

Emergency Energy Delivery using Resilient Solar Power Islands and V2X-Capable EV's

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Summary

Emergency power systems are described based on a foundation of EV charging at solar facilities that can remain operational during storm-induced grid outages → these resilient solar installations form local power islands that operate as microgrids until the larger grid comes on-line again. As an enhancement to this, electric vehicles (EVs) with bi-directional charge/discharge functionality can enhance a power island's utility by being able to deliver some of the microgrid's energy to locations further removed from the site itself. Energy and power limitations of this power-resilience mode are discussed in detail.

Keywords: EV, V2G, energy security, modeling, energy storage

1 Introduction

Photovoltaic systems with battery storage have long been critical for those who live in remote places or want to be completely “off the grid”. Many studies have looked at balancing system design with known demand profiles for remote locations around the world but the system optimum is strongly affected by the particular load profile and power generation mix (and variability). Still, stand-alone PV+battery systems have typically only been a very small fraction of PV systems installed. Most residential installations are actually grid-tied, which means that under conditions of local usage extra solar-generated power is fed back to the grid at large. In addition, these residential systems don't typically have any local storage options; the solar is used when it is generated and any shortage or excess relative to the local need is moderated by the grid connection. This widely distributed renewable generation has taken hold in California, New Jersey, Germany, and a number of other localities around the world. However, the recent “superstorm” events (Sandy and others) have exposed a key weakness of these systems: that the typical residential inverters used do not usually have “islanding” capability, which forces the vast majority of the solar generation capacity to be turned OFF when the larger grid gets disabled. Thus, a widely distributed power generation resource (that could be particularly valuable during storm recovery) is restricted because of the simplicity of the common strategy for installation. This has naturally led to calls for the design and installation of combined PV+battery systems with an inverter having islanding capability and some systems like this have already been fielded.

The present work builds on this situation and adds the idea that there might be a fleet of EV's that could charge at such microgrid emergency power islands and then re-deploy that power to locations not far from the solar power island location. These EVs would then be able to charge at “home base” during the day (when solar energy is available) and drive to satellite locations to deliver power during emergency situations. Significant power can be provided for emergency responders, health providers, and community shelter locations. In this mode, “V2X” is taken here to represent “vehicle-to-X”, where “X” should be taken to include G for “grid”, H for “home”, or B for “building”, as the V2G, V2H, and V2B acronyms have been coined in the past and where all of these consist of various configuration of potential bidirectional energy transfer in and out of the vehicle.

2 Background

Storm resilient distributed power systems have captured the public's attention due to the massive failures of the power grid during recent superstorm events. In these cases, the many falling trees and flooding damaged

the electricity distribution network so badly that power wasn't reconnected for days or even weeks in many places. Since most solar installations are tied to the grid and abide by certain safety regulations, most of the available solar generation was brought off-line, even when no *local* failure had been caused, until the larger grid was up and running again. This flaw in the distributed generation model can be easily resolved by having local energy storage and inverters with islanding capacity. In these cases "power islands" would exist during storm or other grid outages and critical medical or communication equipment could be powered while workers fix the damaged grid and bring the greater system back to full operation.

The present analysis quantifies the solar resource and its variability and provides recommendations on sizing for the batteries (EV-based) that would be required for a reasonable deployable power-islanding installation. The present deployability analysis is rooted in the resilience specifications recently derived for systems with stationary energy storage [1]. That analysis can be described with reference to Fig. 1. Two sequential days of solar intensity are mapped to illustrate an algorithm for finding the night-time duration and integrating the daytime available sunlight. The falling brightness associated with the end of day 1 ("dusk") is fitted with a straight line and similarly the rising sunlight brightness as the second day starts ("dawn") is fitted with a second straight line. For the present work we have found that excellent dawn and dusk fits have been achieved by picking the steepest point when fitting 5-hour linear regressions of the global horizontal irradiance (GHI) hourly data using NREL's Typical Meteorological Year database [2]. The two lines drawn in Fig. 1 are calculated in this manner. Fig. 1 also contains a representative steady-state power line (flat red line). The area below that line during the night-time (the yellow area) then gives the energy amount that must be stored in the battery from the previous day to provide for operation during the full night. Working backwards we can adjust the power demand (red line height) so that the accumulated stored energy from the previous day can be powering some kind of emergency unit completely through the night. This power demand then becomes a system rating for what expectations might be made for the performance of a system operated under the natural light variability of a selected geographic location.

