TECHNOLOGY DEVELOPMENT NEEDS FOR INTEGRATED GRID-CONNECTED PV SYSTEMS AND ELECTRIC ENERGY STORAGE

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ABSTRACT

Researchers at Sandia National Laboratories and the U.S. Department of Energy's Solar Energy Technologies Program assessed status and needs related to optimizing the integration of electrical energy storage and grid-connected photovoltaic (PV) systems. At high levels of PV penetration on our electric grid, reliable and economical distributed energy storage will eliminate the need for back-up utility generation capacity to offset the intermittent nature of PV generation. This paper summarizes the status of various storage technologies in the context of PV system integration, addressing applications, benefits, costs, and technology limitations. It then discusses further research and development needs, with an emphasis on new models, systems analysis tools, and even business models for high penetration of PV-storage systems on a national scale.

1. INTRODUCTION

Several efforts are currently underway to define and establish the electric grid of the future, such as EPRI's Intelligrid, the DOE's Smart Grid, the Galvin Perfect Power Initiative, and others [1]. These initiatives work to improve grid flexibility, reliability, load management, power quality, and other features of our electricity generation and delivery system through the improved application of information and control technologies. This paper focuses on the use of PV-storage as part of the overall "modern grid" system, while focusing on smaller, distribution-scale applications on the order of 1MW or less.

Figure 1 illustrates the intermittent nature of PV generation. The plot shows voltage and power produced by a small residential PV system over the course of a day with frequent passing clouds. Both the magnitude and the rate of change in output are important: in seconds, the PV system can go from full output to 20% output or less 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. Stated simply, fluctuations on this scale will not be allowable.
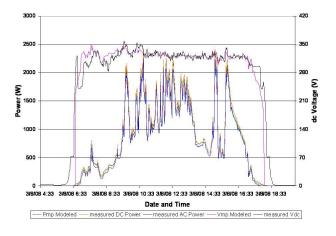

Figure 1: Measured and modeled PV system output on a day with frequent passing clouds.

Figure 2 is a graphical representation of the current need for a utility to add storage or spinning reserve backup capacity as the penetration of PV on its system increases.
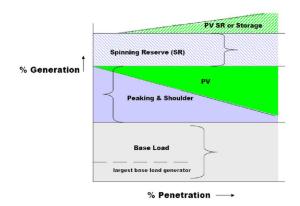

Figure 2: The need for spinning reserve or storage at increasing levels of PV penetration.

As more PV is used to meet intermediate or peaking loads, and thereby offset such generation, additional backup is needed to assure these loads can be met during times of low PV generation. From an economic standpoint, this adds costs to utilities and electricity

consumers that are not directly reflected in the up-front cost of the PV systems.

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;
- 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, including the ability to provide backup power in the event of a grid outage.

This paper addresses the advantages, disadvantages, and costs of several types of electrical energy storage that are considered candidates for integration with PV systems.

2. APPLICATIONS OF ENERGY STORAGE WITH GRID-CONNECTED PV SYSTEMS

Integrated PV-Storage systems provide a combination of financial, operational, and environmental benefits to the system's owner and the utility through peak shaving and reliability applications [2]. Peak shaving, load shifting, and demand response are variations on a theme—supplying energy generated at one 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. Outage protection and power quality control increase the reliability of the electric grid and are not as subject to regulatory and rate-based actions.

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, adequate energy storage to fill the gap. Failure to peak shave for as little as one 15-30 minute period in a month on one day can have severe economic consequences in cases where customers' rates are based on monthly peak demand.

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.

Demand Response: This 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 during high-demand periods. 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. Control systems for demand response systems will require at least one-way communications between the PV-storage site and the utility.

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 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 can be 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.

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 electric 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. 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: The incorporation of microgrids into the larger grid infrastructure is expected to become an increasingly important feature of future distribution systems. Microgrids have the potential to significantly increase energy surety [3]. When operating separately from the local utility (*i.e.,* when 'islanded'), microgrids with PV-Storage systems will use PV-generated electricity (and potentially other sources) to supply power to loads. Energy storage is essential to ensure stable operation by managing load and supply variations and for keeping voltage and frequency constant.

