FINAL TECHNOLOGY PERFORMANCE REPORT

Smart Grid Demonstration Project

Public Service Company of New Mexico

PV Plus Battery for Simultaneous Voltage Smoothing and Peak Shifting

WORK PERFORMED UNDER AGREEMENT

DE-OE0000230

Project Type

Energy Storage

SUBMITTED BY

Public Service Co. of New Mexico

PRINCIPAL INVESTIGATOR

Steve Willard, P.E.

Phone: 505 241 2566

Fax: 505 241 2819

E-mail: steve.willard@pnmresources.com

SUBMITTED TO

U.S Department of Energy

NETL

Ron Staubly

Ronald.Staubly@NETL.DOE.GOV

Revision: 1.1

Date: April 8, 2014

1 Executive Summary and Project Description

1.1 Executive Summary

The Public Service Company of New Mexico (PNM) demonstration project installed an ARRA/DOE funded energy storage system in physical conjunction with a 500kW PV resource (not funded by DOE). All the stated goals in the Project Management Plan have been achieved, if not exceeded. The storage system is now able to automatically acquire real time market pricing, status of PNM distribution feeders, tabular weather forecasts and on site storage system and PV data to make sophisticated, automated control decisions on how to best utilize the batteries and benefit the local and regional grid. The system has achieved its 15% reduction of feeder peak load goal and a dispatchable renewable resource has been created.

The system performs shifting and smoothing of PV simultaneously. The shifting function can perform reliability based peak shaving along with arbitrage or renewable firming applications, depending on market and system conditions. Reliability is the top priority of the shifting algorithm and thresholds can be altered to re-prioritize the storage applications.

The smoothing function is adept at limiting PV ramping even in extreme intermittency conditions. A variety of inputs and control modifications have been tested and thorough optimization analysis performed on the smoothing algorithm.

The test results of the applications, run on an individual basis as well as in prioritized combined operation, have been compiled along with optimization, ramp rate effectiveness, system efficiency and system availability analysis. Economic analysis has also been performed utilizing front end, experienced costs in addition to sensitivity analysis targeting break even costs.

Results show that the system costs need to be mitigated for economic effectiveness even when all applications are contributing value in a prioritized mode of operation. The cost benefit ratios calculated for individual and grouped benefits shows a ratio around 0.2. For the level of benefits calculated the capital cost would have to be much lower than $1M (installed equipment originally cost $2.6M). This, however, neglects many benefits that, although apparent in operational results, are difficult to quantify as they are reliability based. If the feeder being treated with storage in this project had true high penetration PV levels (as originally forecast in the proposed project) and associated voltage stability issues, the reliability benefits would have been less of a challenge to quantify. In this case the PV on the feeder was not presenting issues and hence the observed effects of PV smoothing were nominal. Models of other feeders in this situation (outside the scope of this project) do show substantially more benefits when storage is applied.

The results point to the dependency on sophisticated feeder and PV modeling – without these models the shifting algorithm could not have risen to the level of sophistication achieved. Further, even the limited ability to assess smoothing benefits could not have been performed without dynamic feeder models. These models will be key in establishing the prudency of future distributed resource projects.

The most important achievement of this project has been the development of a scalable, sophisticated and reliable distributed renewable resource that can achieve numerous benefits to the utility system. These benefits are important in assisting growing penetrations of intermittent renewable resources. Work will continue with project partners to further the sophistication and expand the functionality of the batteries and back office control system.

Finally, extensive public outreach has been a key feature of this project. Real world project data has been used to educate a broad spectrum of students studying storage and renewable energy, ranging from 6th graders to PhD candidates. A public project website and mobile phone applications have been created to enhance the educational experience and over 20 technical publications have resulted from this effort.

Disclaimer

Table of Contents

Definitions

"AAC" refers to amperes AC.

"AC" refers to alternating current.

"ACE" refers to Area Control Error

"Advanced Carbon Battery" refers to the sealed lead acid battery technology with advanced carbon features being commercialized by EPM and Ecoult

"Applications Controller" refers to the separate controller integrated with BESS Controller which shall interact with PNM's system level algorithms.

"AUX" refers to auxiliary input

"BAT DPU" refers to the digital processing unit for a set of UltraBatteries (used for battery management).

"Battery Meter" refers to the metering point on the AC output of the associated BESS

"Battery System" refers to either the Smoothing Battery System or Shifting Battery System or both if used in the plural.

"BES" refers to battery energy storage.

"BESS" refers to battery energy storage system.

"BESS Controller" refers to the programmable controller supplied by Ecoult for control of the BES System

"BES System" refers to the entire BES system including the Smoothing Battery System, the Shifting Battery System, the PCS and any other components

"BoP" refers to Balance of Plant

"CAB" refers to a container of Advanced Carbon Battery cells mounted in racks complete with battery monitoring hardware, BAT DPUs and DC switchgear.

"CUB" refers to a container of Ultrabattery Battery cells mounted in racks complete with battery monitoring hardware, BAT DPUs and DC switchgear.

"DAQ" refers to Data Acquisition System

"DC" refers to direct current.

"DERMS" refers to Distributed Energy Resource Management System

"Distributed Resource" a utility interactive (grid connected) inverter or converter and its interconnection system equipment connected in parallel to an electric power system to supply power to common loads, which includes electrical energy storage systems.