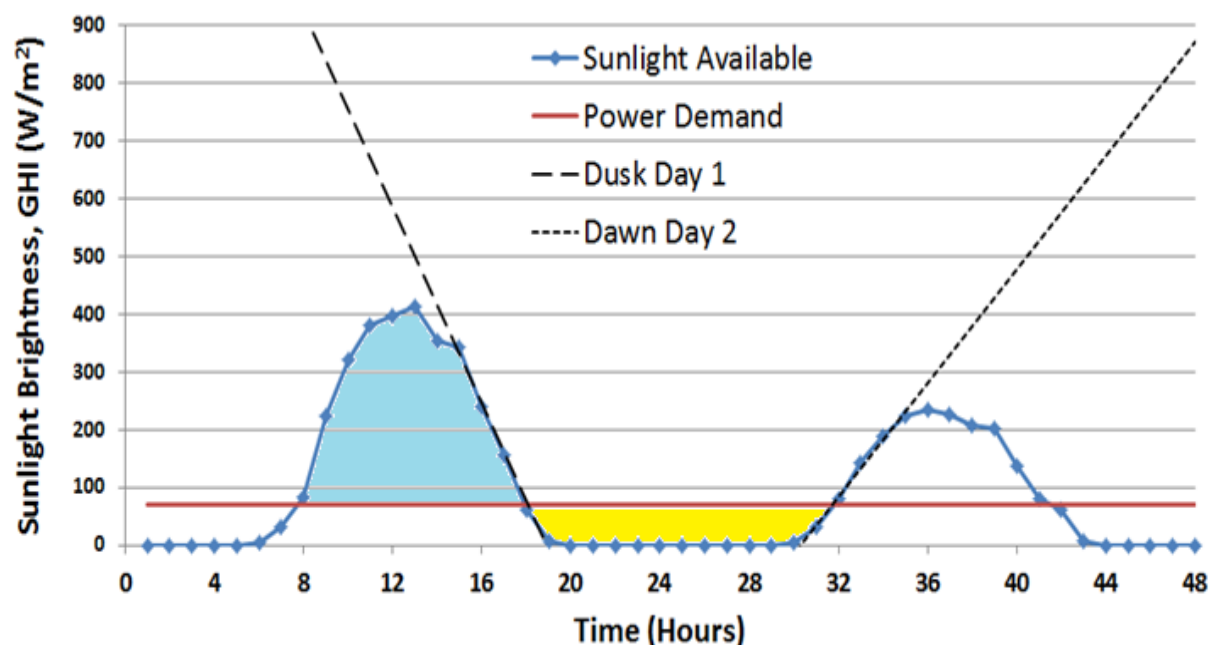


Figure 1: Two sequential days of sunlight brightness with associated fitting of dusk and dawn (dash and dotted lines). The excess collected energy during the day (blue region) should be stored in the battery to provide power during the night-time hours (yellow region) [1].

While this is a relatively straight-forward calculation, the *variability* of the local weather patterns suggests the need for a more statistical analysis of the likely output, as presented in Reference [1]. Working with the energy values identified by Fig. 1 and working through the full year we can develop a probability distribution of the night-time steady-state average power output, as shown in Fig. 2. Here the Y-axis is scaled in proportion to the size of the photovoltaic array as the total energy collected will be proportional to this rating, too. This distribution then represents the range of behaviors found for typical sunlight variability for the location being modeled (here Newark, New Jersey).

