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Performance Assessment of the PNM Prosperity Electricity Storage Project

A Study for the DOE Energy Storage Systems Program

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PNM Prosperity Electricity Storage Project Evaluation

A Study for the DOE Energy Storage Systems Program

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Abstract

The purpose of this study is to characterize the technical performance of the PNM Prosperity electricity storage project, and to identify lessons learned that can be used to improve similar projects in the future. The PNM Prosperity electricity storage project consists of a 500 kW/350 kWh advanced lead-acid battery with integrated supercapacitor (for energy smoothing) and a 250 kW/1 MWh advanced lead-acid battery (for energy shifting), and is co-located with a 500 kW solar photovoltaic (PV) resource. The project received American Reinvestment and Recovery Act (ARRA) funding. The smoothing system is effective in smoothing intermittent PV output. The shifting system exhibits good round-trip efficiencies, though the AC-to-AC annual average efficiency is lower than one might hope. Given the current utilization of the smoothing system, there is an opportunity to incorporate additional control algorithms in order to increase the value of the energy storage system.

keywords: electrical energy storage, ARRA projects, technical evaluation, solar photovoltaic smoothing.

Acknowledgment

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Executive Summary

The Public Service Company of New Mexico (PNM) Prosperity electricity storage project consists of a 500 kW/350 kWh energy-smoothing battery and a 250 kW/1 MWh energy-shifting battery, and is co-located with a 500 kW solar photovoltaic (PV) resource. The smoothing battery was designed to smooth rapid fluctuations in solar PV output due to intermittent cloud cover, and the shifting battery was designed to shift the PV resource's output to better coincide with evening peak load. The project received American Reinvestment and Recovery Act (ARRA) funding.

To evaluate how well the smoothing battery system performed, several metrics were proposed to evaluate the system's ability to mitigate photovoltaic energy intermittency. The smoothing battery is effective at reducing PV output volatility. For the days examined, when using the smoothing battery system, the PV power output standard deviation was reduced by about 60%, and the PV power ramp-rate standard deviation was reduced by about 55%. For an alternate measure, the maximum-minimum adjusted PV power output swing was reduced by about 65%, and the maximum-minimum adjusted PV power ramp rate swing was reduced by roughly 70%, when the smoothing battery was used.[1]

Two factors are of primary interest when evaluating a shifting battery: the ability to charge and discharge in blocks as commanded, and the round-trip efficiency. The system performance was nearly flawless with respect to delivering the commanded charge/discharge energy. Therefore, this report focuses on the round trip efficiency to evaluate the shifting battery performance.

Efficiency is calculated on both an AC-to-AC and DC-to-DC basis. In order to determine the effects of the Balance of Plant (BoP) load on the efficiency of the shifting system, differing energy components are utilized in the efficiency calculations. The efficiencies are determined over two different time intervals: 24 hour and 365 day periods, representing daily and annual efficiencies, respectively. These results are summarized in Table 1.

Table 1: Shifting battery efficiency.

Measurement	Includes BoP Losses?	Round-Trip Efficiency	Annual Efficiency
DC-to-DC	No	89%	85%
	Yes (measured BoP)	83%	69%
AC-to-AC	Yes (measured BoP)	76%	59%

Another way to evaluate efficiency is to compare the energy used to charge the battery versus the energy output from the battery over some time period. The annual average efficiency (on a DC-to-DC basis, not including measured BoP loads) over the twelve months through June 2013 was 85%. If measured BoP load is included, the annual (AC-to-AC) efficiency this number drops to about 59%.

While the round-trip measurements are in-line with our expectations, the annual efficiency estimates including BoP losses are lower than expected. The reason for this is that while the shifting battery is being used for a fraction of the time, there is BoP load the entire time being examined. In other words, BoP load when the battery is not being used (every night, as well as on days the battery is not dispatched) counts against its annual efficiency. Operating the battery system more often

[1]Ten days were examined.

would improve this efficiency, as would drawing less BoP load when the battery system is not in use.

Placing the storage systems and the PV array on the same DC bus would likely improve the AC-to-AC efficiency measure. PV energy must take two more one-way trips through an inverter than it would if the two systems shared a DC bus. Assuming an average inverter efficiency of 96.5% for one-way conversion, these two additional trips amount to nearly 7% higher losses to store PV energy than would be the case if the systems shared a DC bus. One measure that could have been taken during construction to reduce the air-conditioning portion of the BoP load is orienting the containers East-West instead of North-South, exposing less wall area to the harsh West exposure during the afternoon hours. Providing shade for the battery containers would likely reduce BoP load and improve system efficiency.

Even though the storage systems were designed to smooth and shift PV output (and have been almost exclusively operated in this manner), they are not limited to this application. The storage systems are merely co-located with the PV array–they can perform applications that do not depend on PV output. Given this, it makes sense to examine whether the battery systems might provide additional value by performing other applications.

From a bulk-grid perspective, providing frequency regulation by following an automatic generation control (AGC) signal may be a better application than smoothing PV output for this location. If smoothing PV output, the smoothing battery system will necessarily be tasked to operate only during the day, meaning that it will be idle at night. In addition, New Mexico skies are generally clear, meaning that on most days the battery will receive little use. Battery throughput data shows that, assuming cumulative discharge is the limiting factor, the smoothing battery could last another 100 years at the current useage rate. This confirms that the smoothing battery system use is low compared with the battery system's lifetime capacity for work. Having the smoothing battery system follow an AGC signal would increase the battery utilization and be useful over the entire 24-hour period. Following an AGC signal is also of more benefit to the grid, as it means the battery will always be acting in a way to balance generation and load. In contrast, smoothing PV output can be counterproductive if there is a momentary drop in load at the same time there is a momentary drop in PV output.

Moreover, using the energy-shifting battery system to deliver power when most needed and withdraw power from the grid when it is cheapest may provide more value than shifting PV output. To add value shifting energy, the system benefit of shifting off-peak energy to on-peak energy must outweigh the cost of losing energy to storage round-trip inefficiencies. Shifting PV output means taking power generated earlier in the day and shifting it to later in the day. Decoupling the storage resource from PV output allows it to charge at night or during the day, increasing the operator's ability to charge when energy is cheapest. Using the shifting battery to provide spinning reserve is another option that may add more value than PV shifting, and is worth study.

The PNM Prosperity project is one of a few grid-scale battery storage systems in the U.S., is one of two storage systems in the U.S. using the UltraBattery (with the other being at the East Penn factory in Pennsylvania), and is the only grid-scale storage system using the Deka Synergy battery. The Prosperity project has provided, and continues to provide, significant lessons learned from its operations. In addition, the PNM Prosperity and East Penn storage projects have given East Penn experience in manufacturing the UltraBattery, resulting in increased manufacturing efficiency and reduced cost.

Acronyms and Abbreviations

AGC automatic generation control

AGM absorbed glass mat

ARRA American Reinvestment and Recovery Act of 2009

BESS battery energy storage system

BoP balance of plant

CAES compressed air energy storage

CDF cumulative density function

CES community energy storage

ESS electricity storage system

KS Kolmogorov-Smirnov (test)

kW kilowatt

kWh kilowatt-hour

MW megawatt

MWh megawatt-hour

PG&E Pacific Gas and Electric Company

PJM a regional transmission organization that coordinates wholesale electricity generation in all or parts of 13 states and the District of Columbia

PMF probability mass function

PSoC partial-state-of-charge

PV photovoltaic

RSDP reduction in standard deviation of power

RSDR reduction in standard deviation of ramp-rate

SCE Southern California Edison

SGDP Smart Grid Demonstration Program

SoC state-of-charge

V volts

VAC volts alternating current

VDC volts direct current

VRLA valve-regulated lead-acid

WSS wide-sense stationary

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1 Introduction

This study focuses on evaluating the technical performance of the Public Service Company of New Mexico (PNM) Prosperity project's storage resource, which is one of the electricity storage demonstration projects funded by the American Reinvestment and Recovery Act (ARRA) of 2009. Contributing partners are: University of New Mexico, Northern New Mexico College, Sandia National Laboratories, East Penn Manufacturing Company, and Electric Power Research Institute.

The PNM Prosperity electricity storage project consists of a 500 kW/350 kWh energy-smoothing battery and a 250 kW/1 MWh energy-shifting battery, and is co-located with a 500 kW solar photovoltaic (PV) resource. The smoothing battery was designed to smooth the PV resource's rapid output fluctuations due to intermittent cloud cover, and the shifting battery was designed to shift PV resource output to better coincide with evening peak load.

Time-of-day shifting of solar PV output is useful, as the PNM Prosperity solar array's peak energy production occurs before the evening load peak. Having an energy system to 'shift' (i.e., store then discharge) solar production to better coincide with the evening peak is therefore likely to benefit the bulk grid. Likewise, smoothing rapid PV output fluctuations, due to intermittent cloud cover, is useful. At the bulk grid level, higher PV output variability requires more operating reserve to be set aside, which is costly. At the distribution level, rapidly varying PV output can cause voltage flicker and voltage excursions outside of the desired band.

This evaluation attempts to identify the technical value of the PNM Prosperity project, that is, the benefit that the battery system provides as a grid asset. This includes energy, capacity, and ramp-rate mitigation of the associated PV system amongst other services. It includes the deferment of the use of other resources to provide these services. It does not evaluate system economics in this use–either independently or relative to other resources.

A publicly-available, independent PNM Prosperity storage project evaluation serves several purposes. First, any utility or developer considering a storage resource of this type will want to understand the nature, and magnitude, of the technical risks associated with the project. A storage system performance evaluation should contribute to a clearer understanding of technical risk. Second, an evaluation helps provide perspective on the role of ARRA funding in facilitating advances in electricity storage, specifically in the type of storage used at the PNM Prosperity site.

This report, and others that follow, will serve to identify the performance-based value proposition for the ARRA energy storage demonstration projects. They will provide the public, utilities, and potential owners an in-depth understanding of energy storage uses as demonstrated by the ARRA demonstration projects, and address utility and developer concerns about using energy storage on their systems.

After a brief introduction to the ARRA Energy-Storage Demonstration Projects, the PNM Prosperity storage project will be discussed in detail.

1.1 ARRA Energy-Storage Demonstration Projects

ARRA brought significant government stimulus funds into private industry, with about $4.5 billion allocated to the U.S. Department of Energy to fund projects to modernize the electric grid. The

Smart Grid Demonstration Program (SGDP) is one primary avenue through which this funding has been distributed.

The SGDP is authorized by the Energy Independent Security Act of 2007 Section 1304 and amended by ARRA to demonstrate the technical, operational, and economic feasibility of existing and emerging smart-grid technologies. The DOE selected projects for this program through a competitive solicitation, where up to 50% of the project cost was provided through the program.

Approximately $140 million in funding was allocated for the U.S. Department of Energy to fund 16 energy-storage demonstration projects. The remainder of the funding for these projects was provided by state and private investment. The grid-connected demonstration projects are listed in Table 2, and the research and development demonstration projects are listed in Table 3. A more complete description of each of the projects is provided in Appendix A.

The SmartGrid.gov website provides further information on these projects: their value, current status, and other relevant background information. As a whole, these projects attempt to demonstrate the value of energy-storage technologies in a number of electric system functions and validate their performance and long term capabilities in providing these functions. The overall intention of this effort is to promote the deployment of these technologies by addressing the technical risk that prevents utilities and other developers from deploying energy-storage technologies as solutions to grid problems.

Using this resource and other resources available from the Department of Energy's Energy Storage Program and other publicly available sources, a potential developer can evaluate the performance value proposition and the economic value proposition when considering solutions to addressing electric grid needs. A number of modeling tools, regulatory support documentation, a cost database and economic evaluations for potential deployments are available.

Table 2: ARRA grid-connected demonstration projects.

Project Name	Location	Project Description	Funding ($M) ARRA/Total	Project Status
PNM Prosperity	Albuquer -que, NM	750 kW of advanced lead-acid batteries for PV smoothing/shifting	2.3/6.1	Operational
East Penn	Lyons Station, PA	3 MW UltraBAttery storage facility for frequency regulation	2.5/5.1	Operational
Duke Energy - Notrees	Notrees, TX	36 MW/24 MWh Xtreme storage facility for wind smoothing/shifting	22/44	Operational
Southern California Edison	Tehachapi CA	8 MW/32 MWh lithium-ion battery storage facility for wind smoothing	25/55	Under construction
City of Painesville	Painesville, OH	10 MW/80 MWh Vanadium redox battery storage for peaking power	4.2/9.5	In Progress
Primus Power - EnergyPods	Modesto, CA	25 MW/75 MWh Zinc flow-battery storage for wind firming/peak shaving	14/47	In Progress
DTE - Comm. Storage	Detroit, MI	1 MW community energy storage (CES) system to improve grid reliability	5.0/11	Operational
PGE CAES	CA	300 MW/3000 MWh CAES for renewable generation support	25/360	In Study
Beacon Power	Hazle Twp, PA	20 MW flywheel for frequency regulation	24/52.5	Operational
NYSE&G - Advanced CAES	NY	150 MW CAES	1.4/2.9	Discontinued
Premium Power Dist. Storage	MA	Two 500 kW zinc-bromide flow-batteries for PV and wind support	6/12.5	Discontinued

Table 3: ARRA electricity storage research and development projects.

Project Name	Location	Project Description	Funding ($M) ARRA/Total	Project Status
Aquion Energy	PA	Low-temperature sodium-ion battery development for grid-scale storage	5.2/10.4	Complete
Ktech Corp	NM	EnerVault 250 kW/1 MWh redox flow battery coupled with 180 kW PV system	4.8/9.5	In progress
Amber Kinetics	CA	Developing lower-cost flywheel	3.7/7.5	In progress
SEEO	CA	Solid-state electrolyte lithium-ion battery	6.2/12.4	
SustainX	NH	Developing an isothermal CAES device using pressure vessels for storage	5.4/13.0	

1.2 PNM Prosperity Project Description

The Prosperity Project is located in Albuquerque, New Mexico, just south of the Albuquerque International Airport on land owned by PNM, and is in PNM's service territory. An aerial photograph of the project site is displayed in Figure 1. There are eight climate-controlled shipping containers containing batteries. These are connected to a grid-tied inverter with a 750 kW/1.5 MVA rating. Separately, there is a 500 kW PV installation, connected to a 500 kW grid-tied inverter. (The PV installation and associated inverter were not part of this energy-storage project, and did not receive DOE funding).

Figure 1: PNM Prosperity energy-storage project.

The Ecoult/East Penn Manufacturing storage system at the PNM Prosperity site is comprised of:

- A 0.25 MW/1 MWh energy-shifting battery system
  - Six shipping containers of advanced lead-acid batteries (Deka Synergy® batteries)
- A 0.5 MW/0.35 MWh power-smoothing battery system
  - Two shipping containers of advanced lead-acid batteries with integrated capacitors (UltraBatteries)
- A bi-directional grid-tied inverter with a 750 kV/1.5 MVA rating
  - Connected to each battery system through bi-directional DC converters
  - Inverter is capable of power factor modification

Also part of the storage system is an Ecoult battery management and monitoring system, a battery power conditioning system, and a data acquisition and control system. A one-line diagram of the battery system can be found in Figure 2.

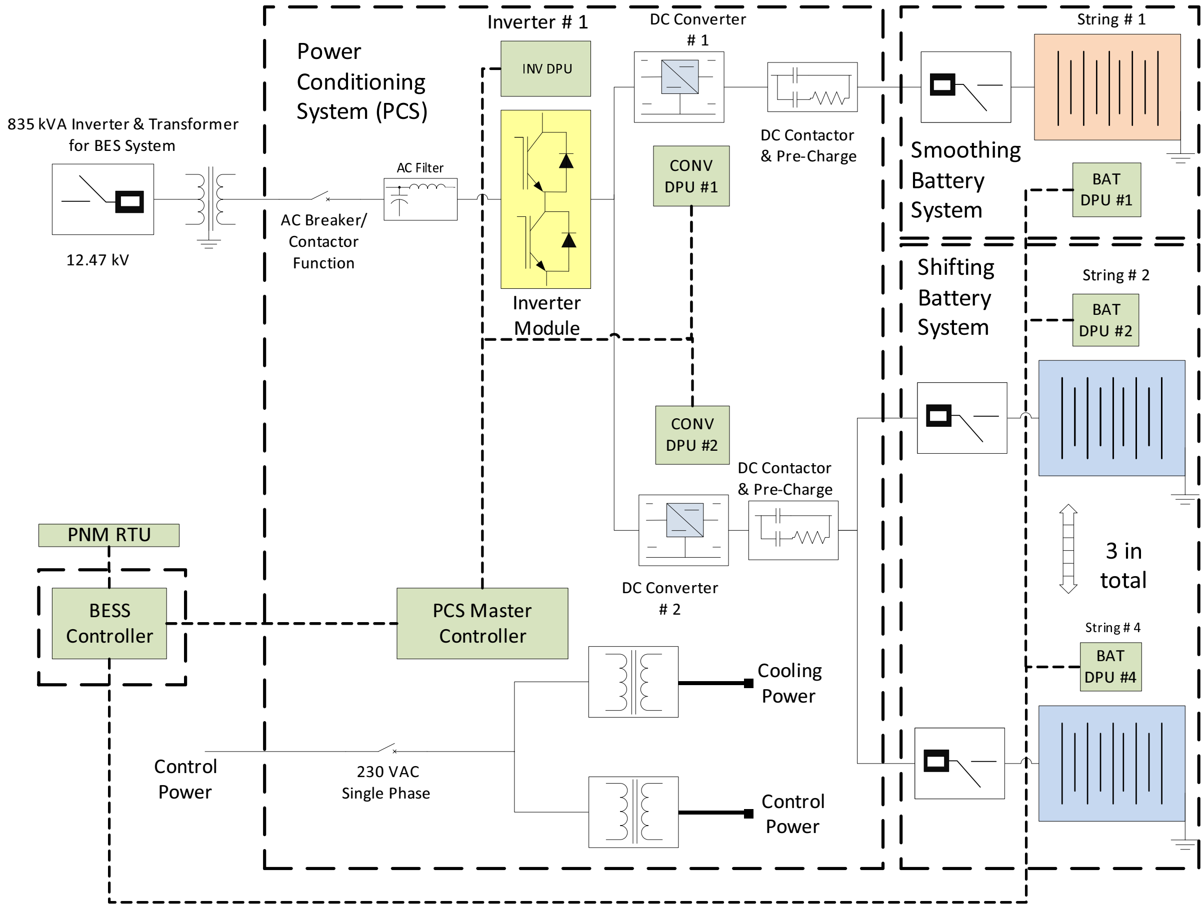

Figure 2: Battery storage-system one-line diagram.

The two containers housing the energy-smoothing battery system are considered a single string. This string is termed an "Ultrabattery Storage Block," and is labeled as an "UBer USB-320/500 kW" storage block. The string voltage is nominally 320 VDC, though actual voltage can fluctuate between 270 VDC and 400 VDC. The string has a power rating of 500 kW and a capacity of 1 MWh. Roughly $\frac{1}{3}$ of this amount, or 0.35 MWh, can be made available for use without adversely impacting battery life.[2] This is termed the maximum energy band available for application use. This can only be achieved at average power levels below the peak power rating.