"DMS" refers to Distribution Management System

"DNP" refers to Distributed Network Protocol

"EPRI" refers to the Electric Power Research Institute

"ESVT" refers to the EPRI's Energy Storage Valuation Tool

"f" refers to frequency

"G1 G2, G3, G4" refer to scaling and error correction gains

"GHG" refers to Greenhouse Gas

"GPS" refers to Global Positioning System

"HVAC" refers to Heating ventilating and Air Conditioning

"HE" refers to Hour Ending

"IEEE " refers to the Institute of Electrical and Electronics Engineers

"Inverter" refers to a bi-directional DC-to-AC and AC-to-DC inverter and its associated controls and power components to connect the PCS to the electrical grid as further described in Section 7.1.

"kV" refers to kiloVolts.

"kVAR" refers to kiloVolts Amperes Reactive.

"**kW**" refers to kiloWatts

"**kW_{base}** **"** refers to baseline kW measurement

"**kW_{shift}** **"** refers to shifted kW measurement

"**kW_{smooth}** **"** refers to smoothed kW measurement

"LCOE" refers to levelized cost of energy

"LPF" refers to low pass filter

"MPPT" -refers to Maximum Power Point Tracking

"NWS" refers to National Weather Service

"NOAA" refers to National Oceanic and Atmospheric Administration

"OSI ACE" refers to OSI Advanced Calculation Engine

"PI" refers to Process Information

"PNM" refers to Public Service New Mexico, the owner of the PNM Project.

"PNM's Distribution Operations" refers to PNM's operation center for power distribution that will control the BES System through a communication link with the BESS Controller.

"PNM Project" refers to the demonstration of BESS in conjunction with a 500kW solar photovoltaic power plant by PNM in the greater Albuquerque area of New Mexico.

"PNM RTU" refers to the PNM supplied RTU

"PNM WSM" refers to PNM Wholesale Marketing Department

"**Primary Meter"** refers to the metering point on the AC output of the high side of the 480/12470 transformer

"PCS" refers to the power conversion system, which is a subsystem of the BES System

"PV" refers to photovoltaic

"PV Meter" refers to the metering point on the AC output of the associated 500kW PV resource

"PCC" refers to the point of common coupling of the BES System with the electric grid, for this PNM Project, the 12.47 kV connection point.

"ROI" refers to Return on Investment

"RSDP" refers to Percent Reduction in Standard Deviation of Power

"**RSDR**" Percent Reduction in Standard Deviation of Ramp-Rate

"RTU" refers to remote terminal unit.

"SCADA" refers to supervisory control and data acquisition.

"Shifting Battery System" refers to a single string of CABs, which is further defined in Section 3.1.

"Smoothing Battery System" refers to a single string of CUBs, which further defined in Section 3.1.

"SNL" refers to Sandia National Laboratory

"SoC" refers to State of Charge

"SoCREF" refers to Reference State of Charge

"**UltraBattery"** (trademarked) refers to the sealed lead acid battery technology with ultra-capacitor features being commercialized by Ecoult (traded under the mark UltraBattery^{TM})

"T1" refers to PV Low Pass Filter Time Constant

"T2" refers to AUX1 (load) Low Pass Filter Time Constant

"T3" refers to AUX2 (ACE) Low Pass Filter Time Constant

" TW" refers to PV moving average Time Window

"UPS" refers to an uninterruptable power supply.

"VAC" refers to Volts alternating current**.**

"VDC" refers to Volts direct current**.**

"Whr" refers to Watt-hour

"WSM" refers to the Wholesale Marketing Group at PNM

1.2 Overview of the Energy Storage Project

The Public Service Company of New Mexico (PNM) demonstration project installed an energy storage system composed of two elements: a 0.5MW Smoothing Battery utilizing Ultra Batteries and a 0.25MW/0.99MWhr Peak Shifting Battery utilizing Advanced Lead Acid Batteries, both manufactured by Ecoult/East Penn Manufacturing. These two systems combined with a single 0.75MW Power Conditioning System, are co-located with a separately installed 500kW solar PV plant, at a utility-owned site, to create a firm, dispatchable, renewable generation resource. [1] This hybrid resource provides simultaneous voltage smoothing and peak shifting through advanced control algorithms, and is capable of easily switching between end-of-feeder and beginning-of-feeder configurations to demonstrate simultaneous smoothing and shifting encompassing a range of applications.

1.3 List of Recipient, Sub-Recipients and Respective Roles

Recipient	***Responsibilities/Role***
Public Service Co. of New Mexico	Project lead, algorithm development, source of signal to BESS
Ecoult/East Penn Manufacturing	Install and support battery system
University of New Mexico	Modeling, algorithm development
Northern New Mexico College	Package data- separated for the individual steps depicted in the methodology
Sandia National Laboratories	Consult on control algorithms

1.4 Objectives

- Demonstrate PV-plus-battery to mitigate voltage-level fluctuations and enable peak shifting
- Quantify and refine performance requirements operating practices, and cost and benefit levels associated with PV-plus-battery as a firm dispatchable resource
- Achieve 15 percent or greater peak-load reduction on distribution feeder using PV plus battery.
- Generate, collect, analyze and share data to advance grid efficiency, optimize supply and demand, and increase reliability

[1] PNM also installed an adjoining 500kW PV installation which was not funded through the DOE ARRA program

- Validate and support the nationwide effort to develop the next-generation utility system and further the integration technologies and standards for renewables and energy efficiency
- Enable distributed solutions that reduce GHG emissions through the expanded use of renewables.