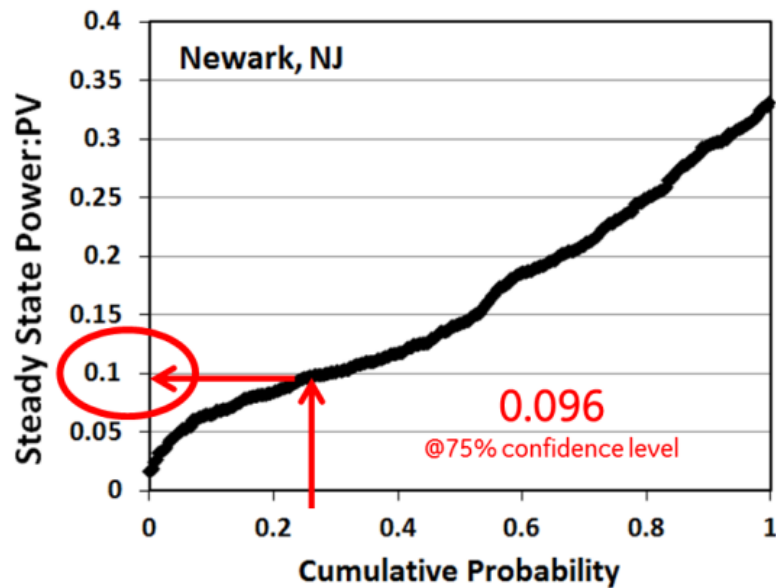


Figure 2: Merged power output as a distribution function – combining solar variability and other system constraints.

Fig. 2 provides a statistical cutoff – selected in this case at a 75% confidence interval. With 75% confidence it is possible to read from the 0.25 fraction to find a nominal steady-state power that would likely be achieved based on the local solar weather-pattern history. Reading up from the 0.25 factor we find a ~ 0.1 power ratio, meaning that the given solar array will provide nighttime power at only a 10% scaled output level when compared with the peak real-world daytime installation output. A similar calculation can be provided for the case where the battery size is too small and again a statistical distribution of nighttime output powers is developed [1]. When the battery-limited and the sunlight-limited cases are combined we get a performance that is limited by the weak-link or more constricted component of the system. Fig. 3 shows this overlay: again the vertical scale is normalized with respect to the PV array's rating. And, the X-axis is the number of hours of full-rated PV output can be stored by the system. We see immediately that larger batteries (further to the right) will be sunlight limited, while smaller batteries (near the origin) will be storage capacity limited.

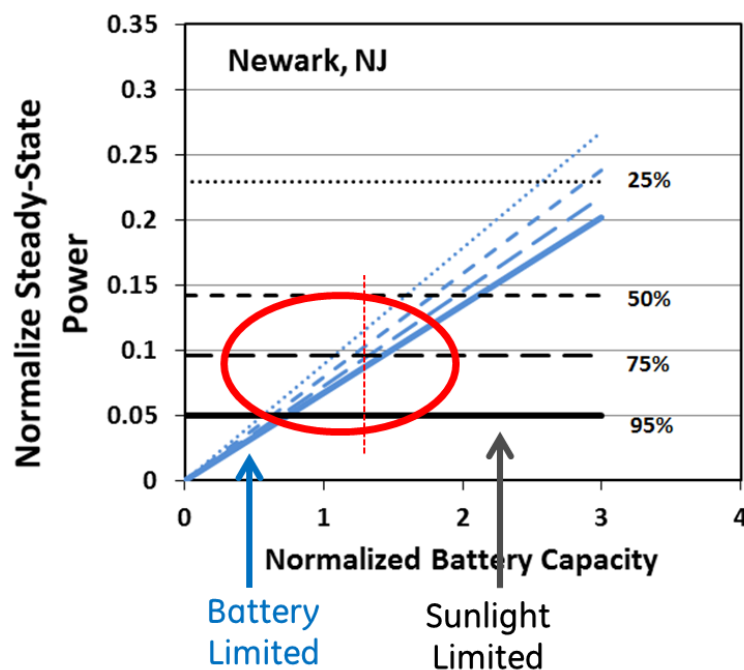


Figure 3: Combined effects of the battery and sunlight limited cases for power-island nighttime steady-state power output. The location cross-over between the two at the 75% confidence interval is indicated in the red oval, which might be considered an ideal design specification for system implementation [1].

