Solar Panels Help When the Power Goes Out?

Planning for PV Resilience

Scott Belding, Andy Walker, and Andrea Watson

NREL is a national laboratory of the U.S. Department of Energy
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Introduction

Resilience captures the ability of an energy system to "anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions through adaptable and holistic planning and technical solutions."[1] Resilience has far-reaching implications for every corner of the energy sector, but in the context of electricity, it most closely corresponds to the ability to continue generating and delivering electric power during periods of intense stress on energy systems. Hurricanes and other extreme weather increasingly threaten to disrupt energy systems, and distributed generation is generally considered an effective recourse to grid-wide power outages caused by severe storms and other hazards. Photovoltaic (PV) solar power systems in particular are often thought of as inherently resilient energy solutions due to their distributed nature and free, abundant fuel supply.[2,3] PV systems can make major contributions to resilience, yet require careful design in order to operate when the grid is not functioning.

Figure 1. PV array in the U.S. Virgin Islands after suffering hurricane damage

(Source: Eliza Hotchkiss, NREL)

The same extreme weather that causes grid-wide outages in the first place is also a serious threat to the constitution of distributed PV systems. If hardware is not procured, installed, and maintained with an eye toward resilience, harsh conditions may easily destroy vital components (Figure 1). Moreover, even solar energy systems that remain intact must be designed to operate without grid connection and meet consumers' prioritized energy demands (what constitutes a high-priority load will vary by consumer). Most distributed PV systems automatically shut off during a grid outage, resulting in zero resilience benefits (i.e., the panels are undamaged, but power is not available during a grid outage). System design is therefore crucial to PV's contribution to resilience, and different energy customers will have distinct criteria for success based on their needs. This document has been prepared to correct misconceptions regarding PV resilience and identify solutions for the most common barriers to PV resilience. It is based on technical reports and post-disaster experiences to share lessons learned, and is intended for a non-technical audience that may include decisionmakers, investors, procurers, and other stakeholders. Lessons are organized by components of PV resilience: hardware, siting, system design, and resilience by consumer class.

Hardware

The full spectrum of PV hardware resilience was recently elucidated by the spate of hurricanes impacting coastal U.S. states and island territories in 2017-2018 (Harvey, Irma, Maria, and Florence), which delivered intense winds, storm surge, and flooding.[4,5] Some solar PV installations were destroyed by these storms, while others were only minimally damaged or unscathed.[6,7,8] Intact hardware is necessary (though not entirely sufficient) for any installation to be resilient, and after analysis of successes and failures, certain procurement and maintenance practices can be directly linked to PV systems that are truly qualified to deliver resilience benefits. Lessons learned related to PV system hardware for resilience include:

- PV modules should be through-bolted to their racks
- Bolts should be kept tightly locked or torqued
- Panel racks should be rigid enough to resist twisting
- Installations near corrosive saltwater should utilize marine-grade steel
- PV panels should be rated to withstand site-appropriate front and back pressures, and very severe hail (VSH)[9,10,11]

Figure 2. Workers alongside walkable rows between solar PV panels

(Source: Dennis Schroeder, NREL)

Siting

Siting concerns go hand in hand with resilient hardware and maintenance. Siting refers broadly to the locations and orientation of PV system components, and can meaningfully interact with hazards to the PV system in multiple ways. For example, effective maintenance may not even be possible if the PV system is poorly sited. Regular torque bolt inspection and tightening require walkable rows between panels in order to make every bolt accessible. Arrays that are too densely packed lower the likelihood of effective maintenance, thus increasing the chance of loose bolts and lost panels during extreme wind events. Siting relates to the physical strength of the system hardware as well: in built environments, wind uplift forces can vary widely even across short distances and can be exacerbated by specific constructed features, such as overhangs and parapet walls.[12] Any PV siting assessment should therefore include an analysis of wind uplift risk and result in panels installed only in low-risk areas.

Virtually all utility-scale PV arrays are ground-based, rather than roof-mounted, making them vulnerable to flooding.[13] High waters pose the greatest threat to non-module elements of the PV system, as submerged wires and power controls necessitate any connected generation assets be taken offline.[14] Siting a resilient ground PV system requires a comparison of the panels' elevation to the site's risk of flooding, and an assessment of concrete pad elevation and drainage capability to protect all electronic components. For ground-based PV arrays in flat landscapes, some wind stress may be mitigated by wind break fencing.[15,16] This is most effective against consistent force vectors, but hurricanes and other storms can often present turbulent wind flows and dynamic loads, which are more difficult to mitigate.[17] In sum, siting PV systems for resilience requires proactive planning:

- PV modules should be placed to allow maintenance access
- Local wind force risk should be matched to PV panel pressure ratings; avoid very high wind regimes like hanging above a parapet wall on the roof or at the crest of a hill
- Electronic system components should be in cabinets on elevated platforms and sealed to prevent water ingress
- Ground-mounted PV arrays should be installed at locations with minimal flood risk; site drainage and storm-water runoff should be improved and maintained
- Passive wind-break technology (e.g. fencing) should be explored to further mitigate risk

