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Solar Energy Grid Integration Systems –Energy Storage (SEGIS-ES)

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ABSTRACT

This paper describes the concept for augmenting the SEGIS Program (an industry-led effort to greatly enhance the utility of distributed PV systems) with energy storage in residential and small commercial applications (SEGIS-ES). The goal of SEGIS-ES is to develop electrical energy storage components and systems specifically designed and optimized for grid-tied PV applications. This report describes the scope of the proposed SEGIS-ES Program and why it will be necessary to integrate energy storage with PV systems as PV-generated energy becomes more prevalent on the nation's utility grid. It also discusses the applications for which energy storage is most suited and for which it will provide the greatest economic and operational benefits to customers and utilities. Included is a detailed summary of the various storage technologies available, comparisons of their relative costs and development status, and a summary of key R&D needs for PV-storage systems. The report concludes with highlights of areas where further PV-specific R&D is needed and offers recommendations about how to proceed with their development.

Contents

1. Executive Summary

In late 2007, the U.S. Department of Energy (DOE) initiated a series of studies to address issues related to potential high penetration of distributed photovoltaic (PV) generation systems on our nation's electric grid. This Renewable Systems Interconnection (RSI) initiative resulted in the publication of 14 reports and an Executive Summary that defined needs in areas related to utility planning tools and business models, new grid architectures and PV systems configurations, and models to assess market penetration and the effects of high-penetration PV systems. As a result of this effort, the Solar Energy Grid Integration Systems Program (SEGIS) was initiated in early 2008. SEGIS is an industry-led effort to develop new PV inverters, controllers, and energy management systems that will greatly enhance the utility of distributed PV systems.

This paper describes the concept for augmenting the SEGIS Program with energy storage (SEGIS-ES) in residential and small commercial (≤100 kW) applications. Integrating storage with SEGIS in these applications can facilitate increased penetration of distributed PV systems by providing increased value to both customers and utilities. Depending on the application, the systems can reduce customer utility bills, provide outage protection, and protect equipment on the load side from the negative effects of voltage fluctuations within the grid. With sufficient penetration, PV-Storage systems are expected to reduce emissions related to generation and will be critical to maintaining overall power quality and grid reliability as grid-tied distributed PV generation becomes more common.

Although electrical energy storage is a well-established market, its use in PV systems is generally for stand-alone systems. The goal of SEGIS-ES is to develop electrical energy storage components and systems specifically designed and optimized for grid-tied PV applications. The Program will accomplish this by conducting targeted research and development (R&D) on the applications most likely to benefit from a PV-Storage system (*i.e.,* peak shaving, load shifting, demand response, outage protection, and microgrids) and developing PV-Storage technologies specifically designed to meet those needs. Designing optimized systems based on existing storage technologies will require comprehensive knowledge of the applications and the available storage technologies, as well as modeling tools that can accurately simulate the economic and operational effect of a PV-Storage system used in that application.

This paper describes the scope of the proposed SEGIS-ES Program; why it will be necessary to integrate energy storage with PV systems as PV-generated energy becomes more prevalent on the nation's utility grid; and a discussion of the applications for which energy storage is best suited and for which it will provide the greatest economic and operational benefits to customers and utilities.

Because selecting and optimizing a storage technology for an application will be critical to the success of any PV-Storage system, this paper also provides a detailed summary of the various storage technologies available and compares their relative costs and development status (*e.g.,* mature, emerging, *etc.*).

Finally, the paper highlights areas where further, PV-specific R&D is needed and offers recommendations about how to proceed with the proposed work.

2. Vision

The U.S. infrastructure for electricity generation and delivery is undergoing a revolution that will lead to increased efficiency, improved reliability and power quality for customers, ‘smart’ communications to match generation and loads, and the development of distributed generation from local and renewable resources. The high penetration of PV and other renewable energy technologies into the infrastructure will be enabled by developing managed, efficient, reliable, and economical energy storage technologies that will eliminate the need for back-up utility base load capacity to offset the intermittent and fluctuating nature of PV generation.

These dispatchable storage technologies will bring added benefits to utilities, homeowners, and commercial customers through greater reliability, improved power quality, and overall reduced energy costs.

3. Program Objective

The SEGIS Program will develop advanced energy storage components and systems that will enhance the performance and value of PV systems, thereby enabling high penetration of PV-generated electricity into the nation’s utility grid. Through its RSI initiative, the DOE Solar Energy Technology Program is identifying needs and developing technologies to facilitate the high penetration of distributed electricity generation. The need for improved energy storage has been highlighted as a key factor for achieving the desired level of PV generation.

The electrical energy storage industry is well established and offers a variety of products for vehicle, uninterruptable power supply (UPS), utility-scale, and other storage applications. The design and development of storage products specifically for PV applications, however, is almost nonexistent. Traditional PV-Storage systems have been used for off-grid applications that required some amount of autonomy at night and/or during cloudy weather.

However, the objective of this Program is to develop energy storage systems that can be effectively integrated with new, grid-tied PV and other renewable systems, which will provide added value to utilities and customers through improved reliability, enhanced power quality, and economical delivery of electricity.

4. Program Scope

In late 2007, DOE began a series of studies to address issues related to the potentially high penetration of distributed PV generation systems on our nation’s electricity grid. The RSI initiative resulted in the publication of 14 reports and an Executive Summary that defined needs in areas related to utility planning tools and business models, new grid architectures and PV system configurations and models to assess market penetration and the effects of high-penetration PV systems.[1] As a result of this effort, the SEGIS program was initiated in early 2008. SEGIS is an industry-led effort to develop new PV inverters, controllers, and energy management systems that will greatly enhance the utility of distributed PV systems.

SEGIS-ES is closely related to the SEGIS Program, a three-year program with a goal to develop new commercial PV inverters, controllers, and energy management systems with new communications, control, and advanced autonomous features.[2] The heart of the SEGIS hardware, the inverter/controller, will manage generation and dispatch of solar energy to maximize value, reliability, and safety, as the nation moves from 'one-way' energy flow in today's distribution infrastructure to 'two-way' energy and information flow in tomorrow's grid or microgrid infrastructure.

The applicable markets for the SEGIS Program[3] are defined in Table 1, which shows the size of the PV system in watts, or power output. Storage systems are typically rated in terms of energy capacity (*i.e.,* watt-hours), which is highly dependent on the application for which the storage is being used. The applications are discussed later in this document.