The six containers housing the energy-shifting battery system are considered three strings. Each string is comprised of two containers, and is termed a "Deka Synergy Storage Block," and is labeled as an "UBer SSB-320/250 kW" storage block. As with the smoothing battery system, the string voltage is nominally 320 VDC, though actual voltage can fluctuate between 270 VDC and 400 VDC. Each shifting battery string has a power rating of 250 kW and a capacity of 1 MWh. Roughly 1/3 of the storage capacity of a string (0.35 MWh) can be made available for use without adversely impacting battery life. The three shifting battery strings are connected in parallel, yielding a three-string system which has the same power rating of a single string, but triple the storage capacity. Therefore, the total useable storage volume of the three shifting-battery strings is roughly 1 MWh.

DC-to-DC converters connect each system (smoothing and storage) to a grid-tied inverter. This

[2]Page 24 of Ecoult brochure.

is done mainly to keep the voltage, as seen by the inverter, constant and to ensure that if both battery systems are operating at the same time, they are sending power to/receiving power from the inverter at the same voltage.

The PV system is connected to the grid through its own 500 kV inverter. Because the PV system and storage system have separate inverters, they are therefore separately connected to the grid. This is shown in Figure 3. Both inverters feed the low-voltage side of a 12.47 kV/480 V transformer. While PNM would have preferred to have a single inverter with a common DC bus serving the PV and battery storage systems, they encountered obstacles to doing so.

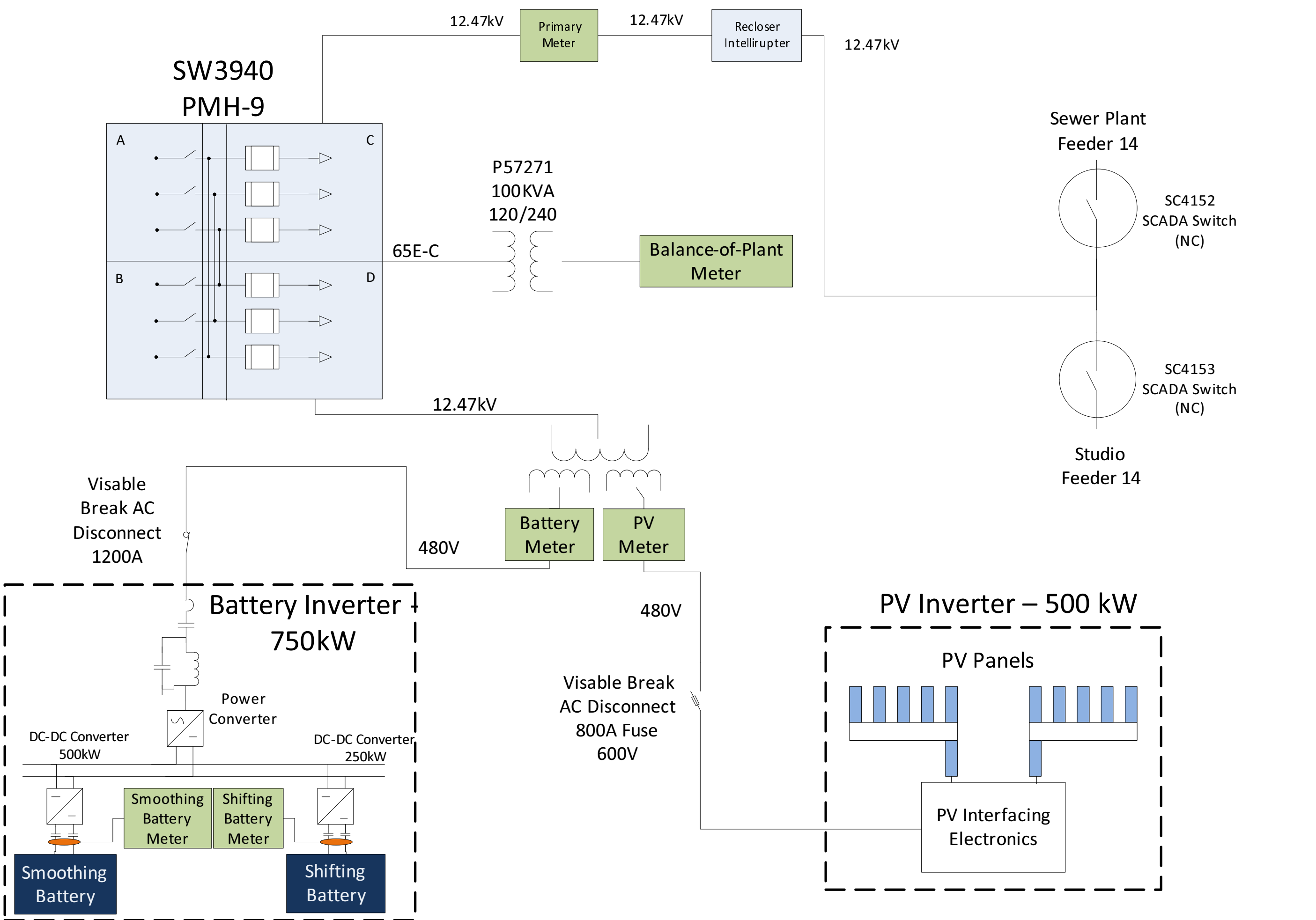

Figure 3: System one-line diagram.

1.3 Battery Description

Both the Deka Synergy battery and the UltraBattery are advanced valve-regulated lead-acid (VRLA) batteries.

VRLA batteries, also known as sealed batteries, use a one-way pressure-relief valve, allowing them to be "recombinant." This means that the oxygen produced on the positive plate is absorbed by the negative plate, suppressing the production of hydrogen and producing water instead. The battery thus never needs for water to be added. The name "valve regulated" refers to the pressure release valve which will activate if hydrogen is given off too quickly (faster than the rate at which hydrogen and oxygen combine within the battery). This can happen if cell is charged at too high a voltage for a sustained period. VRLA batteries can be further classified as absorbed glass mat (AGM) batteries and gelled electrolyte batteries (gel) (Reddy (2011)).

The Deka Synergy battery is manufactured by the East Penn Manufacturing Company, Inc. It is essentially the same as their standard VRLA battery (called Unigy II®, which is an AGM-type battery), with the exception of the electrode plates, which are enhanced with carbon.[3] VRLA batteries can develop crystalized lead sulfate deposits inside the negative plate, which shortens battery useful life, when operated continuously in a partial-state-of-charge (PSoC) regime. Frequent conditioning (or overcharge) cycles act to dissolve the sulfate deposits. Adding carbon to the electrodes enables operation in a PSoC regime, as it greatly reduces sulfate deposit formation when operated in a PSoC regime. Reducing sulfate deposit formation has the potential to increase battery performance and lifetime (U.S. Department of Energy, 2012).

The UltraBattery is a lead-acid battery coupled with an asymmetric supercapacitor. An asymmetric supercapacitor is comprised of a lead-dioxide positive plate and a carbon-based negative plate, while a lead-acid battery is comprised of a lead-dioxide positive plate and a lead negative plate. Placing the lead and carbon-based negative plates in parallel allows both electrodes to share the same lead-dioxide positive plate. This is illustrated in Figure 4.

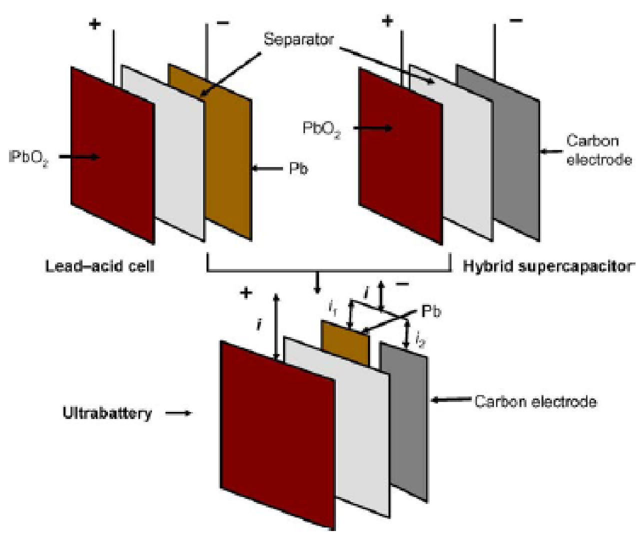

Figure 4: UltraBattery configuration (Lam et al., 2006).

The capacitor incorporated into the Ultrabattery helps to minimize heating and negative plate sulfation at high-rate-PSoC cycling. This battery has shown good longevity when operated within a state-of-charge (SoC) of roughly 40 to 60% (Coppin and Wood, 2011). This battery was developed by Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), and manufactured by East Penn Manufacturing Company.

[3]Conversation with Chuck Mathias, East Penn.

1.4 Battery Operation

The project goal was to use the UltraBattery system solely to moderate fluctuations in PV power output due to intermittent cloud cover and to use the Deka Synergy battery system solely to provide time-of-day shifting.

It should be noted that the UltraBattery system can provide time-of-day energy shifting, just as the Deka Synergy battery system can offer smoothing. However, each application requires a certain balance of energy and power, which each battery is designed to meet. Shifting, for example, is a service that benefits directly from each additional unit of energy that can be stored while only requiring enough power to store and release that energy in the desired time window. Smoothing, in contrast, is a service that benefits directly from each additional unit of power (up to some proportion of the rated power of the PV installation), while only requiring enough energy to keep from saturating the battery either at full charge or at empty.

The optimal temperaure for using stationary lead-acid batteries is between 20 °C to 30 °C. While temperatures up to 50 °C can be tolerated, high-temperature operation increases self-discharge and reduces cycle life. Operation at cold temperatures is also problematic–available storage capacity drops as electrolyte temperature decreases (Reddy, 2011, pp.16.63-16.64). Therefore, all of the containers at the PNM Prosperity site have air conditioners/heaters. When cooling is needed, the targeted temperature is between 24 and 27 °C. When heating is needed, the target temperature is between 21 and 24 °C.[4]

PNM targets operating the shifting battery between 30% and 70% SoC.[5] In addition, both battery systems undergo conditioning charges. These bring the SoC up to 100%, and are performed, on average, once every two months.[6] These charges help to mitigate lead sulfate crystal formation on the battery cell anodes.

[4]E-mail from Steve Willard of PNM, 11-Sep-2013.
[5]Communication from Steve Willard of PNM, 17-Jan-2014.
[6]E-mail from Simon Boland of Ecoult, 9-Sep-2013.

2 Evaluation Metrics

In this paper, we are interested in characterizing how the storage system is performs. The characteristics of interest include: PV smoothing performance, round-trip efficiency, balance of plant load quantity and variability, system availability, and operational requirement impact on system life. Because there are various ways of quantifying these characteristics, it is necessary to define how the calculations are performed. This is the purpose of this section.

2.1 PV Smoothing Effectiveness

PV system power-output variability is primarily a function of time of day, cloud cover, and season. In this study, however, we are mainly interested in the rapid PV power-output fluctuations caused by intermittent cloud cover. The term ‘PV smoothing’ is used to denote the use of an electricity storage system (ESS) to mitigate variable PV output’s rapid power fluctuations. These power fluctuations are an unfavorable PV-system characteristic. At the feeder level, these fluctuations can cause voltage flicker and feeder voltage excursions outside of the desired band. These fluctuations can result in increased switching of tap changing transformers and capacitor banks, resulting in premature failure of components. At the bulk grid level, PV variability requires additional operating reserve to be set aside, and causes conventional generation to cycle more than otherwise. By using an ESS to absorb or supply power at the appropriate times determined by an automatic control system, PV power output can effectively be smoothed, lessening the burden on the system caused by the rapid fluxes. Pumped-storage hydro (PSH), battery systems, flywheels, and compressed-air energy storage (CAES) are some of the technologies used for energy storage.

The following metrics were developed to characterize the degree to which photovoltaic power is effectively smoothed by an energy storage system:

1. Percent reduction in standard deviation of power (RSDP)
2. Percent reduction in standard deviation of ramp-rate (RSDR)
3. Max-min reduction

These three metrics are used in this study to quantitatively describe an energy-storage system’s ability to smooth the fluctuations of a given PV power profile. By using the solar irradiance categorization described in Trueblood et al. (2013), a determination of how well a given ESS performs, the smoothing operation for various solar irradiance profiles can be made.

Mathematically, the variance of power can be defined as:

$$\hat{\sigma}^2 = \frac{1}{N-1} \sum_{n=0}^{N-1} (\hat{R}(n) - E[\hat{R}(n)])^2 \tag{1}$$

where n = 0, 1, ..., N-1; $E[\hat{R}(n)]$ is the expected value of $\hat{R}(n)$; and N = length of $\hat{R}(n)$ in the sample. The standard deviation of power is simply the square root of the variance of power.

The ramp-rate variance can be defined as:

$$\hat{\sigma}^2 = \frac{1}{N-1} \sum_{n=0}^{N-1} (Y(n) - E[Y(n)])^2 \tag{2}$$

where n = 0, 1, ..., N-1; $Y(n) = \frac{X(n+k)-X(n)}{k}$, and $E[Y(n)] = 1/N \sum Y(n)$. The SDRR is the square root of the ramp-rate variance.

Finally, the max-min reduction can be defined as the reduction in:

$$P_{\text{max swing}} = max|\hat{R}(n)| \tag{3}$$

A detailed discussion of these metrics can be found in Appendix B.

2.2 Round-Trip Efficiency

Round-trip efficiency is the efficiency of a single charge and discharge cycle, and can be measured on a DC-to-DC or an AC-to-AC basis. The lower the storage system's round-trip efficiency, the higher the value of the services provided by storage (here, smoothing and time-of-day shifting) needs to be in order to compensate for the losses.

A key question is whether BoP load should be taken into account in calculating the round-trip efficiency. Both the battery-system control equipment and the climate control for the battery containers are AC-powered. They are not fed from the same DC feeder that connects the battery systems to the grid-tied inverter, but from a separate, AC line. This BoP load therefore does not show up as energy in or out of the batteries (as measured directly downstream of the inverter in DC, or directly upstream of the inverter in AC), but it is captured by the 'Station Meter' reading. On one hand, showing efficiency excluding the BoP load is useful, as it isolates the battery string efficiency. On the other hand, the BoP load should be included, both because it is a part of battery operations, and because the efficiency measurement becomes a metric that can be improved through BoP load reduction.

Figure 5 illustrates how the shifting battery has typically been employed at the PNM Prosperity project to shift PV output. The battery charges during the morning and discharges in the afternoon.

Storage-device efficiency can be calculated by simply dividing the amount of energy discharged by the amount of energy charged.

$$\eta = \frac{E_{out}}{E_{in}} \times 100 \tag{4}$$

For the PNM prosperity site, because BoP load is not included as part of the energy input measurement, BoP load must be explicitly taken into account (Equation 5).

$$\eta = \frac{E_{out}}{E_{in} + \text{ BoP load}} \times 100 \tag{5}$$

Any difference between amount of energy charged and discharged must represent energy lost in the charge/discharge cycle.

$$E_{loss} = E_{in} - E_{out} \tag{6}$$

Storage-system inefficiency is due to heat loss and any electrical, mechanical, or chemical losses in the conversion and reconversion processes. Sources of such inefficiencies are electrical inverters,

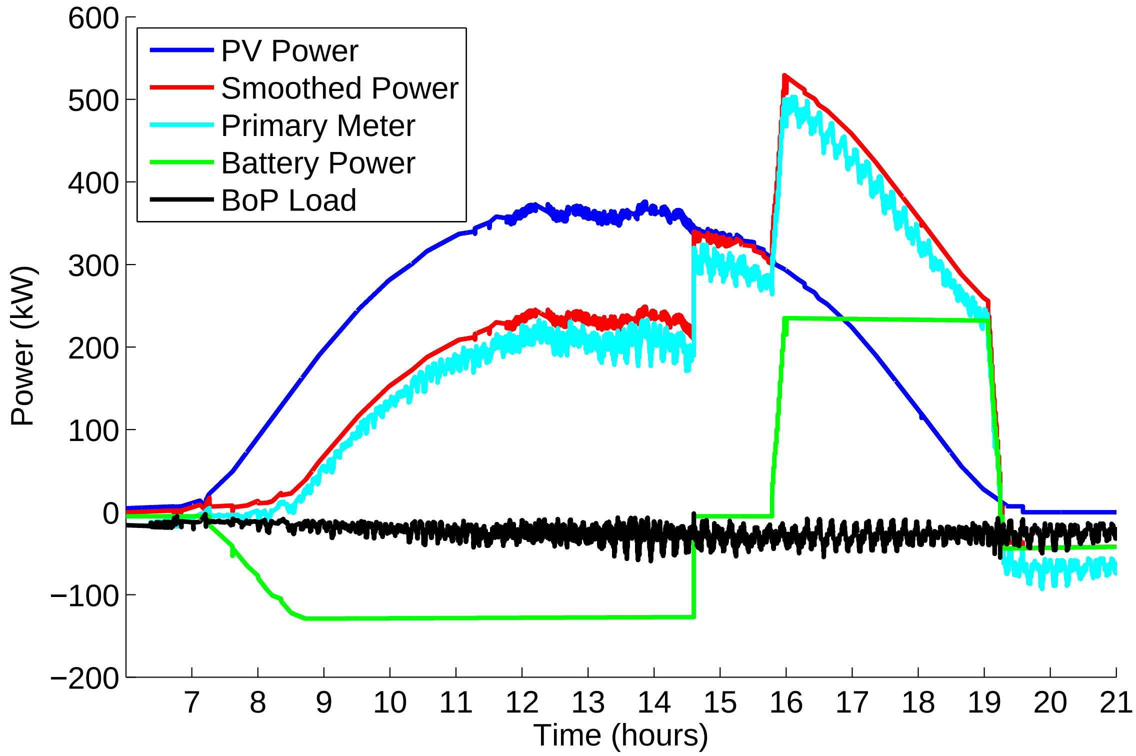

Figure 5: PV shifting, 26-Jun-2013 data.

chemical reactions in batteries, bearings and friction in mechanical storage systems, and resistance-in-wire losses associated with high current.

Again, by taking the BoP load into account, it can be considered as contributing to the energy lost in the round-trip cycle.

$$E_{loss} = E_{in} + \text{BoP load} - E_{out} \tag{7}$$

Expressing DC-to-DC efficiency excludes inverter losses, while the AC-to-AC efficiency accounts for the associated inverter loss. By excluding the inverter losses, only inefficiency in the chemical conversion and connected copper is represented. However, for a more holistic look at what the system efficiency is, inclusion of the inverters is necessary. It is also necessary to examine these quantities across different periods of time. Individual round trips, characterized by a single charge and a single discharge cycle, tend to be more efficient than that of a year-round total charge vs. total discharge cycle.