1.5 Description of Energy Storage Technologies and Systems

The project is a genesis of underlying efforts that began in 2008 under the EPRI Smart Grid Demonstration Program. In this EPRI collaboration extensive use case analyses were developed to describe broad and underlying communication/control architectures for a Smart Grid that incorporates high penetration solar PV. The Prosperity Energy Storage Project was then proposed under the ARRA DOE Smart Grid Storage Demonstration Solicitation in 2009 and was the first ARRA-funded storage demonstration to go online. Major contracts with the DOE, vendors and university partners were finalized in the fall of 2010 and construction began in May 2011, after site permitting was completed. The project was commissioned and operational on September 19, 2011. Tests were completed in February 2014. The system one Line diagram is presented in Figure 1 below.

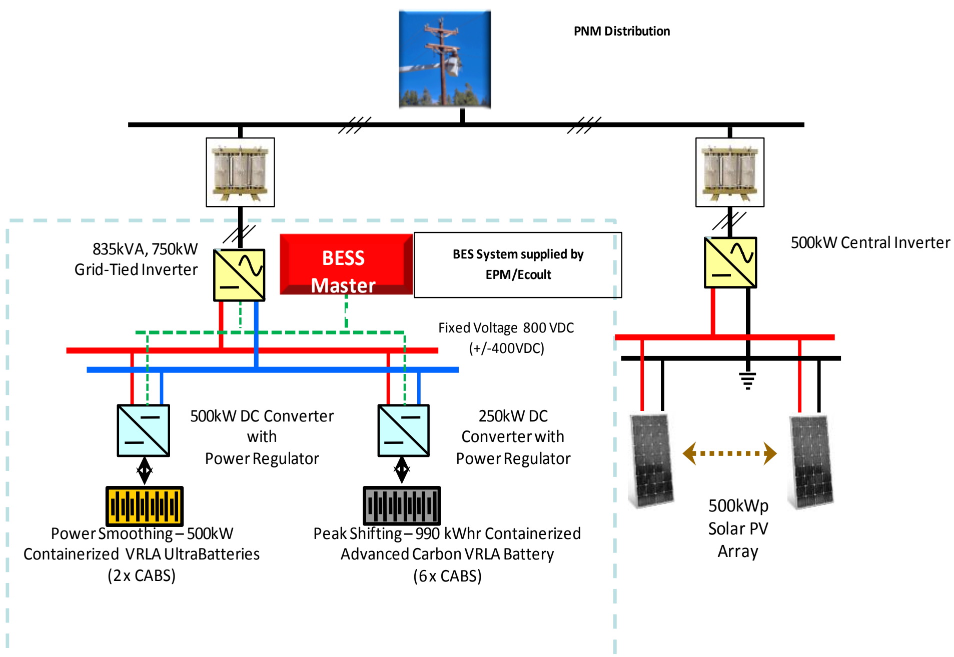


Figure 1 - System One Line Diagram

1.6 Key Project Milestones and Impact Metrics:

Phase	*Milestone*	*Target Completion Date*	*Actual Completion date*
I – Design & Engineer Solution	Negotiate and finalize SGDP Award Revise PMP	30-October-10 30-November-10	30-October-10 30-November-10
II - Establish & Develop Control Strategy	Battery Manufactured Models created, calibrated with algorithms prioritized	20-May-11	7/30/2011 2/1/2012
III – Construct & Commission Demonstration	System Installed and Commissioned	16-August-11	11/1/2011
IV - Demonstrate Evaluate and Report	Successful Completion	24-February 14	02/27/2014

Table 1 Project Milestones

1.7 Applicable Energy Storage Applications and Smart Grid Functions

The following applications were reviewed and deemed applicable to this project:

- Electric Energy Time Shift -Enabled through peak shaving and firming utilizing different source signals into the shifting algorithm
- Area Regulation - Enabled through application of Area Control Error signal into the battery smoothing algorithm – this is a next stage application and beyond the scope of the test plans
- Voltage Support - Enabled through peaks shaving efforts where substation voltage signals are incorporated into the shifting algorithm
- T&D Upgrade Deferral - Enabled through peak shaving and incorporation of a distributed resource to relieve substation service requirements
- Renewable Energy Time Shift - Enabled through peak shaving and firming of the PV energy to align PV production to utility system peaks
- Renewables Capacity Firming - Enabled through firming of the PV energy to align PV production to utility system peaks
- Arbitrage – Enabled through monitoring CAISO real time pricing and using established thresholds for high and low pricing

1.8 Grid or Non-Grid Connected Impacts and Benefits

The main benefits from the demonstration include deferred peaking generation capacity investments and deferred distribution capacity investments. Benefits are derived through the avoided costs of peaking plant investment, substation or feeder expansion due to peak shaving and avoided cost of capacitor banks and voltage regulators by smoothing PV ramp rates and minimizing voltage fluctuations. Creation of a reliable, dispatchable renewable resource also reduces electricity line losses, pollutant emissions as well as fossil based peak shaving fuel.

Optimized Generator Operation

These benefits are enabled by the shifting function of the demonstration. Specifically, various algorithms have been designed, tested through computer modeling and implemented via the test plans to determine the best mode of creating a firm, peaking, renewable energy resource.