Table 1: Target Market Sectors for SEGIS PV Systems

Residential	**Less than 10 kW, single-phase**
Small Commercial	**From 10 to 50 kW, typically three-phase**
Commercial	**From 50 to 100 kW, three-phase**

SEGIS-ES is focused on developing commercial storage systems for distribution-scale PV in the market sectors shown in Table 1; specifically, PV systems designed for applications up to 100 kW that can be aggregated into multi-megawatt systems.

Integrating electrical energy storage into homes or commercial buildings is also a key focus of SEGIS-ES. New storage systems developed under the Program will play an important role in the development of independent microgrids – either individual buildings or communities of buildings – so microgrid-scale storage, on the order of one megawatt of distributed generation, is within the scope of this effort.

Storage systems developed through SEGIS-ES will interface with SEGIS products to further enhance PV system value and economy to customers. Products to be developed through SEGIS-ES include, but are not limited to:

- Battery-based systems using existing technologies that are enhanced or specifically designed for PV applications, including the development of PV-Storage hybrid systems;
- New energy storage system controllers that interface with SEGIS hardware to optimize battery use in order to obtain the highest possible system efficiency and battery life;
- Non-battery storage systems (*e.g.,* electrochemical capacitors [ECs], flywheels) designed specifically for PV applications; and
- New devices that integrate with building infrastructure.

SEGIS-ES does not address:

- Development of PV modules;
- Development of new battery technologies (although collaboration with the DOE Office of Basic Energy Sciences Energy Frontier Research Centers' Funding Opportunity is encouraged);

- Utility-scale storage systems or storage at the level of large distribution feeders (Although these efforts are key to achieving high penetration of distributed generation, they will be addressed through other Program activities);
- PV inverters or related power conditioning devices; and
- Non-solar-related storage system development, smart appliances, and utility portals.

5. The Need for Energy Storage in High-penetration PV Systems

PV systems are a small part of today's electricity infrastructure and have little effect on the overall quality or reliability of grid power. Nevertheless, state and federal efforts are currently underway to greatly increase the penetration of PV systems on local and regional utility grids to achieve goals related to emissions reduction, energy independence, and improved infrastructure reliability. However, when PV penetration reaches sufficiently high levels (*e.g.,* 5 to 20% of total generation), the intermittent nature of PV generation can begin to have noticeable, negative effects on the entire grid.

Figure 1 illustrates the transient nature of PV generation as clouds pass over a typical residential system during the course of a day. Both the magnitude and the rate of the change in output are important: in mere seconds, the PV system can go from full output to zero (essentially), and back again. At high levels of PV penetration, this intermittency can wreak havoc on utility operations and on load-side equipment, due to fluctuations in grid voltage and power factor. Fluctuations at this scale simply cannot be allowed.

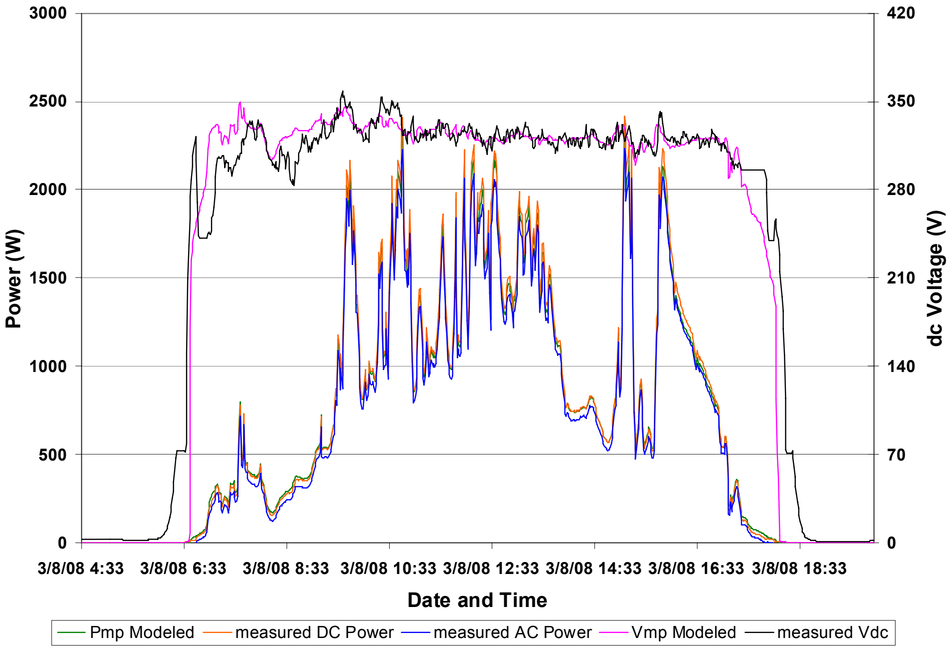

Figure 1: Measured and modeled PV system output on a day with frequent passing clouds.

To some degree, the distributed nature of PV can help mitigate negative consequences of high PV penetration; over large regions, the effects of intermittent generation on the grid will be less noticeable. Nevertheless, utilities must continue to address worst-case possibilities.

When transients are high, area regulation will be necessary to ensure that adequate voltage and power quality are maintained. When PV generation is low, some type of back-up generation will be needed to ensure that customer demand is met. Additionally, because most utilities require an amount of 'spinning reserve' power that typically is equal to the power output of the largest generating unit in operation, the amount of spinning reserve necessary will increase with the amount of distributed PV generation that is brought online. Without such measures, the benefits of high PV penetration are partially lost—carbon and other emissions are offset through PV-produced electricity; but, utility infrastructure is not reduced and power quality is not necessarily improved.

As the graph in Figure 2 illustrates, high PV penetration might reduce intermediate fossil fuel generation; but, without storage, PV will do little, or nothing, to reduce a utility's overall conventional generation due to the higher requirements for spinning reserve.