3 Emergency Energy Deployment Model

Connecting photovoltaic electricity with plug-in vehicles is an obvious linkage that can provide transportation with nearly zero green-house gas (GHG) impact. Significant work has already been directed to matching PV generated power with electric vehicles (EV), though typically the PV is not directly installed on the vehicles in question [3-5], though the energy value is preserved by connection to the grid. However, when the EV's are charged at the self-contained microgrid then we need to view it's energy storage and the possible remote delivery in regard to the PV-vs-battery capacity limitations outlined above.

For situations where the solar island capacity is relatively large it will be possible to charge EVs locally at a relatively rapid pace and have them drive to near or distant locations to provide emergency power in various ways. Fig.4 shows the energy and power framework for this: at time $t=0$ we start to charge the battery. When full it is able to drive to a nearby location (naturally losing some energy) and is able to deliver energy to whatever is needed at that local site. Finally the EV needs to drive "home" to the power island ("travel back") before the EV's battery is empty so that it could be charged again.

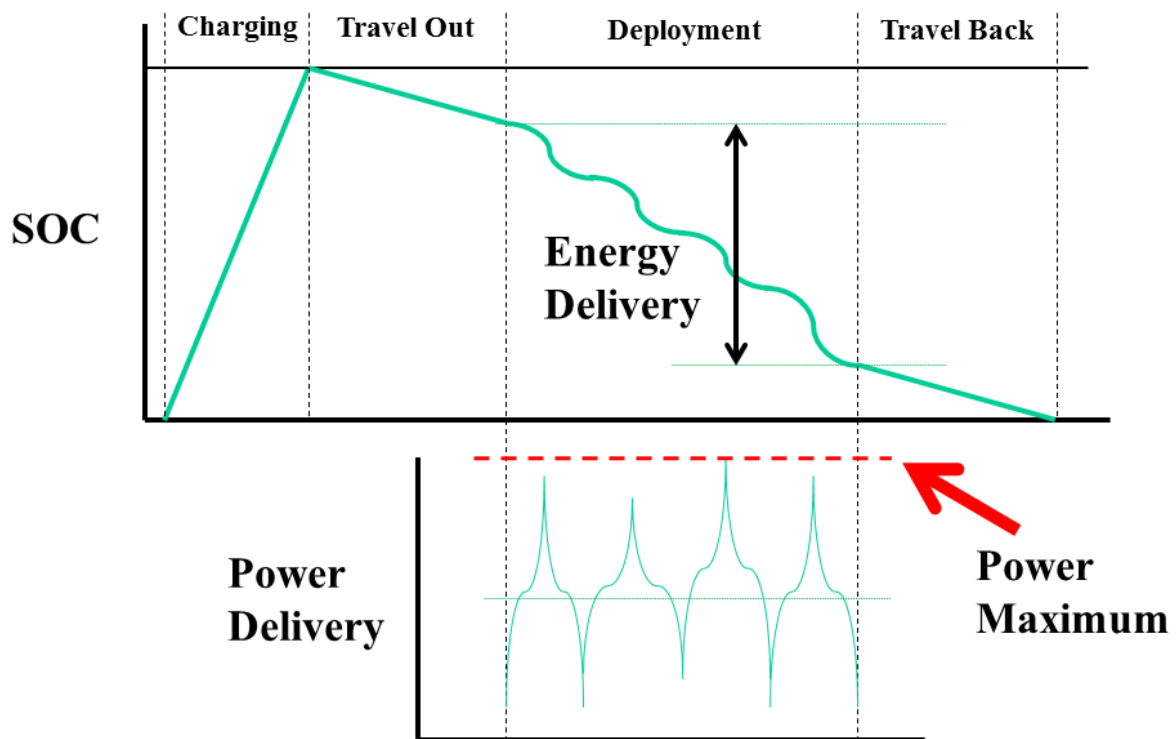


Figure 4: Energy deployability effectiveness during a single day's operation during a grid outage.