Deferred Generation Capacity Investments

These benefits are attributed to the ability of the system, as a firm peaking resource, to avoid fossil based peaking resource additions. By establishing a firm resource from PV a much higher capacity factor can be allowed these systems in resource planning. Benefit will be measured by success of targeting an increase in allowable peak contribution of PV (from 55% current to 90% - typical of a gas peaking unit).

Deferred Distribution Capacity Investments

These benefits are enabled by the smoothing function of the demonstration. The smoothing function alleviates voltage swings and avoids extra distribution system protection in the face of high penetration PV. The cost of avoided protection for an unsmoothed system will be stacked with other benefits.

Reduced Carbon Dioxide Emissions

Reduced losses and substitution of fossil fuel based generation with PV will reduce carbon dioxide emissions. Establishing the amount of such reductions requires: 1) tracing the load profile of the load change attributed to the project back to ascertain how the generation dispatch was affected, 2) determining which generation units had their output reduced (and which had their output increased, if appropriate), and 3) associating with each affected generation unit a CO2/kWh emission rate. EPA's AVERT program will be utilized for this effort.

Reduced SOX, NOX, and PM-2.5 Emissions

Establishing these emissions effects involves tracing the load profile to the generation origin method, as is required for CO2 impact, but in this case the effected generation output is associated with an SOX, NOX, and PM-2.5 Emissions rate. CO2,SOX and NOX reductions were estimated in the AVERT program.

1.9 Synopsis of Steps Taken to Achieve Interoperability and Cyber Security

PNM has developed and successfully submitted a comprehensive Cyber-Security plan to DOE relating specifically to this project. The plan has identified and documented distinct steps to identify, isolate and mitigate all security risks associated with its Smart Grid program, both for the near-term energy storage applications for grid support deployment and for longer-term smart grid investment decisions. PNM has completed and documented phases 1 through 9 (Operations and Maintenance). The results from these nine phases consist of 183 documented controls. Phase 10 is pending as the operation of the system is slated to continue. Management of these controls is used to meet the systems security requirements also covered in PNMs Information Security Manual (ISM). Controls are rated and documented with a status of “inherited” or “in Place”, described by the PNM Cyber Security Plan.

- Phase 1 - Initiation
- Phase 2 - Concept
- Phase 3 - Planning
- Phase 4 - Requirements Analysis
- Phase 5 - Design
- Phase 6 – Development
- Phase 7 – Security Test
- Phase 8 - Implementation
- Phase 9 - Operations And Maintenance
- Phase 10 - Disposition Phase

1.10 Synopsis of Interactions with Project Stakeholders

The following Table 2 and ensuing compendium outline outreach activities and project related publications that have been externally disseminated.

1.8.1 Project Related Presentations

Title	Description	Expected (or Actual) Completion Date	Intended Audience	Benefit to Audience
TPR	Technical Progress Report	07/12	DOE	Update on project results, issue and resolution ID, lessons learned and next steps
Smart Grid Update	Update to NM Public Regulation Commission	4/16/2012	NMPRC	Update on PNM SSG activities with focus on DOE Storage Project
PNM PV + Storage Update	Update with project results to EPRI PDU (storage and renewable integration advisory councils)	2/13/2012	EPRI staff and members	Present key findings, issue and lessons learned on project
Maximizing the Benefits of Energy Storage Combined with Utility Scale PV	Update with project results to ESA – to be published in proceedings	5/2/2012	ESA	Present key findings, issue and lessons learned on project
Applying UltraBattery® Technology to Deliver MW Scale Energy Storage Solutions for Smoothing and Shifting of Solar Power	Description of Battery Technology and with project results to Intersolar Europe Conference – abstract available	6/13/2012	InterSolar Europe	Display abilities of battery technology deployed against PV
Mitigating Renewable Energy Intermittency with Energy Storage	Highlight drivers for storage in the face of renewable energy growth	3/27/2012	NM Tech	Educate on utility system operations and how storage can allow increased renewables, describe DOE project and present results
Renewable Energy and the Need for Energy Storage	Highlight drivers for storage in the face of renewable energy growth - describe DOE project i	12/20/2011	NM Assoc. of Energy Engineers	Educate on utility system operations and how storage can allow increased renewables, describe DOE project and present results
Renewable Energy and the Need for Energy	Highlight drivers for storage in the face of renewable energy growth - describe DOE project i	2/24/2012	NM Society of Prof. Engineers	Educate on utility system operations and how storage