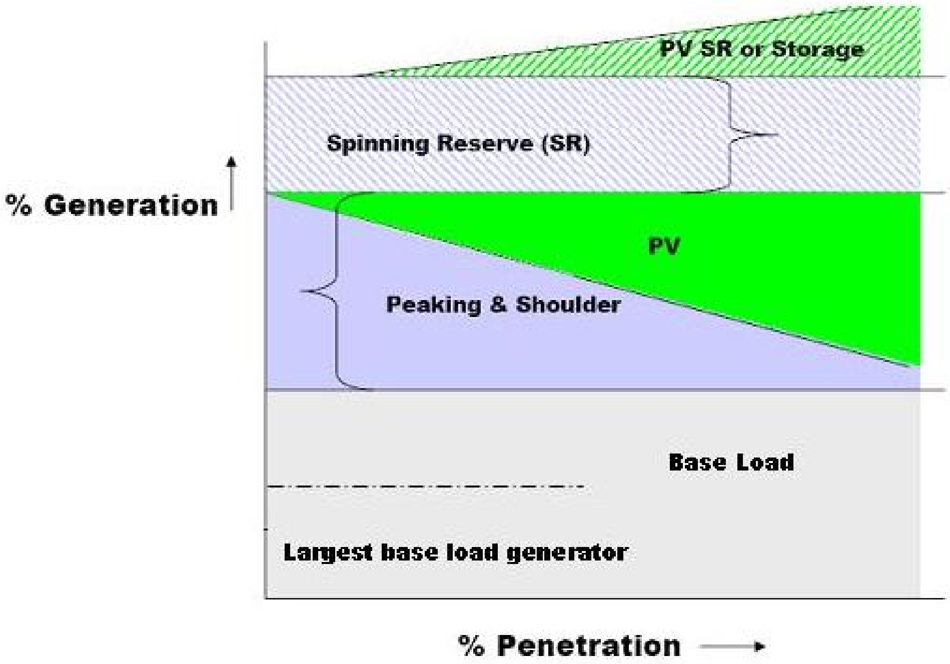

Figure 2: The need for additional spinning reserve or storage to back up intermittent PV generation at increasing levels of penetration.

As a whole, the utility grid must evolve in several ways to accommodate any increased penetration of PV and other distributed and intermittent electricity generation sources; including improved flexibility, better load management, integration of storage technologies, and even limited curtailment for extreme events. Several efforts are underway to define the next-generation grid infrastructure, which will include those characteristics.[4]

A recent study that specifically focused on the current grid and high-penetration PV called energy storage the 'ultimate solution' for allowing intermittent sources to address utility baseload needs. The report stated that "a storage system capable of storing substantially less than one day's worth of average demand could enable PV to provide on the order of 50% of a system's energy."[5] This paper focuses on incorporating storage as part of the overall 'systems' solution.

Successfully integrating energy storage with distributed PV generation in grid-connected applications involves much more than selecting an adequately sized system based on one of the many, commercially available technologies. Optimal integration of storage with grid-tied PV systems requires a thorough understanding of the following:

- The application for which the storage is being used and the benefits integrated storage provides for that application;
- The available storage technologies and their suitability to the application;
- The requirements and constraints of integrating distributed generation and electrical energy storage with both the load (residential, commercial, or microgrid) and the utility grid;
- The power electronics and control strategies necessary for ensuring that all parts of the grid-connected distributed generation and storage system work; and
- The requirements to provide service to the load and to maintain or improve grid reliability and power quality.

The complexity of an integrated PV-Storage system is illustrated in Figure 3, which shows SEGIS-based generation integrated with electrical energy storage for a residential or small commercial system.

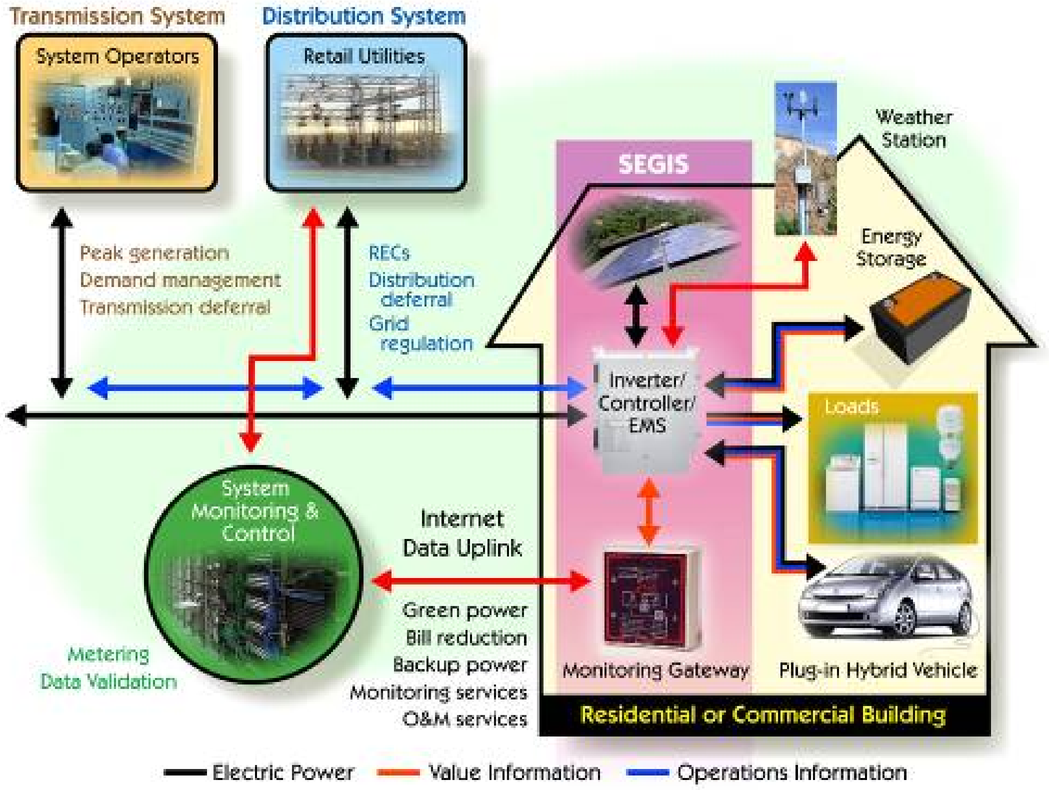

Figure 3: The relationship between SEGIS, electric energy storage, the customer, and the utility in an optimal configuration.[6]

6. Applications of Energy Storage in High-penetration PV Systems

Integrated PV-Storage systems provide a combination of operational, financial and environmental benefits to the system's owner and the utility through peak shaving and reliability applications.[7]

Peak Shaving, *Load Shifting*, and *Demand Response* are variations on a theme—supplying energy generated at some point in time to a load at some later time. The rate structure and interactions between the utility and the customer determine which application is being addressed.