The economic benefits to 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. In general, most financial benefits will result from reduced peak-demand and time-of-use charges for consumers and the avoided costs of maintaining sufficient peak and intermediate power generating capability plus spinning reserve for utilities. Additionally, end users can sell power back to utilities and utilities can sell carbon credits realized by aggregating PV generation as a market commodity. To fully realize all of the potential economic benefits will require advanced controls that include 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 brownfields, which can reduce a utility's need to acquire land for building new large-scale generating facilities, the associated local opposition to such acquisitions, and the environmental consequences of large-scale industrial construction.

3. CURRENT ELECTRICAL ENERGY STORAGE TECHNOLOGIES AND COSTS

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 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 electrochemical capacitors (ECs). Figure 3 shows several rechargeable technologies in relation to their respective power/energy capabilities. The traditional lead-acid battery stands as the benchmark. The plot shows that significantly greater energy and power densities can be achieved with several rechargeable battery technologies.

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. New developments in valve-regulated lead-acid (VRLA) technology may revolutionize this well-established technology 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.
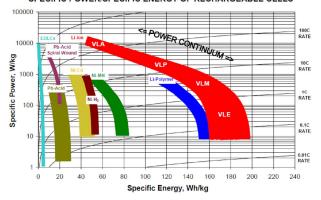

Figure 3: Specific power vs. specific energy of several energy storage technologies.

Traditionally, nickel-cadmium (NiCd) batteries have been the replacement for lead-acid, but industry is moving away from this technology as newer and better technologies are developed. Even in the portable electronics market, lithium-ion (Li-ion) batteries are rapidly replacing NiCd. 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), 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 the technologies themselves may increase their technical and economic viability for such applications.

Some non-battery storage technologies may be integrated with grid-tied distributed PV generation as well. Although they are still in the early development, hybrid lead-carbon asymmetric capacitors are 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. Because of these advantages a great deal of research is being focused on developing ECs that can be used for small-scale stationary energy storage.

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 1 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 1 was compiled from the results of a literature review and discussions with technology leaders at national laboratories and in industry [4]. 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 storage device does not include the power conditioning system necessary for turning DC output from the storage device into 60-Hz AC power suitable for delivery to the load. The capital costs for the systems that include the power conditioning will be lowered by combining the power electronics for both the PV and storage components.

Table 1: Energy Storage Device Capacity Costs (*includes power conditioning system).

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	$1,300	$150
Na/S Batteries*	$450	$350
Zebra Na/NiCl Batteries	$800	$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*	30 kW/45 kWh=$500/kWh 2 MWh=$300/kWh	$250/kWh
Lead-carbon Asymmetric Capacitors (hybrid)	$500	<$250
Low-speed Flywheels (steel)	$380	$300
High-speed Flywheels (composite)*	$2500/kW	$800
Electrochemical Capacitors	$356/kW	$250/kW

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

4. ELECTRICAL ENERGY STORAGE MODELS

There are many algorithms and models that attempt to predict battery performance and lifetime for lead-acid and other batteries used for energy generated by PV and hybrid systems. The European Union (EU) led an international benchmarking project for hybrid power systems in 2005 to better understand battery model limitations and potential fixes, primarily for the widely used Hybrid2 cycle counting software program (which uses Kinetic Battery Model (KiBAM) code) and the FhG/Riso performance-based lifetime model [5]. A recent compilation of battery technologies used by electric utilities [6] discusses energy storage, economics and the need for better battery energy modeling for smart grid and utility scale applications. Other recently-developed models for hybrid power systems are looking beyond conventional batteries at ultra-capacitor and fuel cell technology for energy storage [7].