Storage				can allow increased renewables, describe DOE project and present results
Public Service Co. of New Mexico (PNM) - PV Plus Storage for Simultaneous Voltage Smoothing and Peak Shifting	Update with project status to DOE	10/20/2012	EESAT – DOE Peer Review	Peer Review on project status
Modeling of PV plus storage for peak shifting and simultaneous smoothing at Mesa del Sol	Description of modeled system, modeling techniques and results to date	10/18/2012	EESAT	Expose how storage can be modeled on a utility system, describe approach used and present results
Integrating Utility Based PV and Storage on a Smart Grid Foundation	Describe foundational/architecture based on EPRI Inteliigrid™ used to platform the data acquisition and control system in a Smart Grid Environment	4/17/2012	SEPA Utility Only Conference	Expose the level of sophistication needed to properly site and run a distributed asset in a cyber secure utility environment
PV Smoothing and Shifting Utilizing Storage Batteries	Update with project status to EPRI SG Demo	04/02/2012	EPRI Smart Grid Demonstration Advisor Mtg	Share lessons learned and align to overall SG efforts with EPRI
Maximizing the Benefits of PV with Energy Storage	Update with project status to Storage Week Conference	06/25/2012	Storage Week	Expose how storage can be modeled on a utility system, describe approach used and present results
Integrating Renewable Energy with Battery Storage	Demonstrate how PNM is facing challenge of intermittency associated with increased renewables	03/22/2012 02/23/2012	IEE Power the People Conf NM Green Grid Initiative	Explain how storage can help mitigate effects of renewable intermittency
Public Service Co. of New Mexico (PNM) - PV Plus Storage for Simultaneous Voltage Smoothing and Peak Shifting	Demonstrate how PNM is facing challenge of intermittency associated with increased renewables	10/17/2012	California Energy Commission Staff	Explain how storage can help mitigate effects of renewable intermittency
PNM's Prosperity Energy Storage Project Optimizing the Benefits of PV with a Battery Storage System	Explain how benefits are being assessed and system operations are optimized	8/30/2013	CESA ESTAP	Understand that storage can achieve numerous benefits

Implementing PV Smoothing and Shifting Simultaneously September 2013 Update	Update on project results	08/30/2013	ESNA	Understand performance of technology
Simultaneous Smoothing and Shifting of PV – A Successful Integration of Storage and Renewables	Update on project results	11/15/2012	Energy Storage Virtual Summit	Understand performance of technology, results of tests
Optimization of PV Smoothing and Shifting with Battery Storage	Explain how benefits are being assessed and system operations are optimized	05/18/2013	ESA	Understand that storage can achieve numerous benefits
Enhancing PV with Energy Storage - Implementing PV Smoothing and Shifting Simultaneously	Explain how benefits are being assessed and system operations are optimized	02/14/2013	Solar Powergen 2013	Understand that storage can achieve numerous benefits
Coordination of Utility Scale PV with storage and building micro grid	Display results of coordination test with NEDO micro gird at Mesa del Sol	10/07/2013	EPRI Smart Grid Advisory Panel	Display results of 2 fielded distributed assets operating in coordinated fashion
PNM's Prosperity Energy Storage Project	Update on project results	10/24/2013	DOE Peer Review	Understand performance of technology, results of tests

Table 2 - PNM Prosperity Energy Storage Project DOE-OE-0000230 Outreach Activity Summary - up to Dec. 2013

1.11 Project Related Technical Papers

IEEE Published Papers

"PNM smart grid demonstration project from modeling to demonstration." Abdollahy, S.; Lavrova, O.; Mammoli, A.; Willard, S.; Arellano, B. Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES. Digital Object Identifier: 10.1109/ISGT.2012.6175594. Publication Year: 2012, Page(s): 1 – 6.

"Distributed control strategies for high-penetration commercial-building-scale thermal storage." Mammoli, A.; Jones, C.B.; Barsun, H.; Dreisigmeyer, D.; Goddard, G.; Lavrova, O. Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES. Digital Object Identifier: 10.1109/TDC.2012.6281608. Publication Year: 2012, Page(s): 1 – 7.

"Applying battery energy storage to enhance the benefits of photovoltaics." Cheng, F.; Willard, S.; Hawkins, J.; Arellano, B.; Lavrova, O.; Mammoli, A. Energytech, 2012 IEEE. Digital Object Identifier: 10.1109/EnergyTech.2012.6304684. Publication Year: 2012, Page(s): 1 – 5.

"Analysis of battery storage utilization for load shifting and peak smoothing on a distribution feeder in New Mexico." Lavrova, O.; Cheng, F.; Abdollahy, S.; Barsun, H.; Mammoli, A.; Dreisigmayer, D.; Willard, S.; Arellano, B.; van Zeyl, C. Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES. Digital Object Identifier: 10.1109/ISGT.2012.6175723. Publication Year: 2012, Page(s): 1 – 6.

"PV output smoothing with energy storage." Ellis, A.; Schoenwald, D.; Hawkins, J.; Willard, S.; Arellano, B. Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE. Digital Object Identifier: 10.1109/PVSC.2012.6317885 Publication Year: 2012, Page(s): 001523 – 001528.

"Distributed compensation of a large intermittent energy resource in a distribution feeder." Abdollahy, S.; Mammoli, A.; Cheng, F.; Ellis, A.; Johnson, J. Innovative Smart Grid Technologies (ISGT), 2013 IEEE PES. Digital Object Identifier: 10.1109/ISGT.2013.6497911. Publication Year: 2013, Page(s): 1 – 6.

IEEE Papers Pending Publication

"Real-Time Control of Utility-Scale Storage on a Distribution Feeder with High PV Penetration." Cheng, F.; Willard, S.; Hawkins, J.; Arellano, B.; Lavrova, O.; Mammoli, A. Energytech, 2013 IEEE. Publication Year: 2013, Page(s): 1 – 5.

"Low-cost solar micro-forecasts for PV smoothing." Mammoli, A., Menicucci, A.; Caudell, T.; Ellis, A.; Willard, S.; Simmins, J. 2013 IEEE Conference on Technologies for Sustainability (Sustech).