Peak Shaving: The purpose of this application is to minimize demand charges for a commercial customer or to reduce peak loads experienced by the utility. Peak shaving using PV-Storage systems requires that the PV provide all required power above a specified threshold and, if PV is not available, then provide adequate energy storage to fill the gap. Failure to peak shave on one day can have severe economic consequences in cases where customers' rates are based on monthly peak demand. Thus, reliability of the PV-storage system is a key element. If PV is unavailable to meet the load, the system controller must be able to dispatch power from an energy storage system in order to implement peak shaving.

Load Shifting: Technically, load shifting is similar to peak shaving, but its application is useful to customers purchasing utility power on a time-of-use (TOU) basis. Many peak loads occur late in the day, after the peak for PV generation has passed. Storage can be combined with PV to reduce the demand for utility power during late-day, higher-rate times by charging a storage system with PV-generated energy early in the day to support a load later in the day.

Pacific Gas and Electric (PG&E) offers the experimental rate structure shown in Table 2 for residential customers. In this schedule, peak rates apply between 2 p.m. and 7 p.m. on weekdays and super-peak rates apply between 2 p.m. and 7 p.m. for no more than 15 days in a calendar year during critical events (as designated by the independent system operator, or ISO) and emergencies. Thus, customers with a PV-Storage system could use PV to charge the storage device earlier in the day (*i.e.,* during peak insolation) and then use the storage system to supply all or part of the load when peak or super-peak rates are in effect. With rate structures such as these in effect, a PV-Storage system could potentially provide significant economic benefits to residential and small commercial customers.

Table 2: PG&E Rate Schedule E-3 – Experimental Residential Critical Peak Pricing Service[8]

Total Energy Rates ($/kWh)	Super Peak	Peak	Off Peak
Summer Baseline Usage	0.67439	0.23096	0.08039
Winter Baseline Usage	0.50997	0.31197	0.10497

Demand Response: Demand response is rapidly becoming a viable load management tool for electric utilities. During high-demand periods, demand response allows the utility to control selected high-load devices, such as heating, ventilation, and air conditioning (HVAC) and water heating, in a rolling type of operation. Utility rate structures are currently changing to accommodate this new operational strategy by reducing rates for customers who choose to be included in the demand response program. For both residential and small commercial customers, using an appropriately sized PV-Storage system should allow the implementation of demand response strategies with little or no effect on local operations.

While both residential and commercial PV-Storage systems have the inherent capability to manage demand response requirements, control systems capable of reacting to demand response must be developed. Specifically, control systems must dispatch the PV-Storage system, as necessary, to manage the loads curtailed by the demand response program. Consequently, at least one-way communication with the utility might be required.

Outage Protection, *Grid Power Quality Control,* and *Microgrids* increase the reliability of the electricity grid and are not as subject to regulatory and rate-based actions.

Outage Protection: An important benefit of a PV-Storage system is the ability to provide power to the residential or small commercial customer when utility power is unavailable (*i.e.,* during outages). To provide this type of protection, it is necessary to intentionally island the residence or commercial establishment in order to comply with utility safety regulations designed to prevent the back-feeding of power onto transmission and distribution (T&D) lines during a blackout. Islanding requires highly reliable switching equipment for isolating the local loads from the utility prior to starting up local generation.

Islanding capability, whether utility or customer-controlled, is mutually beneficial to both the utility and the customer, because it allows the utility to shed loads during high demand periods while protecting the customer's loads if the utility fails. To realize the full benefit of these capabilities, however, new controllers are needed to respond to both utility and customer needs. Additionally, new regulations will be needed to define how these controllers will be managed safely to benefit both the utility and the customer.

Grid Power Quality Control: In addition to outage protection, power quality ensures constant voltage, phase angle adjustment, and the removal of extraneous harmonic content from the electricity grid. On the customer side, this function is currently supplied by UPS devices. A UPS must sense, within milliseconds, deviations in the AC power being supplied and then take action to correct those deviations. A common deviation is a voltage sag in which the UPS supplies the energy needed to return the voltage to the desired level.

UPS functions can be added to PV-Storage systems in the power conditioning system by designing it to handle high power applications and including the necessary control functions. UPS functionality can be combined with peak shaving capability in the same system.

Microgrids: Microgrids have the potential to significantly increase energy surety,[9] and their incorporation into the larger grid infrastructure is expected to become an increasingly important feature of future distribution systems. Renewable generation and energy storage are essential to achieving highly sustainable, highly reliable microgrids. When operating separately from the local utility (*i.e.,* when 'islanded'), microgrids with PV-Storage systems will use PV-generated electricity to supply power to the load.

Energy storage is essential to ensure stable operation of the Microgrid, through management of load and supply variations, and for keeping voltage and frequency constant. Successful integration into the larger utility grid infrastructure of microgrids that include PV-Storage systems will provide many operational benefits to utilities and customers. However, microgrids will require a high level of system control, a detailed knowledge of the load(s) being served, and thoughtful design of the PV-Storage system.

Table 3 summarizes current and future applications that can be addressed by integrating energy storage with distributed PV generation.

Table 3: Applications for Storage-integrated PV

Residential			
Homeowner-owned Systems		**Utility-owned Systems**	
Current: • Save solar energy for evening use in TOU operations • Back-up power (UPS)	**Future:** • With time of day residential rates, load shifting • Lower cost than utility • Smart grid interface	**Current:** • Solar community – ride-through during cloud cover • Distributed generation • Congestion reduction	**Future:** • Smart grid applications (*e.g.,* distributed energy management, microgrid islanding, peak shaving/shifting.) • High penetration ramp control (short-term spinning reserve) • Emission reduction, carbon credits (with high penetration)
Commercial			
Business-owned Systems		**Utility-owned Systems**	
Current: • Peak shaving to reduce TOU and/or demand charges • Power quality and UPS	**Future:** • Carbon credits • Microgrid generation and islanding • Smart grid/building management interfaces	**Current:** • Distributed generation • Congestion reduction • Improved power quality	**Future:** • Microgrid generation and islanding • Emission reduction, carbon credits (with high penetration)

The economic benefits that can be realized from PV-Storage systems are a function of the application, the size of the system, the sophistication of the system's electronic control equipment, the customer's rate structure, and the utility's generation mix and operating costs. Systems that include UPS features are expected to mitigate the costs of power quality events and outages.