2.3 Balance-of-Plant Load

The Balance-of-Plant (BoP) load is an important consideration in calculations of storage system efficiency.

At the PNM Prosperity project, BoP load is not withdrawn from the batteries – instead, it is taken from the grid, as AC power is needed for the BoP loads. These loads include air conditioning and heating for the containerized battery strings, control systems, and data measurement systems.

The BoP load can either be directly measured, or indirectly calculated. The method we have chosen for evaluating shifting battery efficiency in this report is direct measurement. At the PNM Prosperity site, the BoP load is measured by a meter called the 'Station Meter.' This meter is on a low-voltage distribution circuit. According to PNM, it measures most, but not all, of the BoP load. (There is an additional 1 to 2 kW load not on this same circuit, according to PNM.) While there is the risk of under-counting BoP load, we know that we will not be including loads and losses at the Prosperity site that are unrelated to the storage systems.

The other option is to indirectly calculate the BoP load. In this case, this can be done by taking the Primary Meter reading and subtracting PV output (as measured at the PV meter on the AC side of the circuit) as well as the Storage Battery output (also measured on the AC side of the storage systems). While this calculation is more comprehensive, there is the risk that loads and losses not related to the storage systems would be counted against storage system performance.

2.4 Availability

It is useful to understand how often the storage-system has been available. Because we are interested in the storage system performance, it seems reasonable to exclude outages for reasons external to the storage system (such as a system power outage, fault on the feeder connecting to the storage system, etc.). Therefore, battery system forced outages and maintenance requiring the system to be taken off-line were counted against the system's availability. Specifically, downtime would be considered the length of time the storage system recorded any of the following:

1. An inverter fault,
2. A battery string fault, or
3. Any instance the system was taken off-line for maintenance or manual charging/discharging.

Note that this definition of availability does not require that there be any charge or discharge commanded to the battery system–it measures the amount of time the storage system was available to be used, whether or not a command to charge or discharge was given.

2.5 Estimated Remaining Battery Lifetime

For the UltraBattery USB-320/500 kW (as is installed at the PNM Prosperity site) under recommended operating conditions, Ecoult estimates the total energy available before battery replacement to be 2 GWh (Ecoult, 2013, p. 24).[7] The energy output of the smoothing battery on a cloudy day can be compared with this estimated lifetime energy available to determine on how many cloudy days the battery system might be expected to help mitigate PV output fluctuations.

Instead of being tasked to smooth PV output, if the UltraBattery installed at the PNM Prosperity site were given an automatic generation control (AGC) signal to follow its expected lifetime may differ. A representative AGC signal can be used to calculate how much battery energy output would be required, which can then be used to calculate an expected lifetime when following an AGC signal.

[7]Here, available energy means the total amount that the battery is capable of discharging before it fails. It is not throughput, which would also count energy used to charge the battery.

For the Deka Synergy SSB-320/250 kW storage block, we assume that the overall battery throughput expected lifetime is the same as that for the Unigy II battery.[8] While the Unigy II battery is a standard VRLA battery, the primary difference is that it needs to be operated near its maximum SoC, whereas the Synergy battery was designed to operate in a PSoC regime. The Unigy II is rated at 600 cycles at a 100% depth of discharge (East Penn, 2011). Each Deka Synergy Storage Block has a total capacity of 1 MWh. As there are three blocks in parallel, the total capacity is 3 MWh. The total energy available before replacement for the shifting battery system, therefore, should be about 1.8 GWh.[9]

For the estimated remaining lifetime, we will use data from Ecoult on the monthly amount of energy charged and discharged from each battery system, and compare the estimated GWh output remaining with how much the battery is currently being utilized.

[8]The Deka Synergy battery cell is the same as that of the Unigy II, except that the Synergy battery plates are impregnated with carbon.

[9]Calculation: 1 MWh capacity $\times$ 3 storage blocks $\times$ 600 cycles = 1.8 GWh

3 Analysis

This section contains results for the PV smoothing, shifting battery efficiency, BoP load characterization, availability, and battery estimated lifetime.

3.1 PV Smoothing Effectiveness

We begin by analyzing the smoothing function of the UltraBattery at the PNM Prosperity site. The Prosperity site is fitted with various meters and measurement equipment in order to fully measure and analyze the system's performance. The data used for this analysis is recorded at a rate of 1 sample per second. All data sets are one day's worth of sampling, from sun-up to sun-down. Characteristic days were chosen based on the methods described in Trueblood et al. (2013), and span approximately 15 months' worth of data collection.

It is helpful to introduce two metrics in order to help classify daily solar irradiance profiles. The first is the 'Daily Clearness Index', and it is given as "the ratio of solar energy measured on a given surface to the theoretical maximum energy on that same surface during a clear sky day" (Trueblood et al., 2013, p. 35). It is described in equation 8.

$$\text{Daily Clearness Index} = CI = \frac{\text{measured solar insolation}}{\text{calculated clear-sky solar insolation}} \tag{8}$$

The second metric is described in equation 9. It is called the 'Daily Variability Index', and is defined as "the variability in measured irradiance, relative to the variability of the calculated clear sky irradiance, with each quantified by the length of the irradiance versus time plot for the day, where the curve length between two measurements is determined using a line segment. Typical values for daily variability index range from 1 to 30" (Trueblood et al., 2013, p. 35).

$$\text{Daily Variability Index} = VI = \frac{\text{length of measured irradiance plot}}{\text{length of clear-sky irradiance plot}} \tag{9}$$

This analysis contains results for days that fit categories of 'high', 'moderate', and 'mild' variability. The 'clear' and 'overcast' variability classifications also described in Trueblood et al. (2013) will not be used in this analysis. The purpose of smoothing PV power is to smooth large fluctuations, so if the day is classified as 'clear', there is no reason to smooth it. This is because the PV power output will be smooth, because its $VI < 2$, and the ESS will not need to be used. An 'overcast' day has a $VI < 2$ as well, so it is also unnecessary to analyze days that fall in this classification. This analysis will focus on days with mild to highly variable irradiance.

A 60-second time period was used for all ramp-rate calculations, resulting in units expressed in [W/minute].

High Variability

A day with 'high' variability is defined as having a variability index of $VI > 10$. For more information on this classification system, see (Trueblood et al., 2013). Figure 6 represents the unprocessed PV power, the processed (smoothed) PV power, and the battery power on a characteristic day with high variability. All days analyzed with high variability display similar, highly sporadic power output.

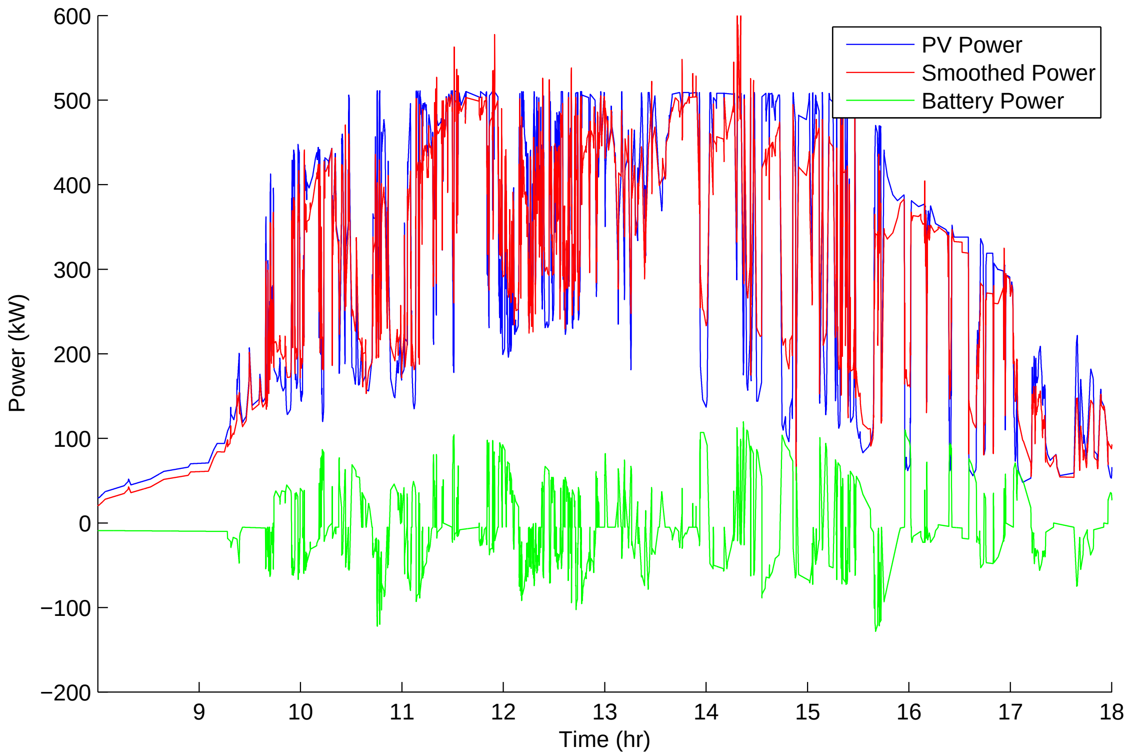

Figure 6: High PV variability, 15-Apr-2012 data.

Moderate Variability

A day with 'moderate' variability is defined as having a variability index of $5 \leq VI \leq 10$. Figure 7 represents the unprocessed PV power, the processed PV power, and the battery power on a characteristic day with moderate variability. All days analyzed with moderate variability display similar, moderately sporadic power output. Some of the days with moderate variability contain large sections of power that is much lower than its clearness index would suggest. This indicates heavy cloud cover for an extended period of time, and the battery system is not designed to smooth these types of power discrepancies. They are too slow for the power system to track.

Mild Variability

A day with 'mild' variability is defined as having a variability index of $2 \leq VI \leq 5$. Figure 8 representing the unprocessed PV power, the processed PV power, and the battery power output on a characteristic day with mild variability. All days analyzed with mild variability display similar, slightly sporadic power output. Some of the days with mild variability contain large sections of power that is much lower than its clearness index would suggest. This indicates heavy cloud cover for an extended period of time, and the battery system is not expected or designed to smooth these types of power discrepancies. They are too slow for the power system to track.

The results in Table 4 are given for ten sample days over the course of approximately 15 months. Many of the results are quite consistent with one another, both across time and across metrics. It appears that the data is quite consistent across the RSDP and RSDR from the beginning of 2013 until the last sampled day in July. However, older data from 2012 suggests that a parameter of the

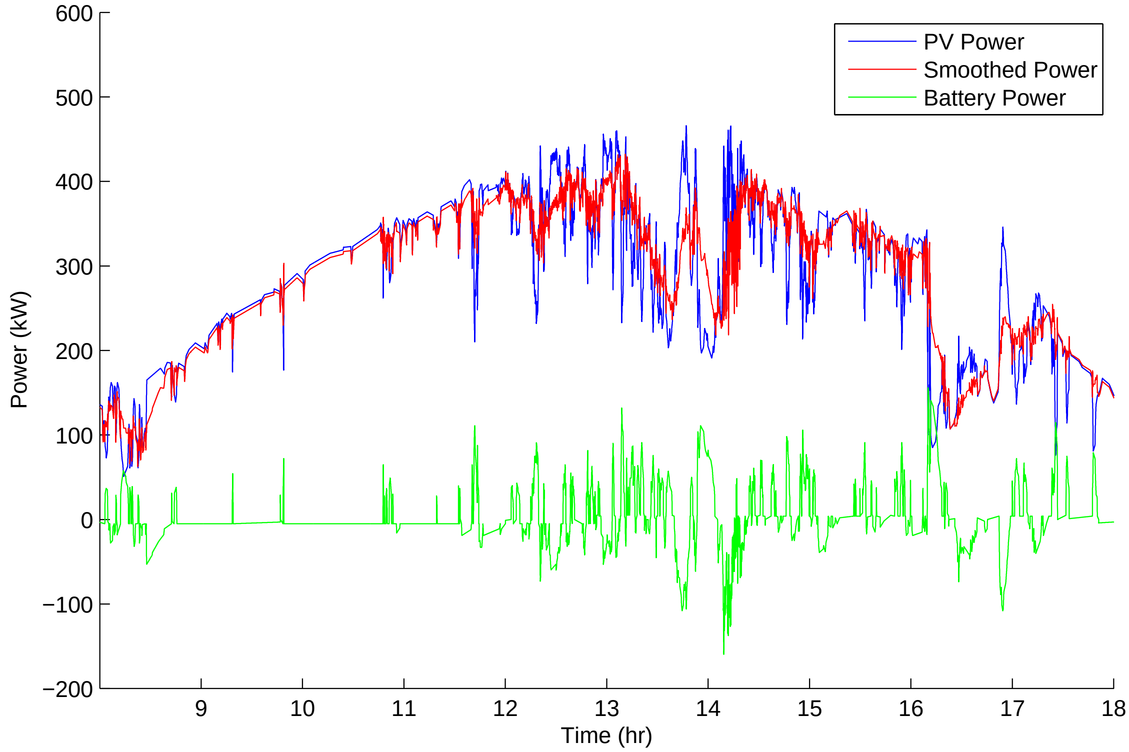

Figure 7: Moderate PV variability, 22-Jun-2013 data.

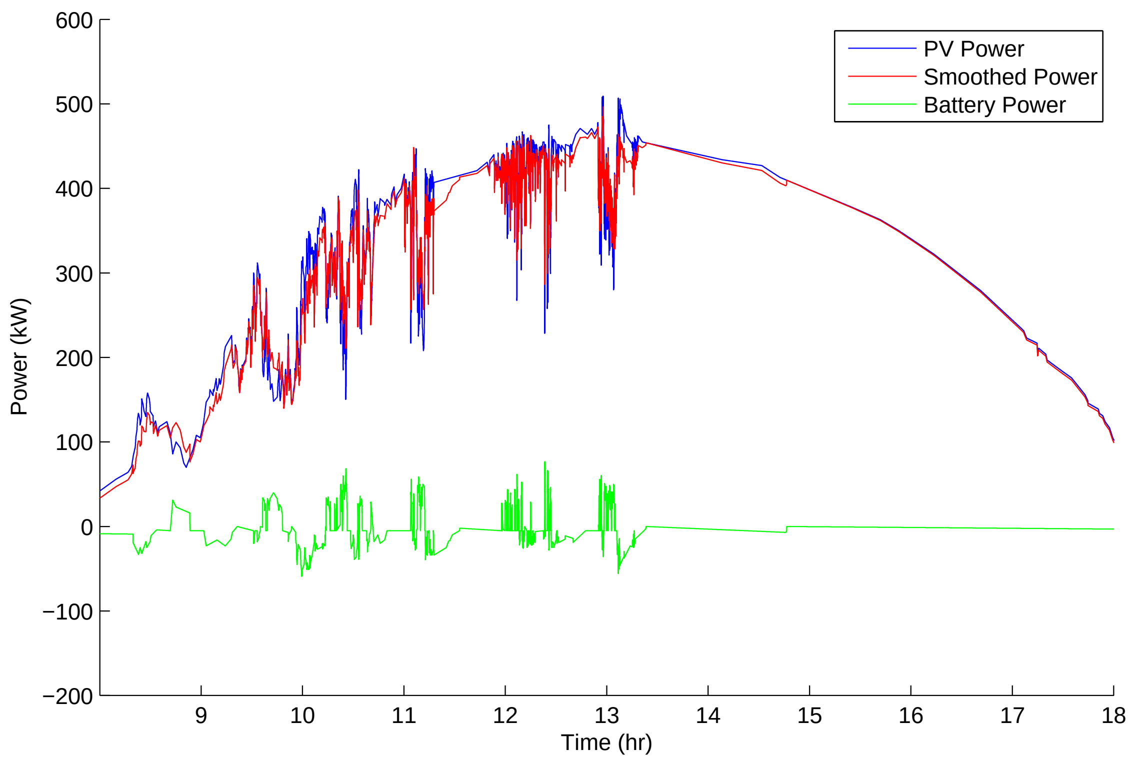

Figure 8: Mild PV variability, 13-Apr-2012 data.

control algorithm may have been changed. This is suggested because ESS performance seems to have increased significantly over time.

Table 4: Reduction in PV Output Variability Due to Smoothing Battery

	4/13/12	5/12/13	6/21/13	6/28/13	7/5/13	3/6/12	6/22/13	4/15/12	2/11/13	5/27/13
Classification	mild	mild	mild	mild	mild	mod	mod	high	high	high
RSDP	32.03	58.82	60.38	65.86	55.22	17.93	60.3	30.48	72.03	63.01
RSDR	30.25	61.23	55.79	63.6	44.68	11.09	57.45	28.81	67.86	60.61
MM Power	32.39	68.78	63.19	69.13	78.21	0	62.78	22.46	76.85	73.14
MM Ramp Rate	41.1	71.21	69.37	72.52	75.76	0.02	64.4	36.54	82.33	73.38

Consistency across the two standard-deviation calculations and the max-min reduction is also seen. This gives confidence in all of the metrics, and lends credibility to the analysis results. The outlier is the date 6-Mar-2012, because it has poor performance. However, by inspecting the plot, it appears that the ESS is offline during a large portion of the day. The time it spends offline contains high variability in power, so the max-min calculation being near-zero is expected, as well.

Perhaps most importantly, note that the system appears to be consistent across the variability of solar irradiance, as well. It does not tend to favor one type of variability over another. This implies that the system can smooth the most variable, rapidly changing cloudy days about as well as it can smooth the less cloudy or potentially partially cloudy days (i.e., thunderstorm moves in late in the afternoon).

The ESS achieved significant reductions in the volatility of solar power output across all conditions (mild-, moderate-, and high-variability days).

3.2 Shifting Battery Efficiency

The efficiency of the shifting battery was estimated by using the metered amount of power input to and output from the battery system. One efficiency measure examines a single charge and discharge cycle, or round-trip efficiency. Efficiency can also take into account the losses associated with keeping the equipment on 24 hours a day, seven days a week–we call this annual efficiency.

Both of these efficiency measures can include or exclude BoP load. They can also both be done on either a DC-to-DC basis or on an AC-to-AC basis. These measures are all valid and help understand battery efficiency from different perspectives. The DC-to-DC round-trip efficiency excluding BoP load, for example, quantifies how the battery system at its most basic level is performing. This measure reflects what is under the control of the battery maker/storage system provider. Including BoP load and site losses is also valid, as this reflects a true cost of operating the system.

These calculations were made using data directly from the PNM Prosperity project. Table 5 contains a summary of the results.

Table 5: Shifting Battery Efficiency

Measurement	Includes BoP Losses?	Round-Trip Efficiency	Annual Efficiency
DC-to-DC	No	89%	85%
	Yes (measured BoP)	83%	69%
AC-to-AC	Yes (measured BoP)	76%	59%

It follows that in all cases, the annual efficiency is lower than the round-trip efficiency. One reason for this is because the annual efficiency reflects losses due to battery self-discharge over time. In addition, when BoP loads are considered, the annual efficiency measurement takes into account BoP loads at night (for round-trip efficiency, only BoP loads and losses during the charge-discharge cycle are taken into account). Self-discharge of the battery is not estimated in this report.