"Integrating heterogeneous distributed energy resources to manage intermittent power at low cost." Abdollahy, S.; Heine, N, Poroseva, S.; Lavrova, O.; Mammoli, A. 2013 IEEE Conference on Technologies for Sustainability (Sustech)

"Maximizing the benefits of PV utility scale storage at PNM prosperity project." Cheng, F.; Greenwood, W.; Arellano, B.; Hawkins, J.; Lavrova, O.; Mammoli, A.; Willard, S. Energytech, 2013 IEEE. Publication Year: 2013, Page(s): 1 – 5.

"PV Output Smoothing using a Battery and Natural Gas Engine-Generator." Johnson, J.; Ellis, A.; Denda, A.; Morino, K.; Shinji, T.; Ogata, T.; Tadokoro, M. 39th IEEE Photovoltaic Specialists Conference, Tampa Bay, Florida, 16-21 Jun, 2013.

Other Source Papers

"Modeling of PV plus storage for Public Service Co. of New Mexico's Prosperity energy storage project." Lavrova, O.; Cheng, F.; Nelson, T.; Abdollahy, S.; Mammoli, A.; Electrical Energy Storage Applications and Technologies Annual meeting, San Diego, CA, October 17-19, 2011.

"Interplay between energy-market dynamics and physical stability of a smart power grid." Picozzi, S.; Mammoli, A.; Sorrentino, F. Bulletin of the American Physical Society 58. Publication Year: 2013.

"Smoothing and shifting PV – Applying energy storage to enhance the benefits of renewable energy." Willard, S.; Lavrova, O.; Arellano, B.; Hawkins, J.; Mammoli, A.; McKeon, B. 2012 World Renewable Energy Forum; ASES 2012.

"Day-ahead cumulative solar irradiance prediction method using percent cloud cover forecasts." Greenwood, W.; Mammoli, A.; Lavrova, O.; Cheng, F.; Willard, S.; Arellano, B. SOLAR 2013; ASES 2013 - Proceedings pending release.

"Optimization of solar PV smoothing algorithms for reduced stress on a utility-scale battery energy storage system." Greenwood, W.; Mammoli, A.; Lavrova, O.; Willard, S.; Arellano, B.; Johnson, J. EESAT 2013.

"Model Predictive Control Application in PV and Storage System." Cheng, F. EESAT 2013.

"Microgrids and clusters of microgrids: Integrating heterogeneous energy resources within a power distribution feeder." Mammoli, A.; Hayat, M.; Heine, N.; Yasaei, Y.; Ghanbari, L. Poster presentation at DOE Santiago 2013 Symposium on Microgrids.

Project related website and media sources

- PNM Project web site: primary public outreach vehicle for the project. It contains access to real-time data, resources and project-specific publications: www.pnm.com/solarstorage
- Annotated results: See accompanying PNM Prosperity Graphed Results.pdf.
- Project-Related Short Videos:
  - http://www.youtube.com/watch?v=lqes0KyNFxs&feature=youtu.be
  - http://www.youtube.com/watch?v=mtkyetyCfSg
- Project Fact Sheet: see accompanying Prosperity Energy Storage Fact Sheet.pdf
- EPRI Smart Grid Demo Demonstration Project: PNM's specific efforts are tracked along with other host-utility efforts.
  - Five-year update: http://www.smartgrid.epri.com/doc/epri-smart-grid-advisory-update-2012_02_09.pdf
  - Three-year update: http://www.smartgrid.gov/sites/default/files/doc/files/EPRI_Smart_Grid_Demonstration_Initiative_Three_Year_Update_201110.pdf
- Project reports to DOE (Project Description and Technology Performance Report), required under the DOE Smart Grid Storage Project: extensive reporting on methodology and interim results. http://www.smartgrid.gov/recovery_act/program_impacts/energy_storage technology_performance_reports
- Northern New Mexico College
  - Android app developed for access to the Project website – available on Google Play: http://tinyurl.com/solarpower-nnmc
  - Public kiosk in the college lobby – interactive, instructional based and internet accessible: http://205.166.231.215:8080/SmartPNM/
- Battery partner Ecoult:
  - Main site http://www.ecoult.com/
  - Prosperity-specific site http://www.ecoult.com/case-studies/pnm-nm-usa-solar-smoothing-and-shifting/
- DOE/EPRI Energy Storage Handbook, featuring the Prosperity Project and a variety of input from PNM: http://www.sandia.gov/ess/publications/SAND2013-5131.pdf

2 Description of Energy Storage Technologies and Systems

2.1 Location of the Storage System and Demonstration Activities

The project is located south of Albuquerque New Mexico in PNM's service territory on PNM owned land. It is adjacent to Mesa del Sol, Albuquerque International Airport and Sandia National Labs.

Figure 2 - PNM Project Site Map

2.2 System Description

The key components of the project feature:

- 500kW PV installation with 2,158 Schott 230 solar panels (not funded by DOE)
- SMA 500kW PV Inverter (not funded by DOE)
- Ecoult/ East Penn Manufacturing Energy Storage Solution:
  - 6 Battery Containers each containing 160 Advanced Lead Acid batteries – with an energy shifting functionality. Energy rating is 1 MWh.