Storage model research currently focuses on new techniques for widely used lead-acid batteries as well as the development of new tools for battery technologies that may be cost effective in the future. Sandia National Laboratories has done a great deal of work in performance based modeling of lead-acid, Li-Ion and NiMH batteries using Equivalent Circuit, Artificial Neural Network (ANN) and fuzzy logic techniques. Those models coupled with PV systems have looked exclusively at lead-acid batteries [8],[9]. Urbina et al. [10] also looked at how inductive modeling of Li-Ion can enhance a phenomenological model. More recently, a hybrid generation model created by Sandia, HYBSIM [11] uses a battery performance-based lifetime model based on the RETscreen hybrid simulator.

Sauer and Wenzl [12] and Wenzl et al., [13] are addressing the many modeling approaches used for determining lifecycle analysis of lead-acid batteries. They show that these types of modeling approaches need large amounts of data, and some models can be transferable from one lead-acid battery to another. In addition, these groups of models *might be* transferable to other systems, like Li-Ion, NiMH, etc. however more information must be made available to populate these models with chemistries other than lead-acid. In contrast to the more complicated data needs in models outlined by [12], Achaibou et al., [14] discusses an application of the CIEMAT model [15] for lead-acid batteries in PV systems that requires much less battery-specific information from manufacturers and can be applied to a large number of currently available lead-acid batteries.

Many of the new battery technologies have been tested for hybrid and electric vehicle applications. Recent work by Parthiban et al., [16] outlines the many applications of ANN for lead-acid battery modeling as well as new directions for applying ANN for Li-Ion. And more recently, Safari, et al [17] looks at relevant battery aging models for Li-Ion and their approach with what they term a "physics-based phenomenological multimodal model."

5. RESEARCH AND DEVELOPMENT NEEDS

The main research needs discussed in this section fall into three broad categories: storage technologies; controls; and comprehensive systems analysis, including the development of new models.

Storage Technologies: 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.

Batteries also do not typically 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 being discharged again. PSOC operation is not fully understood for all battery chemistries. Charge and discharge profiles for grid-connected PV-Storage applications need to be tested on the most promising technologies. Further development and optimization of batteries of various chemistries to improve PSOC operation is also needed.

Controls: To achieve long lifetimes, maximum output, and optimal efficiency from batteries, they must be charged and discharged according to the manufacturer's recommendations. 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 done properly, battery lifetime is shortened and capacity is reduced. For non grid-tied systems such as an islanded microgrid, the 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.

Energy storage devices themselves (batteries, flywheels, etc.) do not discharge power with a 60-Hz AC waveform (nor can they be charged with 60-Hz AC power); a power conditioning system is necessary to convert the output. The DOE Solar Energy Program is currently developing integrated power conditioning systems for PV systems under the SEGIS initiative [18]. 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. 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.

Systems Analysis and Modeling Tools: Successful development of PV-Storage systems will require comprehensive systems analysis, including economic and operational benefits and system reliability modeling. This analysis must include a methodology for determining the life-cycle costs of PV-Storage systems using conventional industry metrics. This 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. For the most part, current PV system models do not accommodate storage well. Ideally, models and simulation tools for grid-tied PV-Storage systems will be able to accomplish the following:

- 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.
- 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 to identify relationships that might create unexpected vulnerabilities or provide additional robustness.

6. CONCLUSIONS

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 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.

DOE's "Renewable Systems Interconnection" studies [19] 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 needed to fully investigate the role of energy storage in this environment. These analytical studies will include developing new modeling tools to address several aspects of PV-Storage system integration, including system technical performance optimization; grid operational performance, stability, and reliability; cost/benefits; life-cycle costs; and overall energy systems management. 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. Finally, new models are needed to explore the role

and potential for plug-in hybrid electric vehicles (PHEVs) to provide grid and PV generation support.

A cross-industry R&D partnership is also needed to strengthen ties between manufacturers and installers in the storage industry with appropriate stakeholders in the PV industry (including utilities), to develop new components and integrated PV-Storage systems 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 should include test and verification of promising battery technologies using charge and discharge profiles specifically designed for grid-connected PV-Storage applications. Additionally, this partnership is needed to provide the training necessary for successfully installing, operating, maintaining, and troubleshooting these highly integrated systems.