In addition, when calculating annual efficiency with BoP loads, then the more energy charged and discharged over the year, the greater the efficiency. This is because BoP loads are relatively fixed, and are added to the total amount of energy used to charge the batteries in the efficiency calculation. In other words, using the battery system more spreads the fixed BoP load out over more MWh, increasing the annual efficiency.

The 7% drop in round-trip efficiency going from DC-to-DC (including measured BoP) to AC-to-AC (as measured at the storage systems meter on the AC-side, including measured BoP) is reasonable. The inverter losses, which are probably on the order of 3.5% in each direction (AC-to-DC and DC-to-AC),[10] are considered in the AC-to-AC calculation, but not in the DC-to-DC calculation. Two trips through the inverter would completely account for the lower round-trip efficiency in the AC-to-AC measurement. (We note that with the PNM Prosperity configuration, inverter losses apply to grid or PV energy that is used to charge the batteries, as well as energy discharged from the batteries.)

Below is a discussion of each of the efficiency metrics and how the efficiency numbers were calculated.

DC-to-DC Efficiency, excluding BoP Load

The DC-to-DC efficiency, excluding BoP load, is an important metric, as it allows one to assess how efficient the battery systems themselves are at storing and releasing energy.

Round-Trip Efficiency

Data from ten days (over a period from December 2012 through June 2013) were used to assess the round-trip efficiency of the smoothing battery.

Figure 9 demonstrates the action of the shifting battery on one of these days, 23-Jun-2013. The shifting battery, shown by the green line, first charges and then discharges later in the day.

Table 6 reports the efficiency of the shifting battery, as calculated from the total charge and discharge energy. All of the days chosen feature a single charge-discharge cycle, in which the shifting battery system is charged from the PV generation in the morning through early afternoon, and then discharge takes place in the late afternoon or evening.

Over the eleven days reported on in Table 6, the average round-trip efficiency not including the BoP load is 89%.

The sampled days show a range of round-trip efficiencies from 85% to 92%. The reason for this rather large difference is likely because of differences in starting and ending SoC. While we chose sample dates where the starting and ending SoC were the same or close together, any errors in the data on SoC level would have a large impact. We believe that taking the average efficiency from this set of data greatly reduces errors in calculating efficiency associated with SoC measurement. The power lost in the conversion is approximately 10% of the total stored, and is attributed to the

[10]The 3.5% losses for one-way conversion is based on the reported weighted efficiencies of similar-sized inverters in a California Public Utilities Commission report (Malashenko et al., 2013).

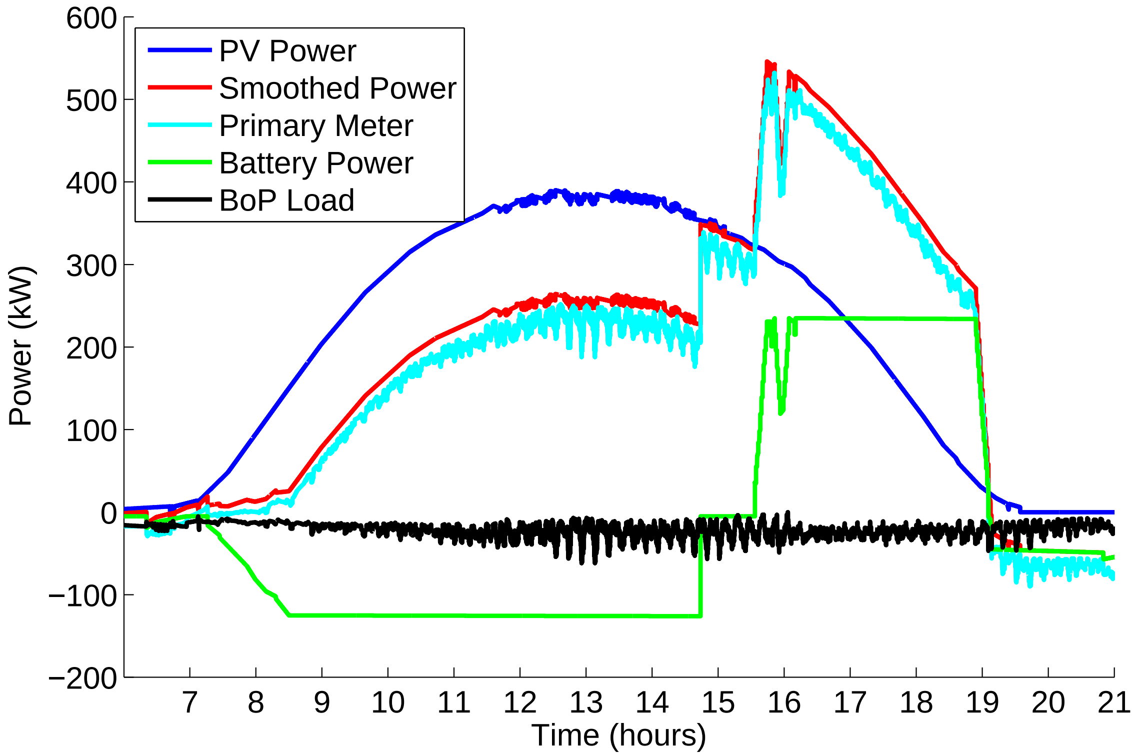

Figure 9: Shifting-batttery action, 23-June-2013 data.

Table 6: Round-Trip Efficiency over Sampled Days

Year:	2012			2013						
Date:	12/1	12/3	12/15	1/14	3/22	3/23	3/24	6/19	6/23	6/26
Efficiency (%, ex-BoP load)	90	86	92	89	92	90	85	90	87	90
Charge Energy (kWh)	892	884	811	799	813	820	788	880	925	898
Discharge Energy (kWh)	801	763	747	711	745	738	668	796	801	807
Max Load Power (kW)	39.3	92.1	49.0	94.9	66.4	89.6	86.9	63.4	61.8	59.2
Average Load Power (kW)	23.3	22.4	28.5	33.4	21.0	24.7	25.6	22.5	21.4	23.7
Std. Dev. Load Power	6.9	5.9	6.8	7.2	10.9	5.3	6.7	8.5	8.3	9.1

heat and conversion processes mentioned previously. Overall, it appears that the shifting battery performs as commanded. It shifts energy stored at a rather slow rate early in the day, and releases it at a higher rate later in the day, when the load is expected to be greater.

Annual Efficiency

One year of hourly average power output (and input) data was obtained from the PNM Prosperity data server. This data measures the average power to and from the shifting battery, and is measured on the DC side of the system. The data is from 1-Jul-2012 through 31-Jun-2013.

It is also important to insure that the battery system was at the same SoC at the beginning and ending points selected. If the battery system is at higher SoC at the endpoint, then this energy that went into increasing the state of charge will appear to be energy that was lost in the efficiency calculation. Likewise, if the battery system is at a lower SoC at the endpoint, then energy simply withdrawn from the battery will be counted as energy that increases the battery system's efficiency. It is possible to adjust the calculation for the situation where the SoC is not equal at the start and end times, but days were chosen that follow the above criteria so that no estimation is necessary.

According to the PNM data, the shifting battery was at a 60.9% SoC on 10-Jul-2012 at 1pm, and was also at a 60.9% SoC on 26-Jun-2013 at 3pm. Over this time frame, 136 MWh were discharged from the shifting battery, and 161 MWh were used to charge the battery. The resulting efficiency is approximately 85%.

Data provided by Ecoult covering the period of July 2012 through the end of June 2013 was utilized to calculate that 138.5 MWh were discharged and 162 MWh were used to charge the battery system over this timeframe. The resulting efficiency is 86%. Figure 10 shows the efficiency by month based on the Ecoult data.

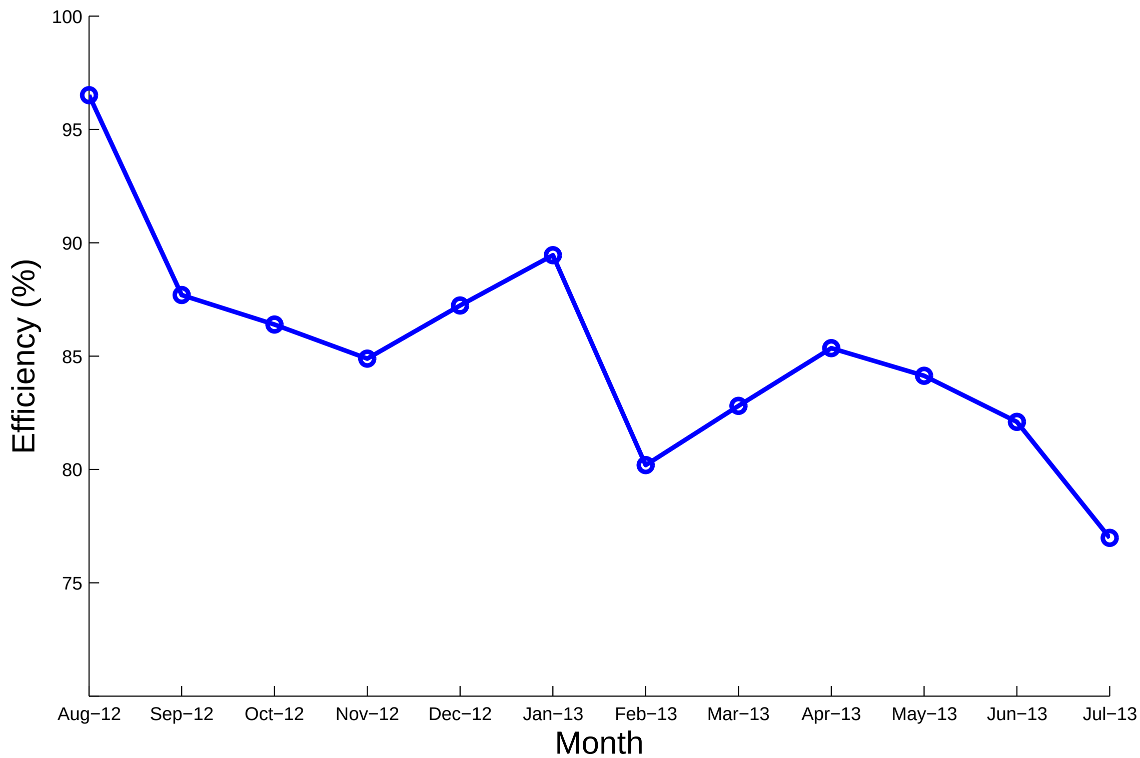

Figure 10: Shifting-battery efficiency, by month.

We note that when summing energy inputs and outputs over a month, errors in efficiency estimates can result from the fact that the SoC at the month's end may differ from that at the beginning of the month. This can give artificially high or low efficiency estimates. At the same time, shifting-battery efficiency shows a clear downward trend.

While these two estimates are close, we believe that the 85% efficiency estimate is probably the more accurate, given that we were able to match the beginning and ending SoC when performing the calculation.

Note the downward trend shown in figure 10. It is expected that the battery efficiency will tend to decrease over extended periods of service time. This is a widely accepted phenomena, explained in part by the lead-acid battery's tendency to have a decreased specific power over time in service (Reddy (2011) p. 15.9 - 15.18). Lower specific power is related to increased internal resistance of the battery. If the internal resistance of the battery is increased, then the I^2R loss associated with the battery is also increased (assuming constant current). This power loss makes the electrochemical conversion process less efficient over time, as shown in figure 10.

DC-to-DC Efficiency, including BoP Load

The DC-to-DC efficiency, including measured BoP load, is designed to take into account battery-container climate-control load and battery control-system load. It is reasonable to penalize battery system efficiency for these loads, as the battery system would not be able to operate without them. In addition, it is possible to decrease these loads. Including BoP load in an efficiency metric ensures that it is measured, and provides incentive to reduce this load.

The reason we term these loads "measured BoP load" is that they are measured at a meter called the "station meter" at the PNM Prosperity project. The station meter is behind the primary meter, and is on a distribution circuit. The station meter is behind the primary meter on the distribution circuit, and includes the battery container climate control as well as the battery control system. It does not include the data acquisition system.[11] Since the shifting-battery efficiency is being analyzed here, the station meter load must be weighted by 75%, as we are interested in the load supporting the shifting battery alone.[12]

Round-Trip Efficiency

Using the same ten days, the measured BoP load is taken during the charge-discharge cycle,[13] and used 75% of this amount to reflect the amount of BoP load attributable to the shifting battery.[14] We then added this BoP load to the total amount of energy used to charge the battery when calculating the efficiency. The BoP loads, as well as the resulting individual daily efficiencies, are in Table 7.

Table 7: Round-Trip Efficiency over Sampled Days, Including BoP Load

Year:	2012			2013						
Date:	12/1	12/3	12/15	1/14	3/22	3/23	3/24	6/19	6/23	6/26
Efficiency[15] (%)	84	80	87	82	85	84	78	84	80	83
Charge Energy (kWh)	892	884	811	799	813	820	788	890	925	898
Discharge Energy (kWh)	801	763	747	711	745	738	668	796	801	807
BoP Load[16] (kWh)	63	64	46	70	65	58	71	71	71	70

The average efficiency including BoP load for a round-trip is 83%.

Annual Efficiency

The average daily measured BoP load is 140 kWh, based on measurements available from 1-Sep-2012 through 30-Jun-2013. Because we are interested in 75% of this amount, this gives us a measured BoP assigned to the shifting-battery system of 105 kWh/day. Taking this to be the average load over the period used for our DC-to-DC efficiency calculation that excludes BoP load, this would amount to 37 MWh.[17] Adding this amount to the energy used to charge the battery yields a

[11] E-mail from Steve Willard on 23-Oct-2013.

[12] The station meter measures the load required to support all eight battery containers. We weight by 75% because there are six shifting battery containers out of the total of eight.

[13] Here, we are interested in round-trip efficiency. We therefore want the BoP load only while the charge-discharge cycle is being performed. BoP load at night is not part of this measurement.

[14] As six of the eight battery containers are for the shifting battery, we can approximate the BoP load due to the shifting battery by multiplying the total BoP load by 75%.

[15] Including BoP load.

[16] Attributable to shifting battery–which is 75% of the total measured BoP load.

[17] The period from 10-Jul-2012 through 26-Jun-2013 contains 351 days. $140kWh \times 351days = 49MWh$.

shifting battery round-trip efficiency of 69% over this same 10-Jul-2012 through 26-Jun-2013 time period.

The drop in efficiency (including measured BoP load) from 83% on a charge-discharge cycle basis to 69% on an annual basis is significant. This drop in efficiency is due to accounting for the measured BoP load not only during the charge-discharge cycles, but also at times when the shifting battery is not performing work (such as at night). The more frequently and heavily the battery system is used, the higher the annual efficiency will be, since the fixed BoP load will be spread out over a large volume of energy charged/discharged. In addition, battery self-discharge over time acts to further decrease the storage system efficiency when measuring continuously over time.

AC-to-AC Efficiency, including BoP Load

This measurement of efficiency is based on the AC meter nearest the battery storage systems. Since this meter measures the power flows to and from both battery systems, it is necessary to adjust the power flows to remove the impact of the smoothing battery system (since here we are interested in the efficiency of the shifting battery system). For this adjustment, we simply subtracted out the measured DC flows to and from the smoothing battery system. For the Shifting Battery BoP Load, the total BoP load is multiplied by 75%, since six of the eight battery containers are for the shifting battery.

The following formula is used for this efficiency calculation:

$$\text{AC-to-AC Efficiency} = \frac{\text{Adjusted AC Discharge Energy}}{\text{Adjusted AC Charge Energy} + \text{Shifting Battery BoP Load}} \tag{10}$$

Round-Trip Efficiency

The AC-to-AC Round-Trip Efficiency is calculated using equation 10. To obtain a round-trip efficiency measure, the Adjusted AC Discharge Energy and the Adjusted AC Charge Energy are measured from the beginning to the end of a charge-discharge cycle, taking care to insure that the SoC at the beginning and end are the same or close to each other. The BoP is measured over this same charge-discharge cycle, and is multiplied by 75% to find the amount attributable to the shifting battery. Table 8 shows the resulting calculated BoP, and round-trip efficiency, for the same ten days examined earlier.

Table 8: AC-to-AC Round-Trip Efficiency of Shifting-Battery System

Year:	2012			2013						
Date:	12/1	12/3	12/15	1/14	3/22	3/23	3/24	6/19	6/23	6/26
Efficiency (%)	90	86	92	89	92	90	85	90	87	90
Efficiency, AC-to-AC[18] (%)	78	76	78	75	75	76	71	77	76	77
AC Charge Energy[19] (kWh)	924	907	883	801	799	837	812	915	942	930
AC Discharge Energy[20] (kWh)	772	735	723	656	648	680	627	758	770	773
Shifting Battery BoP Load (kWh)	63	64	46	70	65	58	71	71	71	70

[18] AC Efficiency of the shifting battery system, as measured in front of the storage systems, net of BoP load attributable to the shifting batery system.

[19] The smoothing battery charge volumes were subtracted from the total AC charge energy to obtain the AC charge attributable to the shifting battery system.

[20] The smoothing battery discharge volumes were subtracted from the total AC discharge energy to obtain the AC discharge attributable to the shifting battery system.

The average AC-to-AC efficiency, including calculated BoP load, over the sampled days is 76%.

Annual Efficiency

Measuring from the AC Battery Meter (which measures power flows to and from both battery systems), we see that 194,500kWh was used to charge the two battery systems, and 133,300 kWh was discharged from the two battery systems over the 350 day period from 10-Jul-12 and 26-Jun-13.

Since here we are interested in isolating flows to and from the shifting battery, we adjust the charge and discharge numbers by subtrating power flows due to the smoothing battery. We then get an adjusted charge of 173,100 kWh, and an adjusted discharge of 123,800 kWh.

We then add 75% of the measured BoP over this same period, which was 36,800 kWh (or 140 kWh per day), to the adjusted charge in order to reflect the total energy inputs. The annual average AC-to-AC efficiency including BoP load, then, is 59%.[21]

3.3 Balance-of-Plant Load Characterization

In the shifting battery efficiency analysis, measured BoP loads were used. This measurement at the PNM Prosperity site is at what they have called the 'Station Meter.' This meter is on a distribution circuit at low voltage. PNM states that it captures most of the BoP load, but that there is a device drawing 1 to 2 kW of power that is not on this same circuit. Therefore, the measured BoP load may understate actual BoP load. This measured BoP load attributable to the shifting battery averaged 4.4 kW per hour for the period from 29-Aug-12 through 30-Jun-13.

For that same period, the calculated BoP load attributable to the shifting battery system averaged 14 kW per hour, or more than three times greater than the measured BoP load. Here, the term 'calculated balance-of-plant load' refers to the difference between energy recorded at the Primary Meter and the AC meter for PV output and the AC Battery Systems Meter. (It is 'calculated' becuase it is determined by a calculation rather than a direct meter reading). This difference must be the result of BoP load and site losses.