Results of a recent study also suggest that adding PV generation to a planned UPS installation is attractive because of the synergy between PV and storage in the UPS market. In other words, sites where customers have already decided to purchase load protection via energy storage might be an attractive near-term target for PV developers.[10]

In general, however, most financial benefits will result from reduced peak-demand and TOU charges for consumers and the avoided costs of maintaining sufficient peak and intermediate, power generating capability plus spinning reserve for utilities. By facilitating an optimal mix of generation options, it is expected that the cost to the utility of adding additional generating capacity and the associated T&D equipment can be reduced, as can the costs associated with upgrading existing T&D equipment to meet new demand.

In the future, additional financial benefits could accrue to the end user by selling power back to the utility and to the utility by selling carbon credits realized by aggregating PV generation as a market commodity. Ideally, rate structures for PV-Storage systems could be designed to benefit both system owners and utilities. To fully realize all of the potential, economic benefits will, however, require an advanced control system that includes communications between the utility, the PV-Storage system, and (possibly) the customer.

Finally, at high levels of penetration, PV systems offer significant environmental benefits. One such benefit is that they create no emissions while generating electricity. Another is that they can be installed on rooftops and on undesirable real estate, such as brown fields, which can reduce a utility's need to acquire land for construction of new, large-scale generating facilities, not to mention the associated local opposition to such acquisitions, and the environmental consequences of large-scale industrial construction. Adding electrical energy storage to distributed PV generation also produces no emissions and, by allowing PV-generated electricity to be used at times when PV would normally not be available (*e.g.,* at night or when it is cloudy), allows greater benefits to be realized than with PV systems alone.

7. Current Electrical Energy Storage Technologies and R&D

Energy storage devices cover a variety of operating conditions, loosely classified as 'energy applications' and 'power applications'. Energy applications discharge the stored energy relatively slowly and over a long duration (*i.e.,* tens of minutes to hours). Power applications discharge the stored energy quickly (*i.e.,* seconds to minutes) at high rates. Devices designed for energy applications are typically batteries of various chemistries. Power devices include certain types of batteries, flywheels, and ECs. A new type of hybrid device, the lead-carbon asymmetric capacitor, is currently being developed and is showing promise as a device that might be able to serve both energy applications and power applications in one package.

Figure 4 illustrates several battery and capacitor technologies in relation to their respective power/energy capabilities.[11] The traditional lead-acid battery stands as the traditional benchmark. The plot shows that significantly greater energy and power densities can be achieved with several rechargeable battery technologies.

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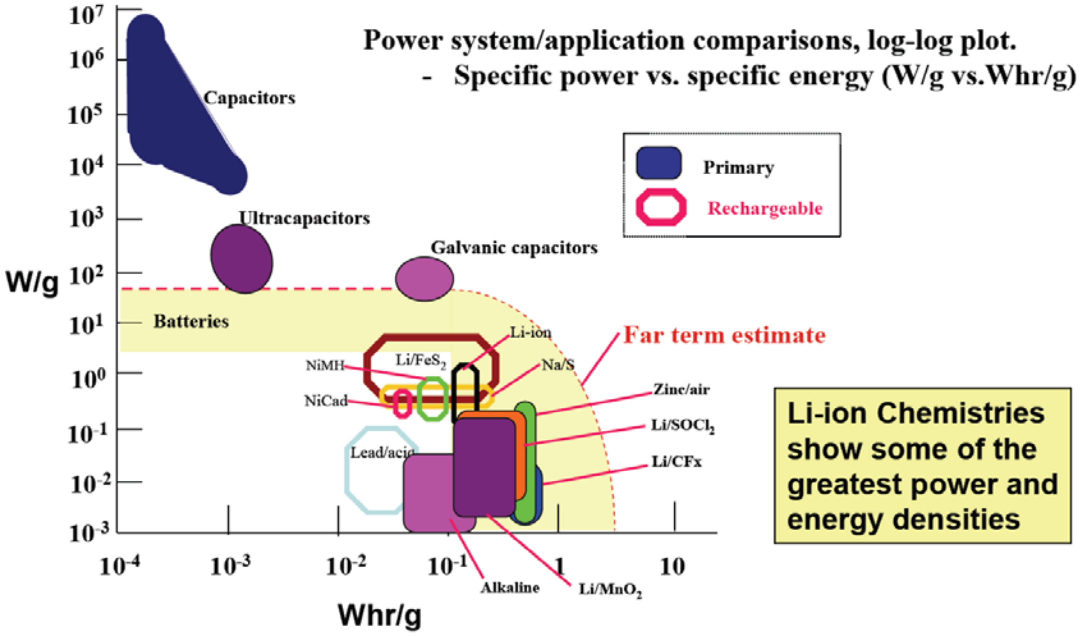

Figure 4: Specific power vs. specific energy of several energy storage technologies.[12]

To date, the advantages of lead-acid technology, such as low cost and availability, have made it the default choice for energy storage in most PV applications. Indeed, new developments in valve-regulated lead-acid (VRLA) technology might revolutionize this well-established technology.

A number of lead-acid battery manufacturers, such as East Penn in the U.S. and Furukawa in Japan, are manufacturing prototype batteries for hybrid electric vehicles (HEVs) that promise to overcome the main disadvantages of VRLA batteries by using special carbon formulations in the negative electrode. The added carbon inhibits hard sulfation, which minimizes or eliminates many common failure mechanisms (*e.g.,* premature capacity loss and water loss). In cycling applications, the new VRLA technology could dramatically lower the traditional battery energy costs by increasing cycle life, efficiency, and reliability.

Traditionally, nickel-cadmium (NiCd) batteries have been the replacement for lead-acid; but, due to various operational and environmental issues, industry is moving away from this technology as newer and better technologies are developed. Indeed, even in the portable electronics market, lithium-ion (Li-ion) batteries are rapidly replacing NiCd.

Additionally, a new Li-ion technology, the Li-iron phosphate (Li-FePO) cell, is rapidly becoming a prime contender for the next generation of HEV batteries, replacing existing nickel-metal hydride (Ni-MH) technology. This Li-ion technology is proving to be much safer than the previous generation and is capable of higher power levels, which makes it a better candidate for HEV applications.