System Design

Hardware must withstand extreme weather as a prerequisite for increasing resilience, but the electrical topology of PV systems is equally important. Even in ideal conditions, PV systems may not be able to provide electricity when the grid suffers a power outage. Without additional planning and investment, *grid-connected solar panels are automatically switched off during a grid outage* in order to ensure the safety of workers repairing downed grid components (IEEE 1547).[18] Electricity from these panels is therefore inaccessible during a power outage, even at the home or business at which the system is installed, negating any potential contributions of these PV systems to resilience during a larger grid outage.[19] For a PV system to overcome this issue and locally deliver usable electricity, it must be able to "island" by isolating itself from the grid in a safe manner. Additional power management electronics are necessary to achieve this function.[20]

Without an energy storage component, however, power will only be available when light is hitting the PV modules, which is why islanded PV systems often include an energy storage system (ESS), usually comprised of batteries (BESS). A BESS greatly increases resilience by making power more available and reliable. An islanded system, equipped with a dual-function inverter, can draw from and refill the batteries as necessary (Figure 3).[21] During a grid outage in this type of system, if the BESS is completely drained at night or on a cloudy day, no energy will be available until sunlight returns to enable PV charging of the batteries. A common solution to this problem is to include a backup generator, usually diesel-powered, in a hybrid system. The generator refills the BESS when the BESS voltage drops below the required level. This system topology enhances resilience because it provides even more reliability through a different fuel source and reduces generator load compared to a diesel-exclusive backup. It is possible to retrofit existing grid-connected PV systems with a dual-function inverter and BESS, though a system built from scratch is more efficient (Figure 4).[22]

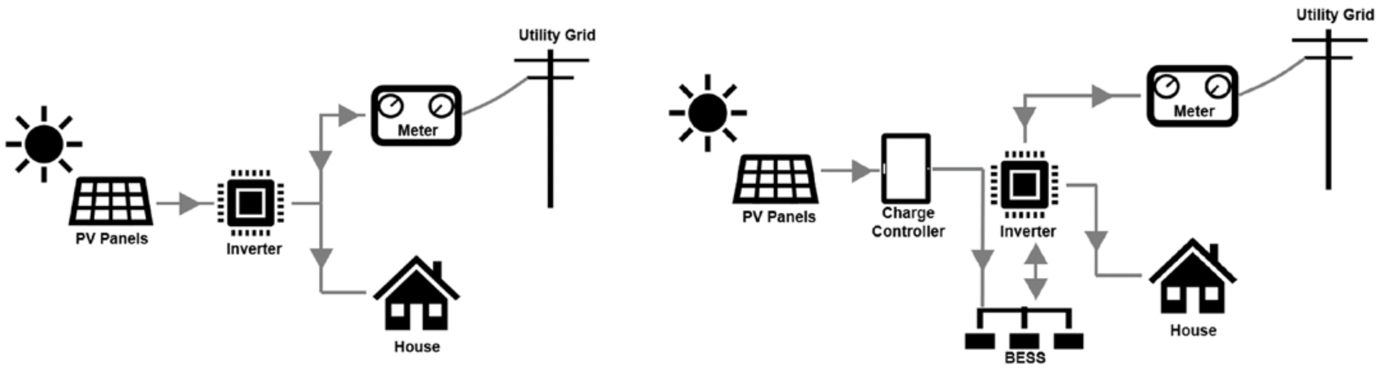

Figure 3. Grid-tied PV system (L) and islandable PV + BESS system (R)

(Source: Illustration by author)

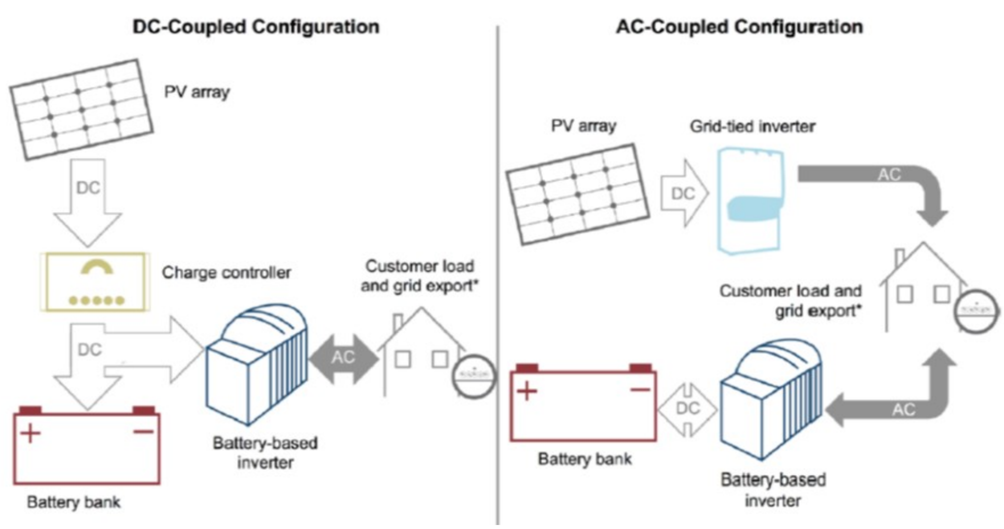

Figure 4. DC- (L, common for new build) and AC-coupled (R, common retrofit) PV+BESS systems