        - Each container weighing approx. 49,700 lbs.
        - Stored energy is being dispatched as "firm" energy when energy demand increases, offsetting the peaking requirements of a natural gas during times of customer peak usage. This allows PNM to use renewable energy when it's most needed.
    - 2 Battery Containers each containing 160 UltraBatteries™– with an power smoothing functionality -
        - Each container weighing approx. 49,700 lbs.
        - Power Rating is 500kW
        - The UltraBattery Storage provides the ability to "smooth" the output of the solar facility. For example, when a cloud casts a shadow on the solar panels, the advanced battery system and smart grid technology immediately dispatches energy to fill the gap created by the cloud
- The PCS is be composed of:
    - 1 x 0.75 MW bi-directional Grid-Tied Inverter (designed for a 1MW rating);
    - 1 x 0.5MW bi-directional DC Converter for the Smoothing Battery System;
    - 1 x 0.25MW bi-directional DC Converter for the Shifting Battery System;
    - A main AC breaker for protection and provision of DC contactor functionality;
    - A DC capacitor pre-charge circuit;
    - An AC filter for the inverter output and DC filters per battery input with an option for AC EMI filters;
    - Inverter controls and protection by a digital processing unit (INV DPU) for the Inverter and each controllable set of DC Converters, and
    - 480 VAC power circuit.
- Ecoult Battery Management and Monitoring System
- Battery Power Conditioning System
- Data Acquisition and Control System collecting 220 points at minimum every second including
    - Solar field metrology
    - Solar field string monitoring
    - Battery system monitoring and control
    - PCS system monitoring and control
    - PMUs for both the site feeder and battery system with data capture ability at 30 samples per second
    - Separate, 1 second interval utility grade metering on the PV, Battery and overall site

  - Secure gateway managing point collection and protocol translation (MODBUS – DNP3)
  - Secure 2 way communication to PNM's Distribution Operations
  - Secure fiber connection to PNM's Data Center
  - Secure partner access to fielded equipment
  - Back Office OSIsoft® PI database with real time access through a Sharepoint portal
  - PI to PI functionality to share data with Project Partners
- Automated distribution system switching allowing the site to change configuration from "end of feeder" to "beginning of feeder" in terms of location of the distributed resource to allow evaluation of impact of energy storage at different locations on a grid

The system is laid out in a grid/isle fashion to minimize overall footprint and allow for efficient and safe access for maintenance and operation activities. Figure 3 details the overall plot plan including a 500kW Solar PV Plant (Not funded by DOE) installed concurrently with the DOE project. Figure 4 details the layout and dimensions of the battery system

Project Costs

Battery equipment and software	$ 2,212,330.63
Data acquisition/Site development	$ 362,612.20
Line extension	$ 80,104.43
Total	$ 2,655,047.26

O & M costs were not forecast or budgeted for the project but do appear through default inputs in the economic analysis in Section 5.