A lesser known technology, sodium/nickel-chloride (Na/NiCl), has been developed by Zebra Technologies in Europe for motive applications, and is currently being considered for some stationary applications, such as peak shaving, in the U.S. Other advanced battery technologies (*e.g.,* sodium/sulfur, or Na/S) are currently targeting utility-scale (> 1MW) stationary applications.

Although these technologies are not currently being considered for use in the smaller applications discussed here, future advances in their developments might increase the technical and economic viability for such applications. Table 4 summarizes the battery technologies that have been identified as potential candidates for integration with grid-tied distributed PV generation in residential and small commercial systems.

Table 5 provides a summary of non-battery technologies that can be integrated with grid-tied distributed PV generation. Although they are still in the early commercial stage of development, hybrid lead-carbon asymmetric capacitors are also targeting the peak-shaving market and low-speed flywheels are currently being used in many UPS applications.

ECs are ideal for high-power, short-duration applications because they are capable of deep discharge and have a virtually unlimited cycle life. Due to these advantages, a great deal of research is being focused on developing ECs that can be used for small-scale stationary energy storage. Any of these battery or non-battery technologies can be appropriate for residential and small-commercial integrated PV and storage systems in the near future.

In addition to the efforts of the technology manufacturers, DOE (through several program offices) is conducting research and executing pilot programs to improve the utilization of electrical energy storage for stationary applications. In particular, since the late 1970s, the DOE Energy Storage Systems Program (DOE/ESS) has worked with the utility industry to develop stationary energy storage systems for utility applications.

In the 1990s, DOE/ESS shifted the focus of its development of advanced storage technologies to include an emphasis on integrating storage devices with power electronics and communications equipment for use in specific applications. Over the past decade, the Program has gained valuable practical experience by partnering with storage technology manufacturers, power electronics and monitoring equipment manufacturers, systems integrators, electric utilities, and their customers to demonstrate integrated electric energy storage systems of all types and sizes. Lessons learned from the Program's demonstrations and research provide uniquely applicable experience for successfully incorporating electrical energy storage with distributed PV generation.

The DOE Vehicle Technologies Program, in partnership with the automotive industry, manages and conducts research on battery technologies for EVs and HEVs (*e.g.,* lithium-aluminum-iron-sulfide, Ni-MH, Li-ion, and lithium-polymer). Li-ion systems come closest to meeting all of the technical requirements for vehicle applications; but, they face four barriers: calendar life, low-temperature performance, abuse tolerance, and cost. Technology advances that address these barriers will have direct applicability to PV-Storage systems for stationary applications.

Finally, the DOE Office of Basic Energy Sciences conducted a comprehensive workshop on April 2-4, 2007, that set R&D priorities for improving the energy density of several storage technologies. Principal barriers identified at the workshop were related to reducing cost, increasing power and energy density, lengthening lifetime, increasing discharge times, improving safety, and providing reliable operation through one-to-ten thousand rapid charge/discharge cycles.

Several associated R&D efforts are underway. One such effort is the announcement of a funding opportunity to establish Energy Frontier Research Centers (EFRCs) specifically focused on "addressing fundamental knowledge gaps in energy storage."[13] The SEGIS-ES program will be closely coordinated with any developments to come from these programs.

Table 4: Battery Technologies for Electric Energy Storage in Residential and Small-commercial Applications

Technology	Advantages	Disadvantages	Commercial Status	Current R&D	Applications
Flooded Lead-acid	• Cost effective • Mature technology • Relatively efficient	• Low energy density • Cycle life depends on battery design and operational strategies when deeply discharged • High maintenance • Environmentally hazardous materials	• Globally commercial • Over $40B in all applications • Estimated $1B in utility applications worldwide	Focused on reducing maintenance requirements and extending operating life.	• Motive power (forklifts, carts, etc.) and deep-cycling stationary applications • Back-up power • Short-duration power quality • Short-duration peak reduction
VRLA	• Cost effective • Mature technology	• Traditionally have not cycled well • Have not met rated life expectancies	• Globally commercial • Over $40B in all applications • Estimated $1B in utility applications worldwide	Improving cycle-life and extending operating life, such as using carbon-enhanced negative electrodes.	• Limited motive power applications (*e.g.,* electric wheelchairs) • Back-up power • Short-duration power quality • Short-duration peak reduction
NiCd	• Good energy density • Excellent power delivery • Long shelf life • Abuse tolerant • Low maintenance	• Moderately expensive • "Memory Effect" • Environmentally hazardous materials	• Globally commercial • Over $1B in all applications • Over $50M in utility applications worldwide	None identified.	• Aircraft cranking, aerospace, military and commercial aircraft applications • Utility grid support • Stationary rail • Telecommunications back-up power • Low-end consumer goods
NiMH	• Good energy density • Low environmental impact • Good cycle life	• Expensive	• Globally commercial for small electronics • Emerging market for larger applications	Bipolar design.	• EVs, HEVs • Small, low-current consumer goods
Li-ion	• High energy density • High efficiency	• High production cost • Scale-up proving difficult due to safety concerns	• 50% of global small portable market	Batteries for use in EVs and HEVs are currently being developed.	• Small consumer goods
Li-FePO^4	• Safer than traditional Li-ion • High power density • Lower cost than traditional Li-ion	• Lower energy density than other Li-ion technologies	• High-volume production began in 2008	Focused on improving performance and safety systems.	• Small consumer goods and tools • EVs, HEVs
Na/S	• High energy density • No emissions • Long calendar life • Long cycle life when deeply discharged • Low maintenance • Integrated thermal and environmental management	• Relatively high cost • Requires powered thermal management (heaters) • Environmentally hazardous materials • Rated output available only in 500-kW/600-kWh increments	• Recently commercial (2002) in Japan • Estimated $0.4B in utility/industrial applications worldwide	Focused on increasing manufacturing yield and reducing cost.	• Utility grid-integrated renewable generation support • Utility T&D system optimization • Commercial/industrial peak shaving • Commercial/industrial backup power