The operation of EV's to deliver energy to remote locations is also limited by the energy need for the simple travel from one place to another. Further, the bidirectional power input/output for the vehicle will typically have limitations, too. Or, if the vehicle is operating relatively low power gear then the duration of deployment could be quite long, even days. Clearly the delivery of energy and power to remote sites will be limited in many ways. In one extreme, even, the "travel out" and "travel back" energy needs may eat up most of what is available and will establish a maximum circle of efficacy beyond which these EVs could not be helpful, or could only go out once and not be able to cycle through many days of operation.

4 Discussion

The operation of such emergency deployable power systems will depend on the scale of battery and PV sizes in a way that is similar to that for PV+batteries used in stationary storage situations [1]. To illustrate these principles we examine two realistic scenarios where one might be able to operate in this mode: (1) a residential situation (the classic V2H, vehicle-to-home scenario), and (2) a corporate-sized solar with EV fleet situation. Fig. 5 shows an annotated version of Fig. 3 highlighting conditions that might be typical at a residential PV array with associated bidirectional EV.

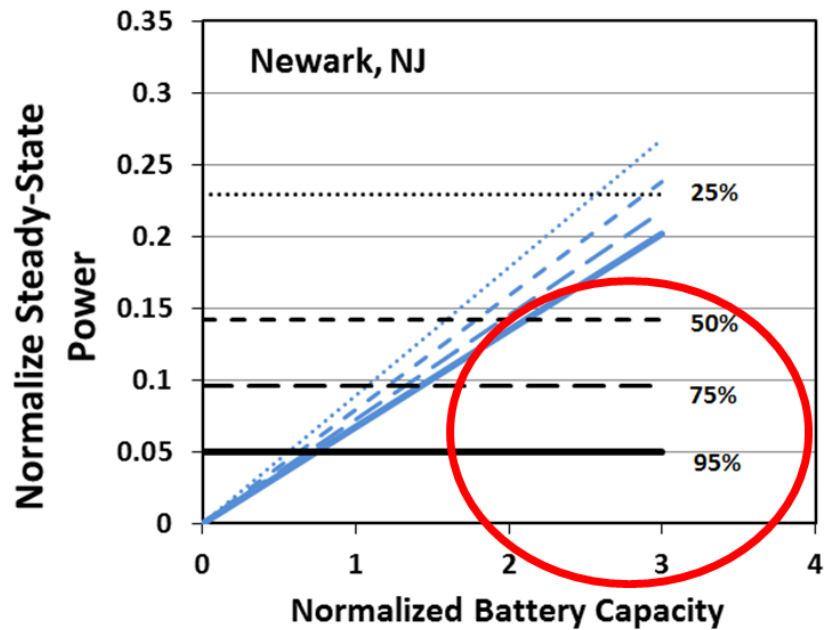


Figure 5: Energy deployability limitation for parameters scaled to a typical residential system. Many EV batteries are large enough that the net daily energy that can be delivered will be limited by the variability of the sunlight rather than capacity limitations.

The red circle encompasses many typical home parameters: for example residential PV arrays might be rated on the scale of 5 to 10 KW, depending on the roof area. For comparison EV's that could support bidirectional charging, like the Nissan Leaf, might have rated battery between 24 and 30 KWH, giving a ratio between those two ratings in the range of 2.4 to 6 hours. This pushes the system comparison into one which is clearly limited by the size of the solar array, and the reliability statistics or confidence of energy delivery will scale what this vehicle might be able to confidently provide as a remote provider of energy in this emergency deployability mode.