(Source: Ardani et al. 2017)

A system's resilience and design also intersect with its financing and contracts. PV + BESS owners may create an additional revenue stream by entering an agreement to provide the grid utility with energy services from the BESS.[23] The nature of those services should also inform battery procurement decisions: providing demand management through time arbitrage requires high-capacity, deep cycle batteries, while providing ancillary services like frequency and voltage regulation requires quick-response batteries with utility-compatible control software.[24] These types of batteries can respond differently to various disruptions, carrying implications for resilience which should be addressed on a case-by-case basis.

PV system design entails more choices than those described in this document, but there are several core considerations vis-à-vis resilience:

- "Modular" PV inverter configurations can be more reliable: micro-inverters on each module or string-inverters on each string can continue to operate even if neighboring units are damaged.
- DC loads, such as data centers and computer network equipment, can be powered by a PV system configured to deliver DC power to those loads even when the grid is down, if sized appropriately to feed critical loads.
- Grid-tied PV systems without specialized inverters and islanding controls will be unusable in the event of a grid outage, since interconnection standards require such systems to disconnect when the grid is down.
- The resilience of PV systems can be increased by adding:
    1. The capability to island, and to operate when the grid is down.
    2. Energy storage systems
    3. Additional generation technology, such as diesel generators.

Resilience by Consumer Class

Resilience's components and value will change between one energy consumer and another, reflecting differences in users' goals. For example, commercial PV owners may strive to maintain their business hours during a grid outage, while residential owners could tolerate more disruption so long as essential electricity demands are met. As such, a highly resilient residential PV system would be unlikely to qualify as highly resilient for the commercial user, regardless of generation capacity. The operational needs of businesses and organizations will also be determinative of their ideal PV system topology and capacity.

Utilities have unique concerns of their own. Utility-scale PV generation assets are vulnerable to both floods, described above, as well as unrelated failures in the transmission and distribution networks that carry PV-generated electricity to customers. The interconnected nature of the grid makes the utility's resilience needs more comprehensive and less focused on islanded PV systems than those of commercial and residential customers. A general summary of consumer classes and their primary resilience needs is shown in Table 1.

Table 1. Resilience Considerations and Needs by Consumer Class

Consumer Class	PV System Location	Disruption Tolerance	Stressor	General Resilience Needs
Utility	Ground	***Very Low***: Every disruption impacts operations	Grid Outage	• Hardened transmission and distribution infrastructure • Assistance from external restoration workers • Regular maintenance and storm preparation
			Extreme Winds	• Wind-resistant siting • Resilient hardware specifications/maintenance • Wind mitigation
			Flooding	• Flood-resistant siting • Elevated structures for panels and electrical equipment
Commercial	Roof	***Low***: Even small disruptions may impact operations	Grid Outage	• Islandable, hybrid system with ESS
			Extreme Winds	• Wind-resistant siting • Resilient hardware specifications/maintenance
Residential	Roof	***Medium***: Stored energy is needed to reliably power critical loads during disruptions	Grid Outage	• Islandable system with ESS
			Extreme Winds	• Wind-resistant siting • Resilient hardware specifications/maintenance
Residential	Roof	***High***: Critical loads are small and can be intermittently powered	Grid Outage	• Islandable system (no ESS, PV-powered emergency outlet only for critical loads, such as refrigerators or medical equipment)
			Extreme Winds	• Wind-resistant siting • Resilient hardware specifications/maintenance

Conclusions

PV systems, like all energy systems, must chart a difficult course in order to improve resilience. They need to simultaneously withstand extreme conditions that cause grid power disruptions, be configured in a way that allows electricity to be delivered to meet the PV user's needs, and overcome disruptions arising from solar resource intermittency. Certain considerations reveal themselves as key to a PV system's resilience benefits.

Choice of hardware is critical, as is site selection for the PV array. Voluminous evidence in a hurricane context demonstrates that durable hardware, properly maintained and sited, leads to PV systems surviving extreme weather with their functionality intact. Structurally weak or poorly maintained PV equipment, on the other hand, has demonstrated failures during extreme weather events. PV system stakeholders should ensure that best practices are followed for hardware procurement and siting. It is also important to understand that PV systems are not one-size-fits-all. While incorporating islanding capabilities and energy storage into the system's electrical topology will typically enhance resilience, the user's needs will determine the optimally resilient conformation of any given system.

These factors – appropriate hardware, siting, maintenance, and system design – are the primary drivers of PV resilience. PV systems possess high potential for resilient energy generation due to their distributed, abundant, and free fuel supply, but the technology itself does not inherently lead to resilient outcomes. Realizing PV's potential for resilience requires consideration of these determinative factors.

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