This cross-industry partnership will also provide an invaluable means to develop new codes, standards, regulations, and safety guidelines related to the many significant ways that high penetration of grid-tied distributed generation and storage will affect the utility grid and those who use it. The development of a new 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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REFERENCES

[1] J. Maire, and D. Von Dollen, "Profiling and Mapping of Intelligent Grid R&D Programs", Report 1014600 to the IEEE Working Group on Distribution Automation, December 2006.

[2] D. Manz et al., "Enhanced Reliability of Photovoltaic Systems with Energy Storage and Controls", NREL/SR-581-42299, National Renewable Energy Laboratory, Golden, CO, February 2008.

[3] J. Boyes, and D. Menicucci, "Energy Storage: The Emerging Nucleus", *Distributed Energy*. **5**, January / February 2007.

[4] C.J. Hanley et al., "Solar Energy Grid Integration Systems – Energy Storage", SAND2008-4247, Sandia National Laboratories, Albuquerque, NM, 2008.

[5] H. Bindner et al., "Lifetime Modelling of Lead Acid Batteries", Riso-R-1515, Riso National Laboratory, Roskilde, Denmark, 2005.

[6] K.D. Divya, and J. Ostergaard, "Battery Energy Storage Technology for Power Systems – An Overview", *Electric Power Systems Research*, **79**, 2009, pp. 511-520.

[7] O. Onar, M. Uzunoglu, and M. Alam, "Modeling, control and simulation of an autonomous wind turbine/photovoltaic/fuel cell/ultra-capacitor hybrid power system", *J. Power Sources*, **185**, 2008, pp. 1273-1283.

[8] A. Urbina et al., "Probabilistic Analysis of Rechargeable Batteries in a Photovoltaic Power Supply System", SAND98-2635C, Sandia National Laboratories, Albuquerque, NM, 1988.

[9] A. Urbina, T. Paez, and R. Jungst, "Stochastic Modeling of Rechargeable Battery Life in a Photovoltaic Power System", 35th IECEC. **2**, 2000, pp. 995-1003.

[10] A. Urbina et al., "Inductive Modeling of Lithium-Ion Cells", *J. of Power Sources*. **110**, 2002, pp. 430-436.

[11] L. Kendrick et al., "Hybrid Generation Model Simulator (HYBSIM)", SAND2003-3790A, Sandia National Laboratories, Albuquerque, NM, 2003.

[12] D. Sauer, and H. Wenzl, "Comparison of Different Approaches for Lifetime Prediction of Electrochemical Systems – Using Lead-Acid Batteries as Example", *J. of Power Sources*. **176**, 2008, pp. 534-546.

[13] H. Wenzl et al., "Life Prediction of Batteries for Selecting the Technically most Suitable and Cost Effective Battery", *J. of Power Sources*. **144**, 2005, pp. 373-384.

[14] N. Achaibou, M. Haddadi and A. Malek, "Lead Acid Batteries Simulation Including Experimental Validation", *J. of Power Sources*. **185**, 2008, pp. 1484-1491.

[15] J. Copetti et al., "A General Battery Model for PV System Simulation", *Progress in Photovoltaics: Research and Applications.* **1**, 1993, pp. 283-292.

[16] T. Parthiban et al., "Exploration of Artificial Neural Network (ANN) to Predict the Electrochemical Characteristics of Lithium-ion Cells", *Electrochemica Acto*. **53**, 2007, pp. 1877-1882.

[17] M. Safari et al., "Multimodal Physics-Based Aging Model for Life Prediction of Li-Ion Batteries", *J. Electrochem. Soc.* **156**, 2009, A145-A153.

[18] D. Ton, C. Cameron, and W. Bower, "Solar Energy Grid Integration Systems 'SEGIS' Concept Paper", Solar America Initiative, DOE/EERE **-** Solar Energy Technologies Program, October 2007.

[19] B. Kroposki et al., "Renewable Systems Interconnection: Executive Summary", NREL/TP-581-42292, National Renewable Energy Laboratory, Golden, CO, February 2008.