While the calculated BoP is a more comprehensive measure, we did not use it for the efficiency calculations. Our goal was to evaluate the performance of the storage resource, not the entire site. Since the calculated BoP is significantly larger than the measured BoP, it may be accounting for losses in the site that are not related to the battery systems. While this probably merits investigation, we did not feel it was fair to penalize the storage systems for losses that are likely taking place elsewhere in the Prosperity site.

3.4 Availability

Ecoult has been keeping data since November 2011 on storage-system downtime. The monthly system availability, measured as the number of hours the system is available in a month divided by

[21] $\frac{AdjustedDischarge}{AdjustedCharge + BoP} = \frac{123,800kWh}{209,900kWh} = 59\%$

the total number of hours in that month, is shown in Figure 11. Based on this data, the availability from November 2011 through July 2013 was calculated to be approximately 91%.

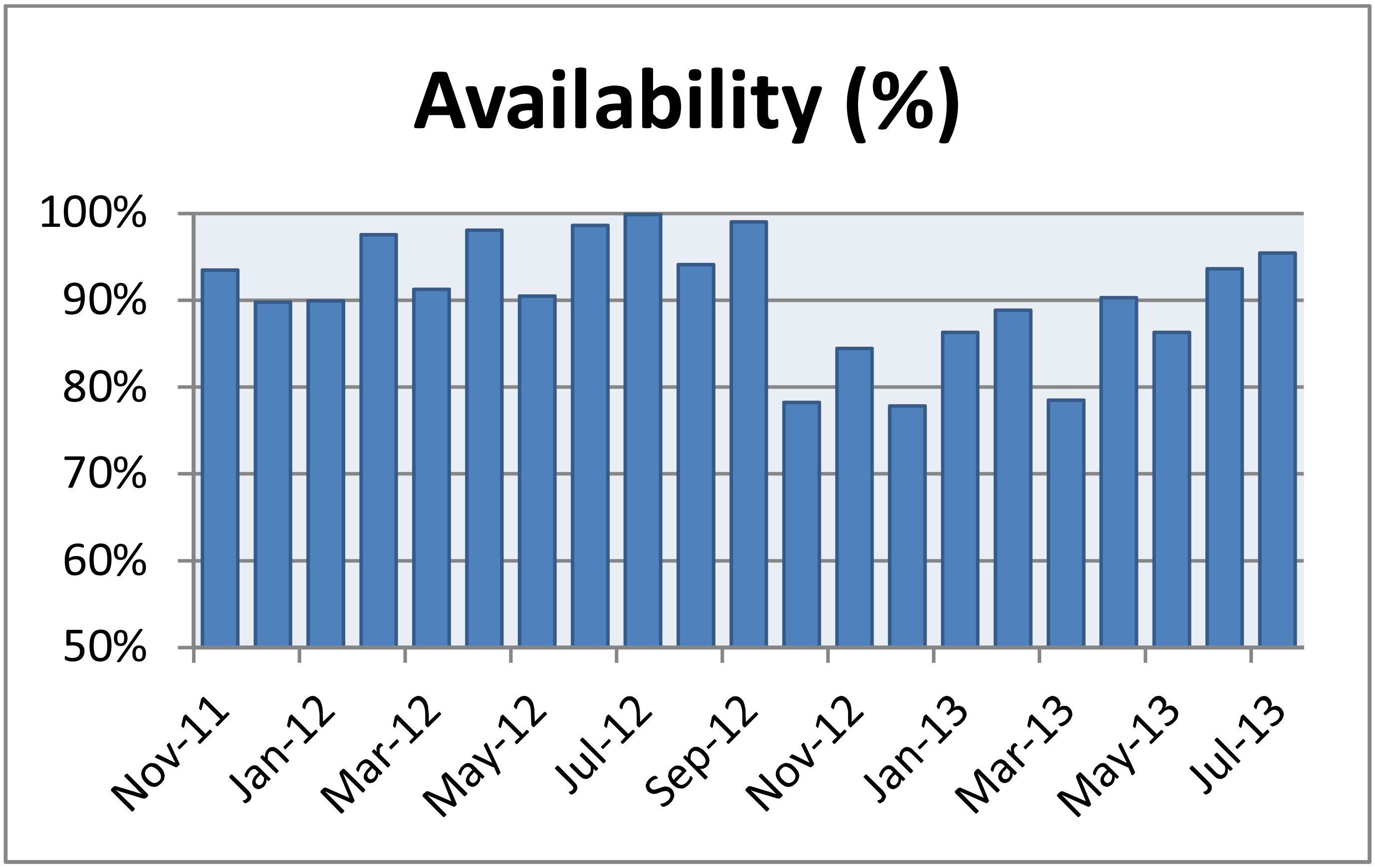

Figure 11: Availability (source of data for calculations: Ecoult)

We should keep in mind that because the storage system here has been used for PV shifting and smoothing, it has been used almost exclusively during the day. Maintenance has generally been performed in the evening, when the system has not been asked to respond. The availability number here, therefore, does not reflect the percentage of time that the battery system was commanded to perform and not available to–it reflects whenever the battery system was off-line, whether or not the system was needed. If availability instead is viewed as the percentage of time the battery was needed but was off-line, the availability would be significantly higher.

3.5 Estimated Remaining Battery Lifetime

Integrating, with respect to time, the battery data (supplied by Ecoult) for both the total smoothing-battery and total shifting-battery output, we find that from November 2011–July 2013, the smoothing battery has discharged approximately 32 MWh, and the shifting battery has discharged approximately 156 MWh.

Based on the estimated total lifetime output of the two batteries, through July 2013 the smoothing battery has expended about 2% of its total lifetime resource, whereas the shifting battery has expended roughly 9% of its total lifetime resource.

While these calculations are rough, they provide us with a sense of how hard the batteries are being utilized, and how much longer they might last if they are required to function similarly to what they are currently. The smoothing-battery system, compared with its capability, is being tasked at a low level. Based on its lifetime discharge capacity, it could continue to be operated as it has historically for roughly another 100 years.[22] (To be clear, other factors will likely prevent the batteries from operating this long. The point made here is that compared to their lifetime discharge capacity, the batteries are being utilized at a low level.) The shifting battery, however, has been used more heavily, and could be expected to last another 12 years if required to perform similarly to what it has been doing.[23]

If the shifting battery were used each day for 0.85 MWh of output (85% of recommended total useable capacity), then the battery would be expected to last for another 5 years, approximately.[24] If the smoothing battery were used for frequency regulation, as opposed to smooth out the variability of PV output, the system would have a much higher utilization. Assuming that following the AGC signal caused an output of 1.0 MWh each day,[25] the smoothing battery would also be expected to last for another 5 years.[26]

[22]Smoothing battery had an average output of 1.6 MWh/month from Aug-12 through Jul-13. Given a 2000 MWh maximum estimated output, and given that about 32 MWh have already been output, this would yield a total additional lifetime of 100 years.

[23]Shifting battery had an average output of 11 MWh/month from Aug-13 through Jul-13. Given a 1800 MWh maximum estimated output, and considering that about 156 MWh have already been output, this would yield a total additional lifetime of 12.4 years.

[24]1800 MWh total lifetime – 156 MWh already output = 1644 MWh remaining. 1644 MWh/(0.85 MWh/day) = 1934 days of life remaining at 0.85 MWh/day. 1934 days/ (365 days/year) = 5.3 years remaining.

[25]Please see Appendix C for more information on this supposition.

[26]2000 MWh total lifetime – 32 MWh already output = 1968 MWh remaining. 1968 MWh/(1.0 MWh/day) = 1968 days of life remaining at 1.0 MWh/day. 1968 days/(365 days/yr)=5.4 years remaining.

4 Recommendations for Battery and Photovoltaic Systems

The following observations and suggestions apply to the PNM Prosperity project, as well as other similar projects that are planned for the future. Some observations are based on this report's analysis; others are based on more general project considerations, as well as on putting the storage and PV plant into the broader context of the bulk grid.

PV Smoothing

When using the battery system to smooth PV output, it would make sense to also take the BoP load into account in the smoothing algorithm. The BoP load is highly variable due to the air conditioning and heating load. The battery systems were installed, in part, to reduce PV output variability–but in addition to doing this, they introduce a new variability of their own. Even if primarily tasked with PV smoothing, the battery smoothing algorithm could be adjusted to take both PV output and battery system BoP load into account. Another option is smooth the feeder voltage, which would, in effect, take BoP load movements into account (as well as taking into account load swings on the feeder itself).

A broader issue is whether PV smoothing is the most valuable use for the smoothing battery. Instead, it could be used for frequency regulation (possibly in combination with PV smoothing). This would increase utilization, and perhaps provide a higher value-added to the grid. It should be kept in mind that the storage systems are merely co-located with the PV array–they do not have to perform either PV smoothing or shifting. They can be used for other applications, such as those that provide greater benefit to the bulk grid. Responding to an AGC signal instead of PV smoothing is discussed below in the "Battery Lifetime and Recommended Applications" subsection.

Battery Lifetime and Recommended Applications

Battery cells have a finite lifetime. While that lifetime depends on multiple factors, two of the most important are the cumulative battery output and battery cell age. Storage-resource owners would like to extend the lifetime of their resource as much as possible. A tendency to use that finite resource sparingly is not surprising.

However, it is possible to have too much conservation. If battery cells have a shelf-life of 20 years, for example, and the batteries are being operated such that they would have a lifetime of 100 years based on usage, then they will still fail after 20 years. At a minimum, it would be better to operate them such that their lifetime based on usage *matches* their shelf-life.

In areas that generally have clear skies, such as New Mexico, one would expect that storage systems designed for smoothing PV output may be used sparingly. This does appear to be the case. This does not mean that the PV smoothing application has little value. It does mean, however, that the storage resource may be underutilized.

Having the smoothing battery follow an AGC signal means that it can be called upon to operate 24-hours a day, as opposed to only during daylight hours when used for PV smoothing. It can be used no matter what the weather. In addition, when performing PV smoothing, there can be a momentary drop in customer load at the same time there is a momentary drop in PV output–in which case it would be better (from the overall grid's perspective) not to inject power from storage to compensate. If an AGC signal is followed instead of PV smoothing, this counterproductive action would not be taken. Our recommendation, therefore, is that frequency regulation be considered as an additional grid service.

PV Shifting

When using the shifting battery to shift PV output forward in time to better coincide with peak system load, one must keep in mind that this comes at a cost. Some of the energy generated will be lost due to inefficiencies in the round-trip storage cycle. The amount of energy lost could be as little as 10%, or as great as 35%, depending on how the round-trip efficiency is calculated (discussed below in the "Battery System Efficiency, System Configuration, and Balance-of-Plant Load" subsection). One question is whether the benefits to the system of shifting power output forward a few hours are worth the cost of losing some PV output to round-trip storage cycle inefficiencies. A production cost model analysis could help answer this question.

When considering a storage system to shift PV output, a partial substitute worth evaluating is that of using a tracking PV array. Installing a tracking PV array results in higher PV output–especially in the afternoon (Trueblood et al., 2013)–at the expense of additional capital and maintenance costs. Installing a tracking PV array can therefore be thought of as a partial substitute to adding a shifting storage system to a fixed PV array. The PV array at the PNM Prosperity site is fixed–converting it to a tracking array at this point is not a realistic option. However, for future projects, the costs and benefits of a fixed PV array plus shifting storage system versus a tracking PV array can be compared.

The incremental cost of making a fixed PV array tracking can be compared with the cost of installing a shifting battery system. As for the benefits, the utility to the grid of a tracking PV system versus a fixed PV system plus shifting battery can be compared by using a production cost model that uses the power production profile of each as an input. The annual production cost (from conventional power plants) difference between the two scenarios will reflect the difference in value to the bulk grid between the two options.

Of course, the shifting battery at the PNM Prosperity site does not have to be used to shift PV output. Instead, it could supply a block of power when it is most needed, and charge when energy is cheapest (i.e., arbitrage). This application may have higher value than PV shifting, because the battery could charge at night, when energy is least expensive. Using the shifting battery to provide spinning reserve is another option that may add more value than PV shifting, and is worth study.

Battery System Efficiency, System Configuration, and Balance-of-Plant Load

Battery system round-trip efficiency, measured on a DC-to-DC basis, was found to be 89%. Including BoP load, the DC-to-DC round-trip efficiency drops to 83%. When measuring on an AC-to-AC basis (which factors in inverter losses and BoP load), the round-trip efficiency drops to around 76%.

While the round-trip measurements are in-line with our expectations, the annual efficiency estimates including BoP losses are lower than expected. The reason for this is that while the shifting battery is being used for a fraction of the time, there is BoP load the entire time under consideration. In other words, BoP load when the battery is not being used (every night, as well as on days the battery is not dispatched) counts against its annual efficiency. Operating the battery system more often would improve this efficiency, as would drawing less BoP load when the battery system is not in use.

Future projects may be able to reduce the level of losses due to BoP load and inverter losses exhibited here. Orienting the battery containers East-West instead of North-South, exposing less wall area to the harsh West exposure during the afternoon hours, would have reduced the air-conditioning load for the PNM Prosperity project, and can be taken into account for future projects. Locating the energy storage containers underground may also be a possibility for future projects, in order to decrease temperature regulation costs. In addition, the number of trips through inverters could be reduced (when shifting or smoothing PV power) by placing the PV array and battery systems on a common DC bus.

To store PV-generated energy, the PV generation must be first converted to AC at the PV array, and then be converted back to DC to charge the battery-storage system. Therefore, PV-generated energy must pass through inverters three times in order to be stored and put on the grid (once at the PV array, a second time to charge the battery, and a third time to discharge the battery to the grid).

If the PV array and battery-storage systems were connected on a DC bus, PV power would only need to go through an inverter once, even if the battery were used to shift PV power. Assuming an average inverter efficiency of 96.5% for one-way conversion,[27] these two additional trips amount to nearly 7% lower efficiency (two additional passes through an inverter, at about 3.5% losses each pass) to store PV energy than would be the case if the systems shared a DC bus.

While the PNM Prosperity project planners would have liked to have connected the two systems via a DC bus, there were technical issues preventing this. For future projects, it would be preferable to plan for the PV and battery resources at the same time, in order to insure that they can be connected via a DC bus. Even if the storage system were to be used to respond to an AGC signal, it could charge during the day from the PV generation in DC. Charging directly from a DC resource would avoid an extra trip through the inverter, reducing losses.

Finally, the large difference between measured BoP load and calculated BoP load plus losses warrants investigation, in our view. While this difference may not be due to the storage systems, the site losses are real (assuming there is no systematic data error). A site loss / BoP load audit may uncover the root cause of the losses.

Smoothing- vs. Shifting-Battery System Selection

As the smoothing battery (UltraBattery) can both perform high ramp-rate smoothing and can store as much energy as the shifting battery (Deka Synergy), it is the more versatile of the two. When the PNM Prosperity storage project was built, the UltraBattery cost significantly more to manufacture than the Deka Synergy battery. Since then, East Penn has been able to produce the UltraBattery more efficiently, reducing the cost differential between the two batteries. Additional experience in producing the UltraBattery may further reduce the cost.

We believe that the additional capability an UltraBattery system can provide allows it to provide greater benefits to the grid than a Deka Synergy-based system. How much more depends on the specifics of the grid where it will be installed. In a number of the power grids studied at Sandia National Laboratories, reserve provision–especially regulating reserve provision–appears to be more valuable than time-of-day shifting.[28] Given that storage value depends on other system factors (such as the conventional generating fleet, amount and variability of renewables, load variability, etc.), we recommend evaluating storage for the specific grid under consideration. The UltraBattery system's capability to do both smoothing and shifting may well justify the additional cost.

[27] Estimate derived from Malashenko et al. (2013), pp. 8–9.
[28] For an example of this, see Ellison et al. (2013).

5 Conclusions

The Public Service Company of New Mexico (PNM) Prosperity electricity storage project consists of a 500 kW/350 kWh energy-smoothing battery and a 250 kW/1 MWh energy-shifting battery, and is co-located with a 500 kW solar photovoltaic (PV) resource. The site demonstrates it's ability to accomplish both smoothing and energy-shifting tasks as required. It is dispatchable, acting as a distributed generator when commanded. The smoothing functions mitigate high-frequency power swings when cloud cover rapidly changes the PV site's output.

In order to determine the degree to which the battery smooths the output, a set of metrics were developed. These metrics compare the pre-smoothed output of only the PV site to the post-smoothing output of the battery and PV site combined by a statistical relationship of the fluctuations of their power. This allows for a quantitative demonstration of the system's effectiveness.

Two factors are of primary interest when evaluating a shifting battery: the ability to charge and discharge in blocks as commanded, and the round-trip efficiency. As no problems were reported with the system charging and discharging as commanded, round-trip efficiency was chosen as the metric to evaluate smoothing battery performance.

Because the shifting battery acts as a dispatchable energy source as commanded without fault, the focus of the analysis of this battery system shifts to the efficiency with which it dispatches the energy. The round-trip efficiency of the charging and discharging cycle is studied, across two different time horizons. The results from this study show that the battery system can charge and discharge relatively efficiently for one cycle, but over the course of a year, is significantly less efficient. The reason for this is that the shifting battery is only being dispatched for a small portion of the entire time horizon, during which there is a BoP load. To clarify, the BoP load is present when the battery is not being used (all night, as well as on days the battery is not dispatched), which decreases its annual efficiency. Table 9 illustrates the results of the shifting battery efficiency evaluation. The two ways to increase this efficiency are: dispatch the battery more frequently, and decrease the BoP load.

Table 9: Shifting battery efficiency.

Measurement	Includes BoP Losses?	Round-Trip Efficiency	Annual Efficiency
DC-to-DC	No	89%	85%
	Yes (measured BoP)	83%	69%
AC-to-AC	Yes (measured BoP)	76%	59%

Various suggestions are discussed in order to increase efficiency. Placing the storage and PV array on the same DC bus would likely improve the AC-to-AC efficiency, since the PV energy would avoid one extra trip through the AC inverter. Also, an East-West instead of North-South orientation of the battery containers may increase efficiency by exposing less wall area to the harsh west exposure during the afternoon hours. Taking this a step further would be a shading canopy for the battery containers, for an additional increase in efficiency (passive cooling).

While the battery system is conveniently co-located with a PV array, it is not limited to performing actions related to the PV output. It is able to provide additional value by performing other applications, such as the following of an automatic generation control (AGC) signal. Using the smoothing battery to follow an AGC signal will allow it to be useful over a full 24-hour cycle, instead of only the days where clouds cause intermittent output on the PV array. As discussed, the battery can be utilized more often than it is currently, making it more valuable to the utility (vs. standing by). Also, following the AGC signal is useful by balancing load and generation on the grid; smoothing PV output can be counterproductive if there is a simultaneous drop in load and PV output.