Technology	Advantages	Disadvantages	Commercial Status	Current R&D	Applications
Zebra Na/NiCl	• High energy density • Good cycle life • Tolerant of short circuits • Low-cost materials	• Only one manufacturer • High internal resistance • Molten sodium electrode • High operating temperature	• Globally commercial for traction applications.	Focused on cost reduction and systems for stationary applications.	• EVs, HEVs, and locomotives • Peak shaving
Vanadium Redox	• Good cycle life • Good AC/AC Efficiency • Low temperature/low pressure operation • Low maintenance • Power and energy are independently scaleable	• Low energy density	• Commercial production since 2007	Focused on cost reduction.	• Firming capacity of renewable resources • Remote area power systems • Load management • Peak shifting
Zinc/bromine (Zn/Br)	• Low temperature/low pressure operation • Low maintenance • Power and energy are independently scaleable	• Low energy density • Requires stripping cycle • Medium power density	• Emerging commercial products	Focused on system integration.	• Back-up power • Peak shaving • Firming capacity of renewables • Remote area power • Load management

Table 5: Non-battery Technologies for Electric Energy Storage in Residential and Small-commercial Applications

Storage Type	Advantages	Disadvantages	Commercial Status	Current R&D	Applications
Lead-carbon asymmetric capacitors (hybrid)	• Rapid recharge • Deep discharge • High power delivery rates • Long cycle life • Low maintenance	• Lower energy density than batteries • Lower power density than other ECs	• Non-commercial prototypes	Laboratory prototypes Field demonstration planned FY08 in NY.	• Peak shaving • Grid buffering
Electrochemical Capacitors	• Extremely long cycle life • High power density	• Low energy density • Expensive	• Commercialized in US, Japan, Russia, and EU, emerging elsewhere • Over $30 million in all applications • $5 million in utility applications by 2006	Devices with energy densities over 20 kWh/m^3 are under development.	• HEVs • Portable electronics • Utility power quality • T&D stability
Flywheels	• Low maintenance • Long life • Environmentally inert	• Low energy density • High cost	• Commercialized in US, Japan, Europe, emerging elsewhere • Projected to sell over 1,000 systems per year, estimated rated capacity of 250 MW • Retail value exceeding $50 million by 2006	Focused on low cost commercial flywheel designs for long duration operation.	• Aerospace • Utility power quality • T&D stability • Renewable support • UPS • Telecommunications

8. The Costs of Electrical Energy Storage

Both current and projected costs for battery and other storage systems are related to capital costs (first costs) and are based on the overall energy capacity of those systems. Table 6 shows the current and projected first capital costs of energy storage systems based on technologies identified as suitable for residential and small-commercial PV-Storage systems.

Table 6 was compiled from the results of a literature review and discussions with technology leaders at national laboratories and in industry. Recent increases in the prices of materials, such as lead, for existing battery technologies have led to increased system costs. These trends are likely to continue, possibly driving the prices for established technologies even higher.

Unless noted, the system costs include the storage device and the power conditioning system necessary for turning DC output from the storage device into 60-Hz AC power suitable for delivery to the load. For these systems, capital costs will be lowered by combining the power electronics for both the PV and storage components.

Table 6: Energy Storage System Capacity Capital Costs[14] [15] [16] [17] [18] [19] [20] [21] [22]

Technology	Current Cost ($/kWh)	10-yr Projected Cost ($/kWh)
Flooded Lead-acid Batteries	$150	$150
VRLA Batteries	$200	$200
NiCd Batteries	$600	$600
Ni-MH Batteries	$800	$350
Li-ion Batteries	$1,333	$780
Na/S Batteries	$450	$350
Zebra Na/NiCl Batteries	$800 [1]	$150
Vanadium Redox Batteries	20 kWh=$1,800/kWh; 100 kWh =$600/kWh	25 kWh=$1,200/kWh 100 kWh=$500/kWh
Zn/Br Batteries	$500	$250/kWh plus $300/kW [2]
Lead-carbon Asymmetric Capacitors (hybrid)	$500	<$250
Low-speed Flywheels (steel)	$380	$300
High-speed Flywheels (composite)	$1,000	$800
Electrochemical Capacitors [3]	$356/kW	$250/kW

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[1] €600/kWh

[2] The battery system includes an integrated PCS; the PCS price will vary with the rated system output.

[3] Electrochemical capacitors are power devices used only for short-duration applications. Consequently, their associated costs are shown in $/kW rather than $/kWh.

Determining life-cycle costs depends on a number of factors related to system design, component integration, and overall use. Accurate prediction of life-cycle costs also depends on developing reasonably predictive models for PV-integrated storage. More modeling and analytical work are needed to determine the incremental, levelized cost of energy (LCOE) and the incremental value of increased benefits that storage will bring to PV systems.

9. Summary of Key R&D Needs for PV-Storage Systems

Achieving high-penetration of PV-Storage systems on the nation's utility grid will require overcoming certain technological and economic obstacles. In addition to the specific gaps described below, the successful implementation of optimal, small-scale PV-Storage systems will require further development, testing, and demonstration of complete systems of varying complexities and costs.

9.1. Storage Technologies

To meet the needs of SEGIS-based systems, it will be necessary to develop battery and other storage systems that, although state-of-the-art, are enhanced or specifically designed for use with grid-tied PV systems. It should be noted that any advances in storage technology will be of value to grid-tied PV-Storage systems because they further the understanding of the technology, which facilitates selection of the most appropriate technology for the application and, ultimately, reduces the costs of the storage components.

As previously stated, the main R&D needs for storage technologies address the following aspects of their use:

- Increasing power and energy densities;
- Extending lifetimes and cycle-life;
- Decreasing charge-discharge cycle times;
- Ensuring safe operation; and
- Reducing costs.

Typically, batteries do not work effectively under partial state of charge (PSOC) conditions. PSOC operation occurs when a battery is less than fully discharged and then less than fully recharged before again being discharged. Current research into carbon-enhanced, lead-acid batteries shows high potential for significantly improving PSOC operation. Nevertheless, PSOC operation is not fully understood for all battery chemistries. Charge and discharge profiles for grid-connected PV-Storage applications should be tested on the most promising technologies. To improve PSOC operation, further development and optimization of batteries of various chemistries is also needed.

9.2. Control Electronics

To achieve long lifetimes, maximum output, and optimal efficiency, batteries must be charged and discharged according to the recommendations of the manufacturer. For example, traditional lead-acid batteries require a long (multiple-hour), low-current finish charge to remove sulfation from the lead plates. If finish charging is not completed properly, battery lifetime is shortened and capacity is reduced. This finish charge is very difficult to accomplish with only a PV-based generation source.