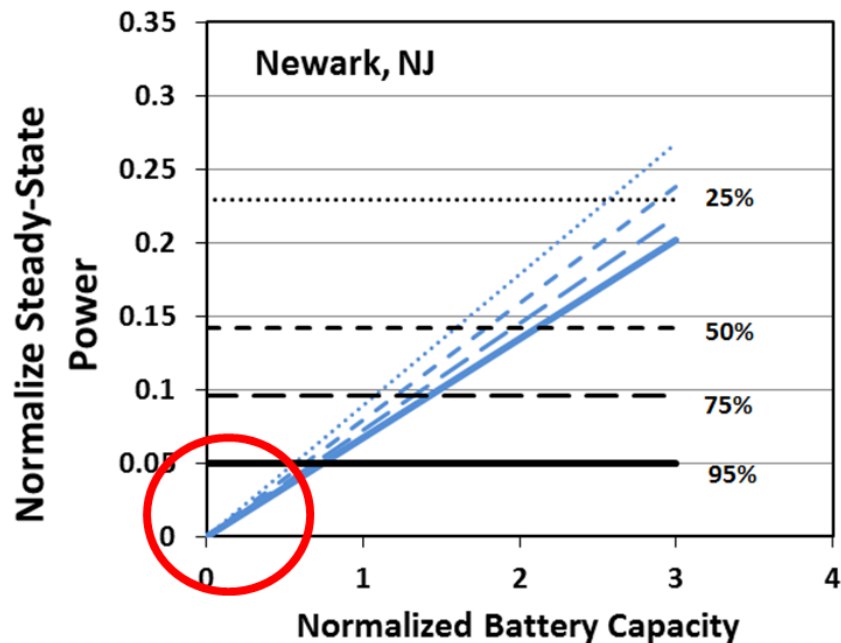


Figure 6: Energy deployability limitation for parameters scaled to a corporate sized system. Many corporate sites have large PV arrays with relatively limited EV charging access and little local storage. Thus, the deployability is limited chiefly by the vehicle's battery capacity and range.

Now, Fig. 6 shows the related situation for a large corporate site which could also be configured as a microgrid during emergency situations. As a specific case, our university has an 8MW solar array built

as a parking lot canopy structure. If this was allied with fleet vehicles at the home location – again with typical battery capacities in the 20-30 KWH range we calculate a ratio where even 100 of these vehicles would still be too small to capture all of the sunlight output. The red circle in this case shows that the deployable power will be limited by the number of vehicles and their range and not by the solar array itself. Obviously at some point the fleet might become too large (and then limited by the solar array size), but this is hard to imagine in the coming few decades, given the slow transition to EV fleet usage.

Overall, we can see that an emergency microgrid “power-island” operating with a small fleet of bidirectionally charging EV’s can be used to deliver power to a nearby region close to the microgrid, but limited by the capacity of vehicle batteries and the fuel economy of driving these vehicles. Further optimization of a utilization plan is difficult because the specific loads being powered during emergency scenarios are as-yet unknown. Further, it may be possible to have battery storage at the location of emergency usage needs and then simply use the vehicle to bring energy to recharge those distant batteries and have more flexibility of deployment of energy.

5 Conclusion

A simple system for deploying emergency power has been described. Solar arrays can be modified to become microgrid power islands and then be active during emergency grid power outages. In these cases, it will be possible to power EVs for use as emergency vehicles. In addition, if the vehicles are outfitted with bidirectional charge/discharge electronics, these EVs can then deliver energy to remote locations within a limited range beyond the solar array location. This provides a new way for municipalities to envision emergency resilience and a further incentive for adoption of EVs.

Acknowledgments

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Prof. Birnie is in the Department of Materials Science and Engineering at Rutgers University’s main campus in New Brunswick/Piscataway. His research interests span from the nanoscale (photovoltaic and battery materials development) and range to macroscale with emphasis on solar and battery systems and resilience. His recent work has focused on system improvements for battery+PV systems, including EV and PHEV concepts and their practical implementation. He received his BS and PhD degrees from MIT in 1981 and 1986, respectively. For many years Dr. Birnie has been faculty advisor to collegiate solar car racing teams, first at Arizona and now at Rutgers. The 2001 team at U of Arizona took First Place in the Stock-Class of the American Solar Challenge. Students from several engineering departments have been involved in this activity.