For the shifting battery, using the system to dispatch power when most needed and withdraw power from the grid when it is cheapest may provide more value than simply shifting the PV output (i.e., arbitrage). To add value shifting energy, the system benefit of shifting off-peak energy to on-peak energy must outweigh the cost of losing energy to storage round-trip inefficiencies. Decoupling the shifting battery from the PV output allows it to charge at night or during the day, allowing the operator to charge the battery at a time when energy is the least expensive, and sell it when it is worth the most. Using the battery as spinning reserve may also be beneficial to the utility.

This project was partially funded by the American Recovery and Reinvestment Act, in conjunction with its partners: University of New Mexico, Northern New Mexico College, Sandia National Laboratories, East Penn Manufacturing Company, and Electric Power Research Institute. As one of the first distribution-scale, grid-connected demonstration systems, the PNM Prosperity site continues to provide valuable information for future storage projects of this scale.

Bibliography

Reddy, Thomas B., editor *Linden's Handbook of Batteries* Fourth Edition, McGraw Hill, 2011.

Coppin, Peter and John Wood. *Ultrabattery Storage Technology and Advanced Algorithms at the MW-Scale* EESAT Conference Proceedings, 2011, http://www.sandia.gov/eesat/2011/papers/EESAT_2011_UltraBattery_Storage_Coppin_Wood.pdf, accessed December 3, 2013.

East Penn Manufacturing Co., Inc. *Deka Unigy II Modults* brochure, http://www.dekabatteries.com/assets/base/0919c.pdf, accessed December 3, 2013.

Ecoult. *Ecoult Megawatt Scale Energy Storage* brochure, http://www.ecoult.com/technology/brochure-downloads/, accessed September 5, 2013.

Ellison, James F., Dhruv Bhatnagar, Nader Saaman, and Chunlian Jin. *NV Energy Electricity Storage Valuation: A Study for the DOE Energy Storage Systems Program.* Sandia National Laboratories, SAND2013-4902, June 2013.

Kay, Steven M. *Fundamentals of Statistical Signal Processing, Volume III*, 1st ed., Prentice Hall, April 5, 2013.

Lam, L.T. and R. Louey. *Development of ultra-battery for hybrid-electric vehicle applications.* Journal of Power Sources, vol. 158, 2006.

Malashenko, Elizaveta, Stephen Appert, and Wendy al-Mukdad. *Advanced Inverter Technologies Report.* Grid Planning and Reliability, California Public Utilities Commission (CPUC), January 18, 2013.

Proakis, John G. and Dimitris K. Manolakis. *Digital Signal Processing, 4th ed.* Prentice Hall, April 7, 2006.

Trueblood, Chris, Steven Coley, Tom Key, Lindsey Rogers, Abraham Ellis, Cliff Hansen, and Elizabeth Philpot. *PV Measures Up for Fleet Duty.* IEEE Power and Energy Magazine, February 20, 2013.

U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability. Energy Storage Program. *Carbon-Enhanced Lead-Acid Batteries.* http://energy.gov/sites/prod/files/CELA.pdf, accessed December 3, 2013.

U.S. Department of Energy. *Recovery Act Smart Grid Programs, Project Information.* http://www.smartgrid.gov/recovery_act/project_information, accessed December 3, 2013.

Kay, Steven M., *Fundamentals of Statistical Signal Processing, Volume II: Detection Theory*, 1st ed., Prentice Hall, February 6, 1998.

A ARRA Energy Storage Projects

This section highlights the funded projects to provide a context from which to consider the individual project discussed in this report. The Smart-Grid Energy-Storage Demonstration Projects are being managed by the National Energy Technology Laboratory for the DOE Office of Electricity Delivery and Energy Reliability. The information below was primarily derived from project fact sheets contained on the smartgrid.gov website (U.S. Department of Energy, 2013).

A.1 Grid-Connected Demonstration Projects

PNM Prosperity Project
ARRA Funding: \$2,305,931
Total Project Funding: \$6,113,433

PNM installed a 500 kW/1 MWh advanced lead-acid battery and a 250 kW/500 kWh advanced lead acid with supercapaitors battery with a 500 kW solar PV plant to create a dispatchable, distributed generation resource. This hybrid resource provides simultaneous voltage smoothing and peak shifting through advanced control algorithms and switches between two configurations, end-of-feeder and beginning-of- feeder. Data collection and analysis produce information for a wide range of applications including grid upgrade deferral. The project has also yielded modeling tools used to optimize battery-system control algorithms and further the understanding of feeders with storage and distributed generation. The site is located in southeast Albuquerque.

Goals/Objectives

- Demonstrate that intermittent, renewables-based, distributed generation and storage can mitigate voltage-level fluctuations and enable peak shifting
- Quantify and refine performance requirements, operating practices, and costs associated with the use of advanced storage technologies
- Achieve 15% or greater peak-load reduction through a combination of substation-sited PV and storage

East Penn – Lyons Station
ARRA Funding: \$2,543,523
Total Project Funding: \$5,087,269

Project Description
East Penn Manufacturing will design and construct an energy storage facility consisting of an array of UltraBattery™ modules integrated in a turnkey battery energy storage system (BESS). In addition to the UltraBatteries™, the BESS will include a power conditioning system, a master programmable controller, and a battery monitoring system. The completed energy-storage system will be designed to sell up to 3 MW of frequency regulation to PPL EnergyPlus, a designated load-serving entity within PJM. In addition to frequency regulation, the system will provide demand-management services to Met-Ed during specified peak power periods. These services will provide up to 1 MW for 1–4 hours to meet the requirements of PA Act 129. The UltraBattery™is uniquely suited to these applications because it was designed for high-rate PSoC cycling.

The system is sized to maintain the battery's SoC between 70% and 30% for a maximum 40% depth of discharge for continuous regulation services. The UltraBattery™is a hybrid energy-storage device that combines an asymmetric ultracapacitor and a lead-acid battery in one unit cell. The UltraBattery™is expected to provide the same benefits as lead-acid battery systems, such as low initial cost, full recyclability, plus increased cycle life by incorporating ultracapacitor technology within the battery. To demonstrate modularity and portability, self-contained, containerized UltraBattery™system will be designed and included as a subset of this project.

Goals/Objectives

- Integrate advanced energy storage technology into an existing utility grid
- Demonstrate the economic and technical viability of an UltraBattery™ BESS for frequency regulation ancillary services and demand management
- Establish the cost of the UltraBattery™and all of the controlling power electronics required for a utility grid management application

Duke Energy – Notrees
ARRA Funding: $21.8 M
Total Project Funding: $43.6 M

Project Description
The Notrees Project will analyze and discern how, when integrated with wind power, energy storage can compensate for the inherent intermittency of this renewable power generation resource. Incorporating both existing and new tools, technologies, and techniques, this demonstration project will provide valuable information regarding wind energy storage and serve as a model for other entities to adapt and replicate. The energy-storage system will be designed and constructed using fast response, advanced lead-acid batteries configured to provide 36 MW output capabilities with a storage capacity of 24 MWh.

Goals/Objectives

- Store energy during non-peak generation periods and re-issue the power to meet demand
- Quantify the value of wind storage
- Demonstrate the reliability and dispatchability of wind storage
- Use the storage system for system balancing
- Determine if energy storage solutions are commercially viable to support wind generation

Southern California Edison – Tehachapi
ARRA Funding: $24,978,264
Total Project Funding: $54,856,495

Project Description
The Tehachapi Wind Energy Storage Project will be located at Southern California Edison's (SCE) Monolith Substation in Tehachapi, California, and the 8 MW $\times$ 4 hr (32 MWh) BESS and 2 $\times$ 4 MW/4.5 MVA smart inverters will be housed in a 6,300-square-foot facility. The project will evaluate the performance of the BESS to improve grid performance and assist in the integration of large-scale variable-energy-resourced generation. Project performance will be measured by 13 specific operational uses: providing voltage support and grid stabilization, decreasing transmission losses,

diminishing congestion, increasing system reliability, deferring transmission investment, optimizing renewable-related transmission, providing system capacity and resources adequacy, integrating renewable energy (smoothing), shifting wind-generation output, frequency regulation, spin/non-spin replacement reserves, ramp management, and energy-price arbitrage. Most of the operations either shift other generation resources to meet peak load and other electric-system needs with stored electricity, or resolve grid stability and capacity concerns that result from the interconnection of variable-energy resources. SCE will also demonstrate the ability of lithium-ion battery storage to provide nearly instantaneous maximum capacity for supply-side ramp rate control to minimize the need for fossil fuel-powered back-up generation.

Goals/Objectives

- Validate the performance and effectiveness of lithium-ion technology
- Demonstrate the integration of intermittent wind energy
- Develop a smarter, more efficient electric grid
- Advance market readiness of utility-scale storage

City of Painesville
ARRA Funding: $4,243,570
Total Project Funding: $9,462,623

Project Description
The City of Painesville, Ohio and its partners will demonstrate vanadium redox battery-storage capacity at the 32 MW, coal-fired Painesville Municipal Electric Plant. Using stored power enables the facility to attain the same daily output requirement, more efficiently and with a lower carbon footprint. When the project is fully implemented, the plant will operate at a constant 26 MW, 80% of rated capacity. The long-term goal is to scale the battery system in stages, ultimately upgrading the facility to 10 MW of capacity with up to 80 MWh of storage. In the first phase, 1 MW of power with 6–8 hours of storage will be installed. This capacity is sufficient for Painesville to evaluate the benefits of energy storage, assess its uses in optimizing power-generation efficiency, and facilitate American Municipal Power with leveling the peak demands of the system. A bi-directional, four-quadrant inverter, with a rated capacity of 1.0 MW and 1,440 amps at 480 VAC, will be used to provide AC/DC and voltage conversions. The battery will be constructed with two parallel electrolyte flow systems providing the total net electrical capacity of 1.0 MW. Each subsystem will be comprised of sixty four 10 kW stacks. The subsystems will be arranged in parallel to supply peak operating loads. Each stack subsystem will have their electrolyte flow into two 15,000 gallon polymer tanks, at rates ranging between 500 and 1500 gallons per minute. The battery components will be produced in the United States and the stacks will be assembled in Painesville before being installed at the Painesville Municipal Electric Plant Battery Building.

Goals/Objectives

- Demonstrate power storage to provide spinning reserves in a grid environment with expansion to a larger scale
- Establish a template that can be introduced throughout the United States
- Provide data on the active use of storage to manage peak requirements in the most efficient manner

Primus Power, Modesto Energy Pods
ARRA Funding: $14,000,000
Total Project Funding: $46,700,000

Project Description
Primus Power is deploying a 25 MW/75 MWh EnergyFarm™in the Modesto Irrigation District substation in California that consists of a series of EnergyPods™; a plug-and -play zinc-flow battery combined with off-the-shelf components and power electronics housed inside a standard shipping container. The modular design and operation will be field tested at Pacific Gas & Electric (PG&E) with support from Sandia National Lab and the Electric Power Research Institute. The EnergyFarm™will displace a planned $78M fossil-fuel plant. EnergyFarms™can firm intermittent wind energy and mitigate energy price spikes. During a spike the Farm switches to full dispatch power, reducing energy purchases during costly periods, capturing multiple revenue streams, and shortening return on investment. EnergyFarms™are scalable from 330 kW/1 MWh up to systems larger than 100 MW/300 MWh.

Goals/Objectives

- Develop a distributed, mobile energy storage module based on a zinc-flow battery technology that can be mass produced
- Reduce system capital costs and footprint
- Enhance application flexibility
- Validate module performance and functionality

Beacon Power - Hazle Township, Pennsylvania
ARRA Funding: $2,543,523
Total Project Funding: $5,087,269

Plant has been delayed because of Beacon Power bankruptcy and reorganization.

Detroit Edison – community-scale energy storage (CES)
ARRA Funding: $2,543,523
Total Project Funding: $5,087,269

Project Description
Detroit Edison will design, construct, and install an aggregated 1 MW CES system in their service territory at the Hager substation in Michigan to demonstrate the potential of CES systems to strengthen grid reliability. The performance data of the CES devices and control systems under in-service operating conditions will be analyzed and used to identify gaps and facilitate how the devices can be standardized for use across the U.S. The project will also integrate the utility-owned 500 kW solar system to the energy-storage device; provide proof-of-concept testing for an integrated, centralized communication system; and test the use of secondary-use electric vehicle (EV) batteries as CES devices.

Goals/Objectives

- Demonstrate peak shaving, demand response voltage, and emergency load relief of the CES devices when integrated to the utility grid
- Explore remote and automatic monitory and control responses

- Develop and verify advanced modeling and simulation methods for system planning and operations based on existing utility practice and expanded to include photovoltaic systems integration
- Demonstrate intentional islanding of CES devices with a utility distribution circuit and how they can aid in frequency regulation

Detroit Edison is an electric distribution utility serving approximately 2.2 million customers in Michigan. Detroit Edison will work with selected subrecipients, consultants, contractors, and vendors to demonstrate the use and benefits of CES systems in a utility territory and also to test the ability to integrate secondary-use EV batteries into the CES demonstration effort. This project will install 18–20 S&C supplied 25 kW/50 kWh CES units and two Chrysler-supplied secondary-use EV battery CES units into a system that includes a 500 kW storage device integrated into a solar PV system that was installed as part of project cost-share through the Michigan Public Service Commission (MPSC) Smart Grid Storage Program. The CES units will be coupled with the utility scale device to demonstrate a variety of applications. The goal of this project is a proof of concept to demonstrate the use and benefits of CES systems in a utility territory and also to test the ability to integrate secondary-use EV batteries into the CES demonstration effort. This project will install 20–22 CES units into a system that includes a 500 kW storage device integrated into a solar system. The 18–20 S&C-supplied CES units will be 25 kW/50 kWh devices and will be coupled with the utility scale device. Two Chrysler-supplied automotive battery CES units will be installed to demonstrate the same set of applications a year and a half after the installation of the S&C CES devices.

PG&E CAES – no grid connection (if it goes forward) before 2015
ARRA Funding: $25,000,000
Total Project Funding: $355,938,300

Project Description
(PG&E's advanced underground CAES demonstration project is intended to validate the design, performance, and reliability of a CAES plant rated at 300 MW with up to 10 hours of storage. The CAES demonstration project is scoped to test the suitability of a porous rock formation as the storage reservoir in California, and demonstrate the technological improvements in the design of such plants. Porous rock formations are much more plentiful than the salt domes now used by the two operational plants in Alabama and Germany. If this geology is proven viable, this technology has the potential to be replicated throughout California and elsewhere in the United States. The project is also differentiated by its potential use of a new CAES plant design that is much more efficient than first-generation Alabama and German designs. This project is comprised of three phases. Phase I includes site selection, reservoir testing, preliminary plant design, an environmental assessment, and a competitive solicitation to determine if there are interested and viable parties for plant construction, ownership, and operations/maintenance. Phase I is estimated to last 4.5 years. Phase II, which includes obtaining approval to proceed with the construction and commissioning of a full CAES plant, has an estimated 6-year duration. Phase III includes operations and monitoring and is expected to occur over 2 years.

Goals/Objectives

- Verify the technical performance of advanced CAES technology using a porous rock formation as the underground storage reservoir
- Integrate intermittent renewable resources

- Maintain emergency spinning/non-spinning reserve and perform volt-ampere reactive/voltage support

A.2 Research Level (Not Grid-Connected) Demonstration Projects

Aquion Energy
ARRA Funding: $5,179,000
Total Project Funding: $10,359,827

Project Description
Aquion Energy and its partners will demonstrate a low cost, grid-scale, ambient-temperature sodium-ion energy-storage device. The energy-storage chemistry in this device uses an electrochemical couple that combines a high-capacity carbon anode with a sodium intercalation cathode capable of thousands of deep discharge cycles over extended periods of time. The proposed aqueous sodium-ion technology includes the use of thicker electrodes, less expensive separator and current collector materials, and the use of benign materials for electrodes and electrolyte salts. This project will progress the work from bench-scale to pilot-scale, enabling multiple ampere-hour cells to be manufactured and assembled into test batteries. Aquion plans to site units with a capacity between 10 kWh and 100 kWh that have the ability to perform medium-to-long-duration (more than 2 hours) charge and discharge functions with greater than 95% DC-DC efficiency. The units will be safe and environmentally benign. Testing will characterize the energy storage capacity of the units, the response to various signals, compliance with utility interconnection standards, battery and power-conversion-system efficiency, and effectiveness under various cycles typical of the applications being validated. Utility application-level testing will test the functionality of the unit with respect to its ability to respond to external control signals and properly interact with electric grid in carrying out relevant sequences. The pilot line will be commissioned for production at the end of the project.

Goals/Objectives

- Projected capital cost less than $250/kWh at pack level
- Deep discharge cycle life of >10,000 cycles
- Volumetric energy density of >20 kWh/m^3
- Calendar life of over 10 years
- Build and install multiple 100 kWh batteries

Ktech Corp
ARRA Funding: $4,764,284
Total Project Funding: $9,528,567

Project Description
Raytheon Ktech and EnerVault will integrate EnerVault's Vault-20 battery energy-storage system (250 kW/1 MWh) with a Helios dual-axis tracker 180 kW PV system. The system will be deployed at an agricultural site in California's Central Valley. It will store the energy generated and dispatch power to run an irrigation pump and inject energy back into the utility grid during peak times to help offset demand from a section representing 4% of California's electricity demand. System modularity provides scalability for multi-megawatt deployments. The Vault-20 consists of electrolyte tanks

and transportainers, which house stacks, pumps, control system, and power-conditioning systems. Technology development will progress from 15 × 15 cm lab-scale cells and 20-layer stacks, to a 2–5 kW prototype system, then a 30 kW alpha system, concluding with a 250 kW beta system. EnerVault plans to begin manufacturing flow battery stacks in its Northern California plant within 12 months of project completion.

Goals/Objectives

- Develop a modular system rated at 250 kW and 1 MWh that fits inside a standard shipping containers to minimize onsite deployment time and cost
- Integrate a battery energy-storage system with a variable renewable energy resource
- Reduce cost and environmental impacts

Amber Kinetics – not grid connected
ARRA Funding: $3,694,660
Total Project Funding: $7,457,591

Project Description
Amber Kinetics is developing a flywheel system from sub-scale research prototype to full-scale mechanical flywheel battery and will conduct a commercial-scale demonstration. The goal is to deliver a cost-effective prototype flywheel system that can be grid connected and electrically charged and discharged. The flywheel stores energy in a spinning rotor that is connected to an electric motor that converts electrical energy into mechanical energy. To recover the energy, the motor is electrically reversed and used as a generator to slow down the flywheel converting the mechanical energy back into electrical energy. Amber Kinetics will improve the traditional flywheel system by engineering breakthroughs in three areas, resulting in higher efficiency and radically reduced cost: bearings, low-cost rotor, and high-efficiency motor generator. This technology can also be used to optimize existing infrastructure.