Advanced battery management systems can be developed to address some of the charge/discharge issues. The U.S. Coast Guard is sponsoring an effort to develop the Symons Advanced Battery Management System (ABMAS) for off-grid, PV-Storage-Generator hybrid systems.[23] Initial results using the ABMAS system show a 25% reduction in fuel use and improved battery charging and discharging profiles, thus promising increased battery lifetime. Similar management systems are needed for grid-connected PV-Storage systems and applications.

By themselves, energy storage devices (batteries, flywheels, etc.) do not discharge power with a 60-Hz AC waveform, nor can they be charged with 60-Hz AC power. Instead, a power conditioning system is necessary to convert the output. Under the SEGIS initiative, the DOE Solar Energy Program is currently developing integrated power conditioning systems for PV systems. These systems include inverters, energy management systems, control systems, and provisions for including energy storage. It is anticipated that charging and discharging control algorithms for different battery technologies will be included in the SEGIS control package. In the case of lead-acid and NiCd batteries, this will be relatively straightforward.

Other technologies (*e.g.,* Li-ion, vanadium redox, and Zn/Br batteries or flywheels) require more complex safety and control systems. These systems are typically sold by the battery manufacturer as part of an integrated, 'plug-and-play' energy storage system that includes the storage device, an inverter, and proprietary control and safety systems. To achieve the most economical total system using these technologies, SEGIS system manufacturers and manufacturers of these energy storage products could cooperate to design a fully integrated product with minimal duplicated functionality.

9.3. Comprehensive Systems Analysis

Successful development of SEGIS-based PV-Storage systems will require comprehensive systems analysis, including economic and operational benefits and system reliability modeling. Systems must be analyzed based on the requirements of the application. The analysis should include an investigation of all of the possible storage technologies suitable for use in the application and the operational/cost/benefits tradeoffs of each. The analysis must include a methodology for determining the life-cycle costs of PV-Storage systems using conventional industry metrics. The methodology will be used to determine benefit/cost tradeoffs for specific applications and system configurations.

Software-based modeling and simulation tools represent a key component of successful systems analysis. PV system designers use various models to evaluate the needs for, and effects of, various technologies. The system-level modeling software packages that are currently available to designers include Solar Advisor Model (SAM), Hybrid Optimization Model for Electric Renewables (HOMER), PV Design Pro, and HybSim. For the most part, these models do not accommodate storage well. HybSim, funded by DOE's Energy Storage Systems Program, focuses on integrating storage, diesel generation, and wind or PV-generation.

Ideally, models and simulation tools for grid-tied PV-Storage systems will be able to:

- Fully evaluate the benefits of a given PV-Storage system by modeling solar energy production, building loads, and energy storage capabilities relative to capital cost, maintenance, and the real-time cost of alternate energy sources (utility power);
- Accurately simulate residential, commercial, and utility systems and provide recommendations for how to operate, dispatch, and control the PV-Storage system to optimize its economic performance under various loads and rate structures; and
- Provide detailed models of the interrelationships between the various system components and operating parameters, including the physical relationships, operating rules, regulations, and business decision-making criteria to aid in comprehensive systems analysis and identify relationships that might create unexpected vulnerabilities or provide additional robustness.

10. Summary – The Path Forward

To address the technology gaps described above and to ensure that grid-tied PV-Storage systems meet the needs of customers, utilities, and all other stakeholders, a three-pronged approach is recommended:

- Comprehensive systems analysis and modeling,
- An industry-led R&D effort focused on commercialization of new integrated systems, and
- Development of appropriate codes and standards that facilitate broader market penetration of PV-Storage systems and address all related safety concerns.

These three aspects of SEGIS-ES are discussed in greater detail below.

10.1. Systems Analysis and Modeling

The RSI studies resulted in a series of reports that addressed the myriad issues related to high penetration of PV on utility infrastructure and business models, technical system design, and economic effects. A similar set of studies is proposed to fully investigate the role of energy storage in this environment. These analytical studies will include the development of new modeling tools and will address the following:

- Development of models that explore several aspects of PV-Storage system integration, including system technical performance optimization; grid operational performance, stability, and reliability; cost/benefits; life-cycle costs; *etc.* Models will also address advantages and disadvantages of distributed versus aggregated storage systems (*e.g.,* community-scale *vs.* residential), and the integration of PV-Storage systems with building loads, operating rules and regulations and business decision-making criteria to identify relationships that might create unexpected vulnerabilities or provide additional robustness.

- Investigation of integrating Energy Management Systems (EMS) with PV-Storage systems to optimally manage power for commercial facilities, including development of predictive algorithms for loads and PV output to effectively manage storage.

- Exploration of the role and potential for plug-in hybrid electric vehicles (PHEVs) to provide grid and PV generation support. Because they are mobile devices, using PHEVs for grid support or as energy storage devices to support residential/small-commercial distributed PV generation presents unique challenges for system integrators. Consequently, we recommend investigating how PHEV-based storage can best be aggregated to support distributed PV generation and determine the operational requirements and system specifications necessary for doing so.

10.2. Partnered Industry Research and Development

An industry-led effort will be initiated to strengthen ties among manufacturers and installers in the storage industry with appropriate partners and stakeholders in the PV industry (including utilities), to achieve the following goals:

- Development of new components and integrated PV-Storage systems for grid-connected applications by identifying the requirements and constraints of integrating distributed generation and electrical energy storage with both the load (residential, commercial, or microgrid) and the utility grid. This effort will include development of the power electronics and control strategies necessary to ensure that all parts of the grid-connected distributed generation and storage system work as expected to provide service to the load and maintain or improve grid reliability and power quality.

- Test and verification of promising battery technologies using charge/discharge profiles specifically designed for grid connected PV-Storage applications, in order to develop and optimize the PSOC operation of the battery chemistries.

- Provide the training (cross training, in some instances,) necessary for successfully installing, operating, maintaining, and troubleshooting these highly integrated systems.

10.3. Codes and Standards Development

Ultimately, high levels of penetration of grid-tied distributed generation and storage will affect the utility grid and those who use it in many significant ways. Consequently, codes standards, and regulations for integrating these systems with the grid will be needed to facilitate this integration. Additionally, safety guidelines and regulations that specifically address the complexities of these systems will need to be developed and implemented.

The development of this regulatory environment will be a concerted effort that will build on the current codes and standards infrastructures that exist for the PV, energy storage, construction, and utility industries; and will lead to a comprehensive set of guidelines that will facilitate the greater market penetration of PV-Storage systems.

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