Goals/Objectives

- Deliver a prototype system that can be grid connected and electrically charged and discharged
- Develop a commercial-scale prototype of the flywheel technology
- Provide a plan to scale the system to cost-effective price points
- Achieve energy storage efficiencies greater than 85%

SEEO – not grid connected
ARRA Funding: $6,196,060
Total Project Funding: $12,392,120

Project Description
SEEO and its partners are demonstrating a large-scale prototype of a solid-state electrolyte lithium-ion rechargeable battery for use in smart-grid energy storage applications. SEEO seeks to validate this technology to address the needs of CES systems–small (less than 100 kW) distributed energy-storage systems alongside pad-mounted and pole-mounted transformers. The battery pack is more than a 50% improvement in weight and energy density; has 10–15+ year operating life with 3,000–5,000 or more cycles; has no volatile or flammable components; and will be 35% cheaper than existing lithium-ion batteries. This approach allows independent control over mechanical and electrical properties. The cell can withstand temperatures as high as 150 °C and voltages of 10 V

without incident. An independent analysis of the environmental and economic impact of battery improvement will also be conducted.

Goals/Objectives

- Develop and deploy a prototype battery system that validates SEEO's technology
- Improve battery installation and maintenance
- Produce a plan for manufacturing and commercializing the technology at utility scale

Sustain X – not grid connected
ARRA Funding: $5,396,023
Total Project Funding: $13,046,588

Project Description
SustainX is developing and demonstrating a modular, market-ready energy-storage system that uses compressed air as the storage medium. SustainX uses a crankshaft-based drivetrain to convert electrical energy into potential energy stored as compressed air. SustainX's ICAES system captures the heat from compression in water and stores the captured heat until it is needed again for expansion. Storing the captured heat eliminates the need for a gas combustion turbine and improves efficiency. SustainX achieves isothermal cycling by combining patented innovations with a design based on mature industrial components and principles. The system is designed for a 20-year lifetime. It achieves full-power output from start-up in less than one minute, and it does not use toxic chemicals.

Goals/Objectives

- Demonstrate the viability of isothermal compressed air technology to provide cost- effective energy storage
- Validate scalability for applications in both low- and medium-voltage distribution or subtransmission grids

B Solar PV Smoothing Metric Derivation

Justification for developing these metrics stems from statistics theory. The standard deviation from the mean power output represents the average power variation that the power system is likely to experience during the day's particular weather conditions. The percent reduction in the standard deviation of unsmoothed vs. smoothed power shows smoothing ESS's effectiveness by describing the improvement of how far the power is likely to deviate from its mean.

By applying the same statistical treatment to calculated ramp-rates (i.e., discrete-time derivative with varying δt of the same data), a new (but similar) metric can be described. The percent reduction in ramp-rates, however, represents the ESS's ability to dampen the rate at which power fluctuations occur. While the two metrics are very similar, they are not interchangeable.

The third and final metric represents an intuitive measurement of ESS's usefulness by quantifying how well the day's largest power swing is diminished. This particular quantity's mitigation is important to a system because these large swings are of particular concern to the utility connected to the storage system. Combined with the previous two metrics, one can perform a complete quantitative assessment of a PV smoothing energy-storage system.

Mathematically Quantifying Smoothing

In order to calculate the first- and second-order statistics of a given PV power profile, the mean must be calculated and removed. Due to the nature of the diurnal trend associated with PV power, it can be shown that the power output is not wide-sense Stationary (WSS).

Let $X(n) = P_{pv}$ and $F_s = 1$ [sample/sec] and have a typical shape similar to the waveform in Figure 12.

For X(n) to be WSS:

$$E[X(n)] = \mu_x; -\infty < n < +\infty \tag{11a}$$

$$C_x[n_1, n_2] = g(|k|); -\infty < k < +\infty \tag{11b}$$

where E[ ] is an expectation operator, C[ ] is a covariance operator, and $k = n_1 - n_2$ (with $-\infty < n_1 < +\infty$ and $-\infty < n_2 < +\infty$).

While applying an autocorrelation function or formal unit root test to the data would reveal that it is nonstationary in time (due to the autocorrelation function's slow decay), it is more easily and intuitively shown by example that X(n) random process does not meet the requirements to be considered WSS. By visual inspection, the sample mean estimator of E[X(n)] for $0 < n < 5000$ [sec] is not equivalent to E[X(n)] for $30000 < n < 35000$ [sec]. This indicates that the temporal average varies with respect to time. Thus, the mean cannot be removed by simply subtracting the sample mean point-by-point. Because of this, the signal is disqualified from the consideration of WSS and all of the assumptions that go along with the designation. Therefore, a time-varying mean removal method must be developed in order to approximate the signal as being WSS.

Note that the use of a full day's worth of data is analyzed and assumed non-stationary. Because the trend that creates the non-stationarity is shaped (mostly) by the diurnal trend of the sun, the assumption that the sample mean of a sub-set of points limited in length is constant with respect to time can be made. This assumption is justifiable because the maximum rate at which the sun causes appreciable power output change is roughly 2 orders of magnitude slower than the rate at

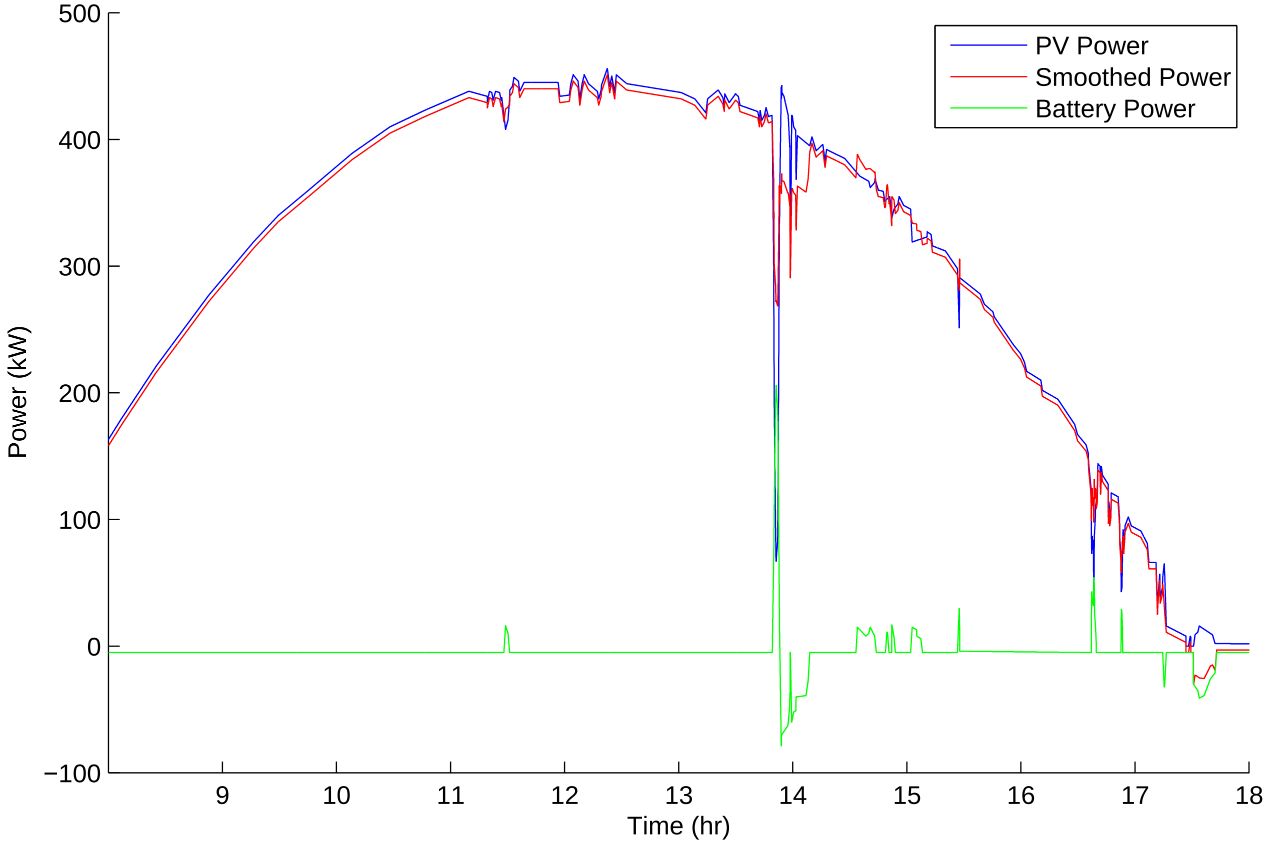

Figure 12: Smoothed power profile, 7-Mar-2012 data.

which the cloud cover can cause appreciable change in power output. The fluctuations of interest are on the order of magnitude of [W/second], while the sun causes a much slower maximum rate of change, somewhere on the order of [W/10 min] in mid-morning and late-afternoon, and even slower during the mid-day time period. If a time window is chosen appropriately such that the power differences associated with the sun's movement are eliminated but the rapid fluctuations are left intact, this is a strong assumption. Further research may be performed in the future to determine optimal window lengths, depending upon time of year and other variables.

Now that the window length has been appropriately chosen, one can perform a moving average.

$$Y(n) = \frac{1}{N+1} \sum_{n=-\frac{N}{2}}^{\frac{N}{2}} X(n) \tag{12}$$

where N = window length in samples, X(n) = PV power signal, and Y(n) = moving averaged PV power signal. Note that the above moving-average calculation is a modified version of Proakis and Manolakis (2006) in that it is centered about 'm.' This is typically referred to as a central moving average. Therefore, the process is a noncausal filter and can only be realized as a post-processing utility. (i.e., real-time application is impossible because the 'current' output relies on future inputs).

The resulting moving average calculation vs. its original signal is shown in Figure 13.

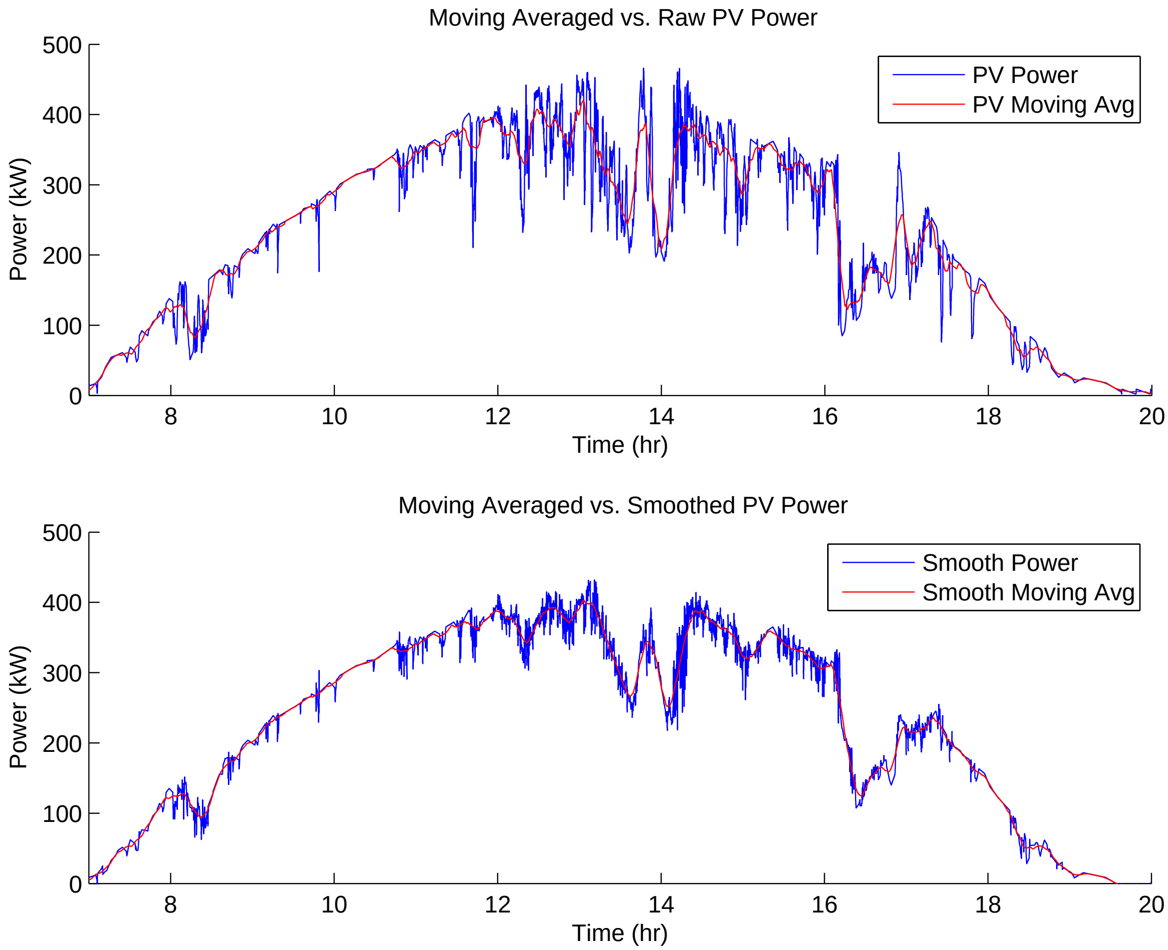

Figure 13: Moving average versus original signal

By subtracting Y(n) from X(n), as in Equation 13:

$$\hat{R}(n) = X(n) – Y(n) \tag{13}$$

where $\hat{R}(n)$ = residue of X(n), X(n) = PV power signal, and Y(n) = moving averaged PV power signal. The resulting signal contains the PV system's high-frequency fluctuations $\hat{R}(n)$ (residues), without the low-frequency movement caused by the diurnal sun trend. $\hat{R}(n)$ comprises the fluctuations of interest because their mitigation is the goal of the ESS.

A first- and second-order statistic-based comparison of the unsmoothed vs. smoothed residues results in the mathematical representation of how well the ESS performs power smoothing; hence the first metric.

$$E[R(n)] = \frac{1}{N}\sum_{n=0}^{N-1} R(n) \tag{14}$$

The temporal or 'sample' mean, described in Equation 14, is used to verify the central moving average's effectiveness in removing the mean from the data. The temporal average is shown to be a minimum variance unbiased estimator in the literature. Intuitively, the expected value of the

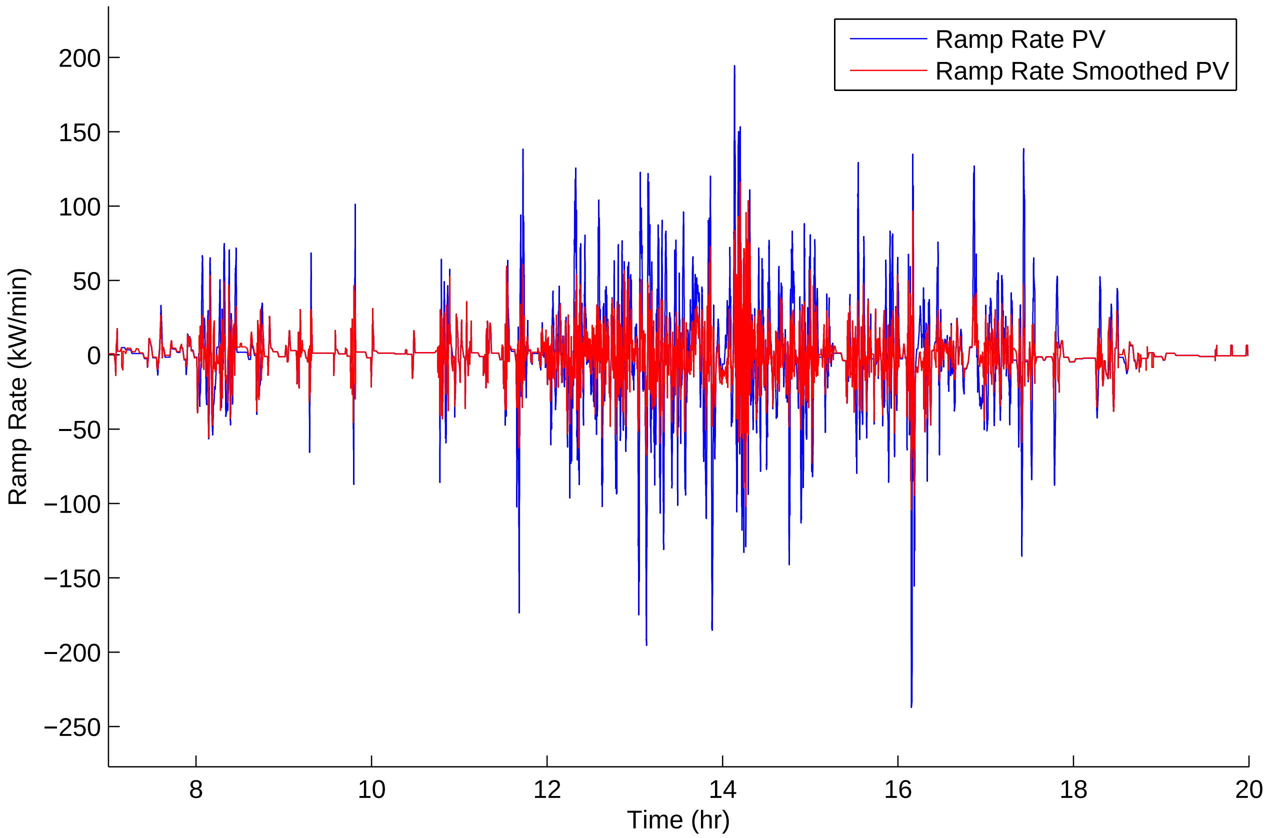

Figure 14: Residue R(n)

residue function R[n] should be approximately equal to 0. If it isn't, a modification to the window length of the central moving average function is necessary to ensure proper mean removal from the data.

Note that the residue function $\hat{R}(n)$ will have a varying statistical distribution based upon the profile of solar irradiance that the PV array is subject to on any given day. However, because the data has been made approximately WSS, it is of interest to attempt to describe the resulting random process as a known random variable distribution. Of course, the first logical assumption is that the resulting distribution is of a Gaussian type with its standard deviation describing the day's cloud cover and a zero mean. This can be visualized by thinking of the width of the Gaussian curve to be much wider on days that experience large, rapid fluctuations, and very narrow on a clear, near-cloudless day.

A statistical distribution comparison can be performed between the calculated cumulative density function (CDF) of $\hat{R}(n)$ and the CDF of a Monte-Carlo simulation of a known distribution with the same mean and standard deviation as $\hat{R}(n)$ to approximate $\hat{R}(n)$'s distribution type. A standard method of comparing the two distributions is described in the Kolmogorov-Smirnov (KS) test, given in Equation 15.

$$D_n = \sqrt{N} \times \sup_{n \in S}[|F(n) - G(n)|] \tag{15}$$

where N = length of $\hat{R}(n)$, sup = the supremum operator, G(n) = CDF of the Monte-Carlo simulation of the estimated distribution, and F[n] = CDF of $\hat{R}(n)$. The KS statistic D_n itself is quite arbitrary, but when comparing the distribution of R(n) to other known distributions, it allows for a quantitative assessment to be made. The KS test is a classical tool that allows for the comparison of distributions to be made quite easily. However, it should be noted that if a more thorough analysis of the distribution of $\hat{R}(n)$ were desired, various other tests are available that may be more appropriate. The Anderson-Darling or Cramer-von Mises tests can provide more information on the distribution comparisons, but are unnecessary in this case.

To calculate the estimated CDF of the residue function, it is first necessary to approximate its probability mass function (PMF). The PMF is approximated using a histogram approach. This gives a nice data-distribution visual representation, with particular interest shown to the 'tail' ends of the distribution where high-power swings occur. PMF visual inspection should lead to several observations about the data.

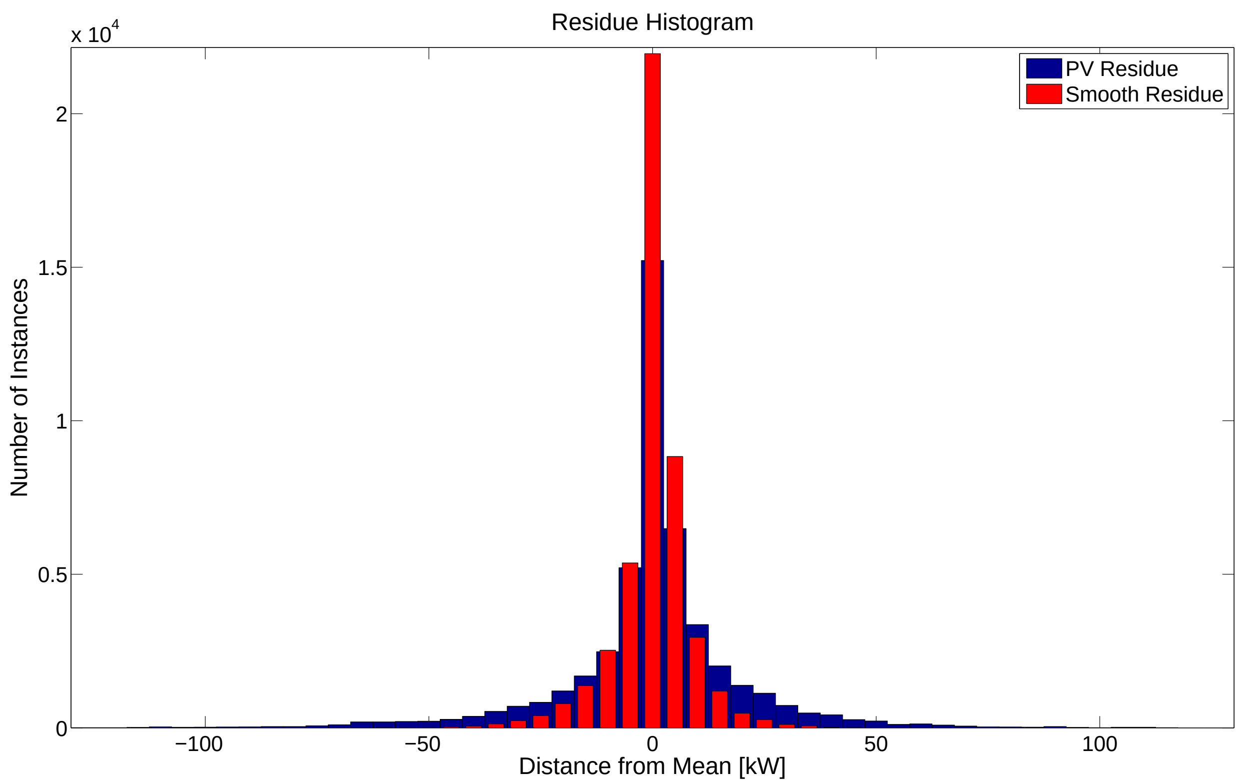

Figure 15: Probability mass function.

First, note the mean. This value is calculated in Equation 14, but a quick inspection of the PMF should provide visual verification that most of the data falls in the zero (or near-zero) bin. The PMF should have no skewness, as the removal of the moving average should result in a data set that is no more likely to have a value higher than the temporal mean than it is to have a value lower.

Also, note that the tail ends of the distributions compare (i.e., are the tails 'pushed' toward the zero-mean in the smoothed PMF compared to the unsmoothed PMF). Because the energy-storage system's desired function is 'smoothing,' the smoothed PMF should not have as high a probability of containing large power deviations as the untreated $\hat{R}$(n) PMF does.

The PDF of $\hat{R}$(n) is then summed cumulatively to produce the CDF. The KS statistic in equation 15 is applied to the CDF against a set of equal-length data simulated by a Monte-Carlo simulation. As stated previously, the logical first assumption is that the data $\hat{R}$(n) is distributed in a Gaussian shape. While this is a good starting point as it is symmetrically distributed, easily visualized, and a likely distribution for such a signal, other distributions appear to fit this data slightly better, according to the KS statistic.

The Laplacian distribution, described in Equation 16 and found in Kay (2013), is a noticeably better fit for $\hat{R}$(n) than a Gaussian distribution (Kay (1998) p.382).

$$p\left(\hat{R}(n)\right) = \frac{1}{\sqrt{2\sigma^2}} \exp\left(-\sqrt{\frac{2}{\sigma^2}}|\hat{R}(n)|\right); -\infty < n < +\infty \tag{16}$$

where σ^2 = variance of the random process. It appears quite similar to a Gaussian distribution, but with a steeper probability concentration at the mean. It is symmetric about the mean, and can be described by its standard deviation much like a Gaussian distribution. More information on the Laplacian distribution and why it fits $\hat{R}$(n) is provided in the Results section.

$$\hat{\sigma} = \sqrt{\frac{1}{N-1}\sum_{n=0}^{N-1}(\hat{R}(n) - E[\hat{R}(n)])^2} \tag{17}$$

where n = 0, 1, ..., N-1; $E[\hat{R}(n)]$ is the expected value of R[n]; and N = length of $\hat{R}(n)$. A proven minimum variance unbiased estimator for the WSS signal's variance is the sample variance estimator given in equation 17. It is important to choose the standard deviation R(n) estimator appropriately as the smoothing metric of choice will directly depend upon this calculation.

The standard-deviation calculation in equation 17 is the most important result of the statistical analysis. This is because the standard deviation represents how much variation or dispersion from the expected value exists in a particular data set. In power-system terms, it represents the amount of power that can be expected to deviate from the projected power output at any given time. Due to this, the standard deviation of both the unsmoothed and smoothed powers is of great importance in quantifying the impact that the ESS device has, as shown in equation 18.

$$\eta = 100 \times \left(1 - \frac{\hat{\sigma}_{smooth}}{\hat{\sigma}_{unsmooth}}\right) \tag{18}$$

where $\hat{\sigma}_{smooth}$ = standard deviation of smoothed PV residue $\hat{R}_{smooth}(n)$, and $\hat{\sigma}_{unsmooth}$ = standard deviation of unsmoothed PV residue $\hat{R}_{unsmooth}(n)$. Ultimately, the metric for quantifying the impact that the ESS device has on smoothing the PV power output is the so-called percent reduction in standard deviation of power (RSDP). This measurement shows the relationship between the smoothness of the raw PV power and its battery smoothed counterpart. It captures the battery's smoothing effects, and makes efficient use of all the data points. These are highly desirable qualities of the estimator function, and they justify its use as the 'smoothness metric.'

As mentioned in the Methods section, using 'ramp-rates' to further quantify the ESS's ability to smooth PV power as an additional metric is important for several reasons. First, it can be used as a general check for consistency with the previous smoothing metric. Because a large PV array's power output can change very rapidly (on the order of killowatts per second), a smoothing system's performance will need to dampen the rate of the power fluctuations appreciably in order to be considered an effective smoothing device. This is acceptable because if the storage system is capable of reducing the magnitude of power fluctuations by a certain amount, it should also cause a similar effect on the rate at which those fluctuations occur. Comparing the two metrics for a system should produce similar results for a given smoothing system.

Second, as alluded to above, rapid ramp-rates can be a nuisance to a power system. They can cause undesirable voltage magnitude changes at the distribution level, 'flicker,' and other unwanted noise on the line. The rapid fluctuations also make PV generation more difficult to predict as a generating asset, and may cause other equipment on the system to try to compensate for rapid generation fluctuations (load tap changers, VAR compensation devices, etc.). In this context, the phrase ramp-rate will be defined as follows:

$$Y(n) = \frac{X(n+k) - X(n)}{K}; n = 0, 1, ..., (N-1) - k \tag{19}$$

where k = sample lag related to time interval of interest, and N = length of $X[n]$. As shown in equation 19, the definition of ramp-rate will follow that of a discrete-time derivative. However, there is a slight modification, in that k can take on a number of values. Note that k is chosen based upon the desired time interval of interest. Choosing k for a particular sampling frequency and desired time interval creates a definition of ramp-rate that varies.

For instance: If $f_s = 1$ Hz (sample rate), and desired time interval is 1 second = t_0, then Y(n) is in terms of W/s. If t_0=1 hr, then Y(n) is in terms of W/hr.

While this may seem quite obvious, it is important to note the units of Y(n). The resulting ramp-rate signal is highly dependent upon the time interval chosen, and its units describe the utility of the particular time interval chosen. For example, we are not interested in the second case above where Y[n] is described in terms of [W/hour]. That calculation is far too slow for the purposes of this metric. We are interested in ramp-rates on the order of [W/min], with the motive discussed previously.

A very useful property of the derivative (in this case, discrete-time derivative) is that it has a de-trending effect on data that is non-stationary in time. In the literature, a stationary series is considered 'integrated of order one [or I(1)]' if the series becomes stationary after a first differencing. The data sets of interest in this discussion are known to be non-stationary in time. However, after applying the ramp-rate calculation above, they have been effectively zero-meaned. This makes the calculation incredibly powerful because the resulting Y(n) from 19 represents the ramp-rates of the power with the bonus of being approximately WSS.

Y(n) from equation 19 can now be treated similarly to R(n) from the previous set of calculations. That is, equations (3), (4), (5), and (6), as well as the distribution characterization, can be applied to Y(n) with the final metric being the so-called percent reduction in RSDR. It should be apparent that the metric put forth as the RSDR is closely related to the previously described RSDP. A close relationship between these two is to be expected when applied to a system, but it is important to note that they describe different parameters.

A third metric termed in Methods as 'max-min reduction' is highly intuitive, but less insightful than the two previously described methods. As was formerly mentioned, power fluctuations on large PV arrays may be on the order of kilowatts/second, and these large power swings can be of concern to a utility with a large PV system tied to it.

$$P_{\text{max swing}} = max|\hat{R}(n)| \tag{20a}$$

$$\eta_{swing} = 100 \times \left(1 - \frac{\hat{R}_{smooth}(m)}{P_{\text{max swing}}}\right) \tag{20b}$$

where m = linear index of $P_{\text{max swing}}$. By looking at the maximum of the above described residue function R(n) of the unsmoothed power data set, we can determine the magnitude of the biggest power swing of that particular day. The time index of that power swing is noted, and the value of smoothed power at that particular time is gathered. The significance of this calculation is to determine how well the maximum power swing of the day is mitigated. A high-performing smoothing ESS will reduce these maximum power swings well.

C AGC Signal Assumptions for Smoothing Battery

An AGC signal from PJM (originally Pennsylvania-Jersey-Maryland, PJM is a Regional Transmission Organization covering all or portions of 13 states and the District of Columbia) was used to examine how the PNM Prosperity smoothing battery system might operate taking such a signal.

The PJM data used represents an AGC signal in four-second intervals over a 24-hour period. This data is normalized to be between –1 and +1, and so it was multiplied by 250 kW to scale the signal up to a magnitude that is reasonable for the 500 kW shifting battery. The resulting power demanded signal is shown in Figure 16.

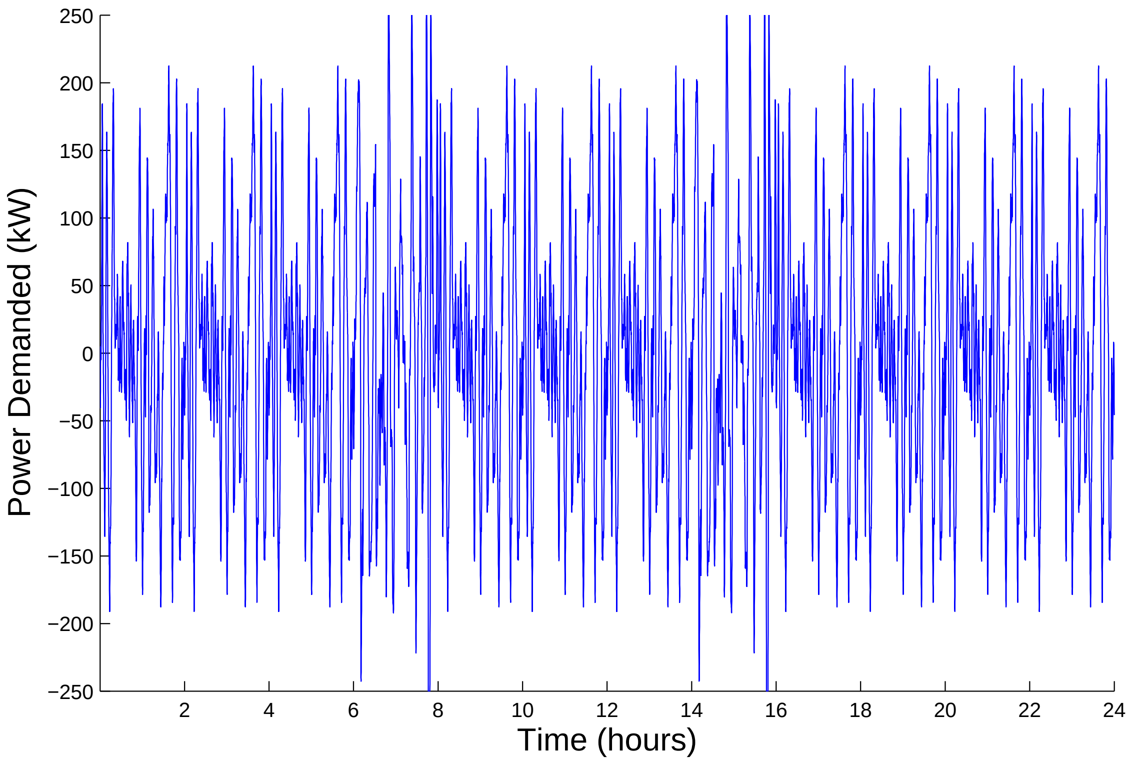

Figure 16: Power demanded (kW) over time by the sample AGC signal from PJM.

The signal in Figure 16 would require the smoothing-battery system to discharge 900 kWh over the 24-hour period. It would also require charging of the same amount. Note that the signal does not take into account losses due to inefficiencies, which would require the battery to charge more than it discharges. In order to prevent the SoC from drifting ever lower, the signal would need to be modified to take round-trip losses into account. Such a modification was not made here.

The SoC resulting from this signal would keep the battery in a tight band, as shown by Figure 17 which illustrates the cumulative energy flows this signal would produce. Even though the commanded power reaches plus or minus 250 kW at times, the cumulative power flows never exceed plus or minus 15 kWh–meaning that the state of charge never changes by more than about 2%.[29] Therefore, following this AGC signal would not require a storage system with the useable storage

[29]For a battery system of 1 MWh total capacity (the capacity of the PNM Prosperity smoothing battery), the change in SoC can be found by 15 kWh/1000 kWh = 1.5%, which here is rounded to 2%.

capacity that the PNM Prosperity smoothing battery has (approximately 350 kWh)–a battery with a much smaller capacity would suffice.

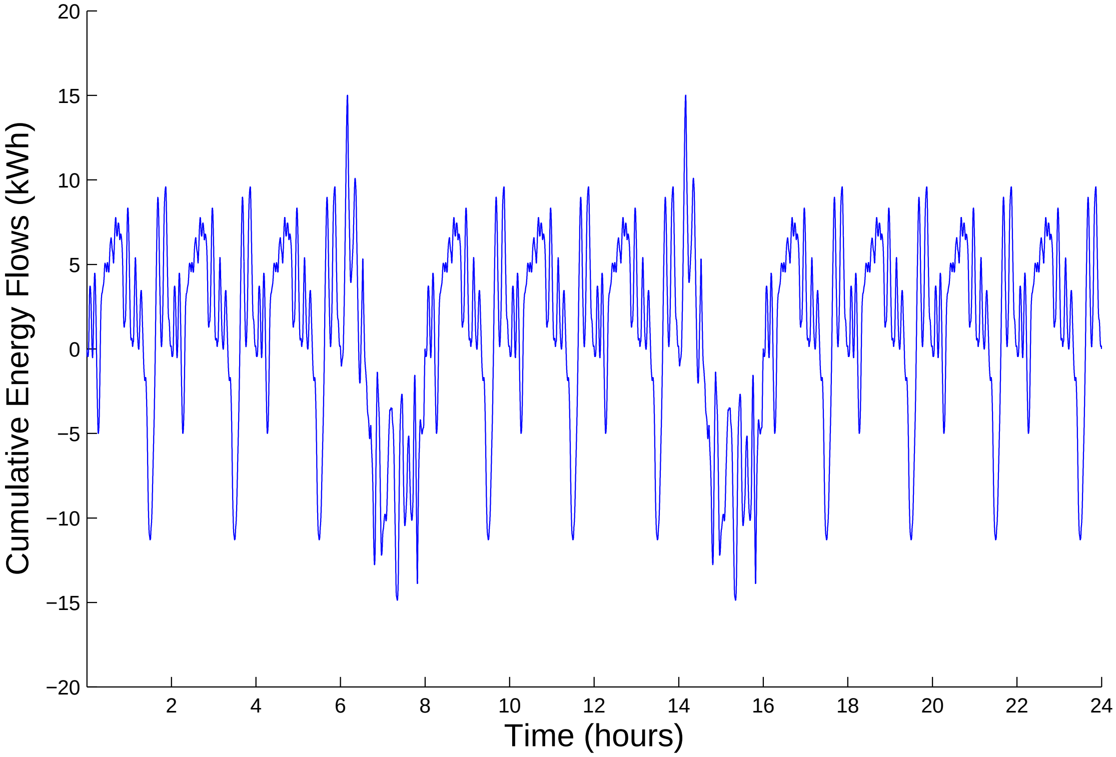

Figure 17: Cumulative Energy Flows (kWh) resulting from the sample AGC signal from PJM

For this sample PJM signal, the maximum up ramp rate of is 13.8 kW/second, and maximum down ramp rate is 30.6 kW/second.

While we realize that PJM's AGC signal differs from day to day, and that PNM's AGC signal is likely to differ from PJM's signal, this analysis is intended to show that following an actual AGC signal is a task that the PNM Prosperity smoothing battery could reasonably be expected to handle.

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