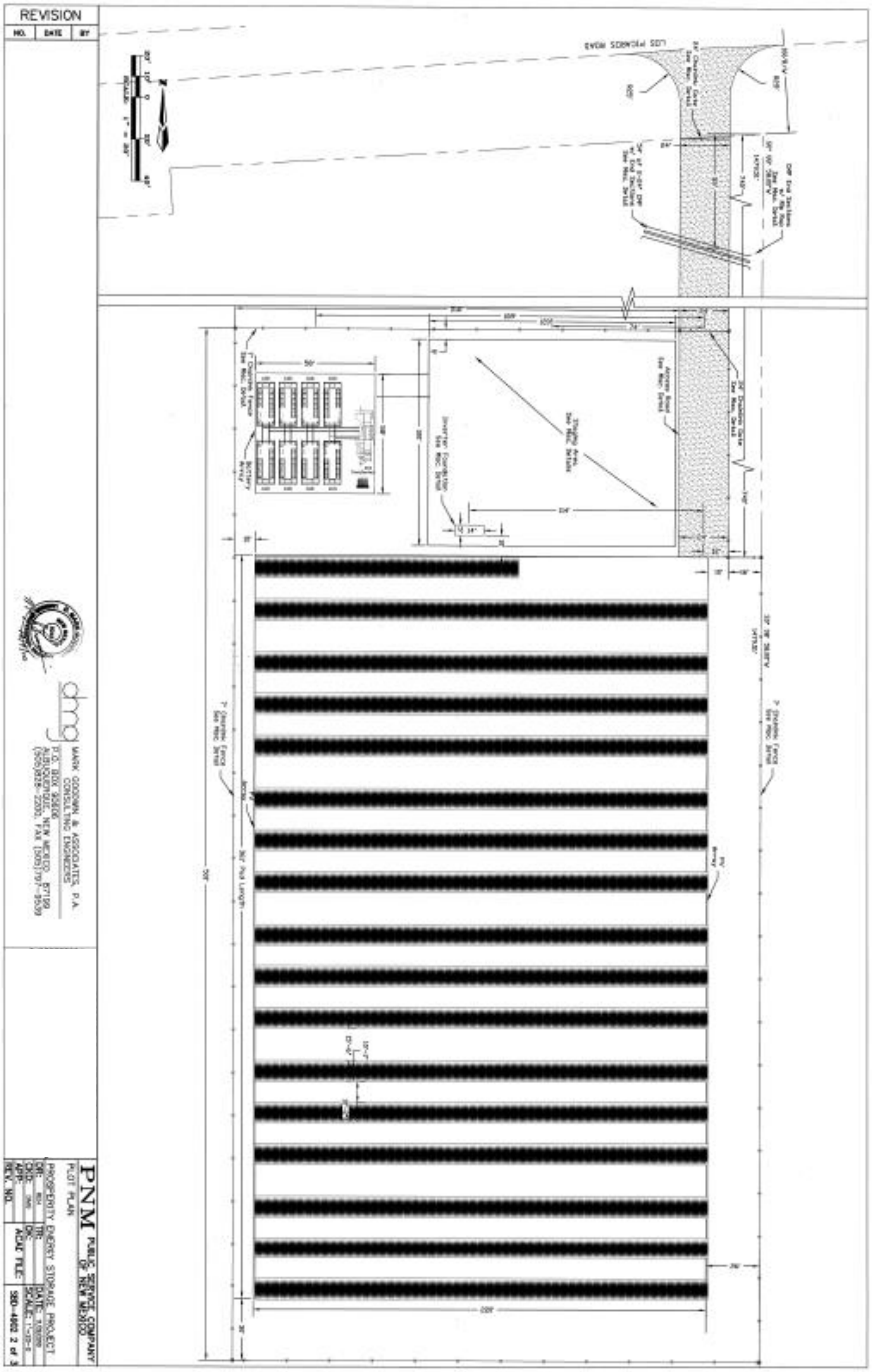


Figure 3 - PNM Prosperity Energy Storage Project Plot Plan

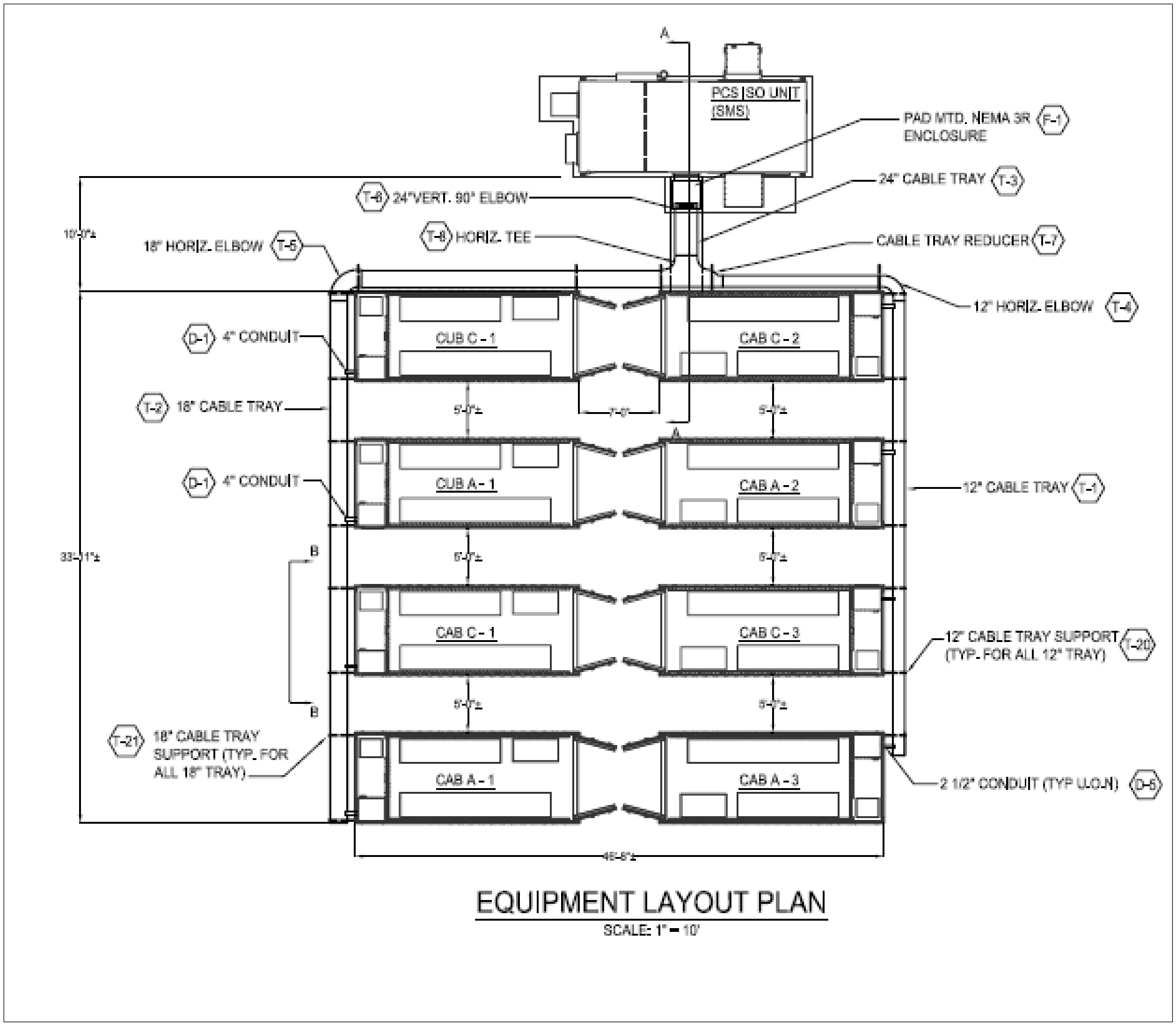


Figure 4 - Battery Layout Plan

The system one line diagram is provided in Figure 5 below. The electrical configuration of the system includes two inverters with one serving the PV system and the other engrained in the battery PCS. Both inverters feed the secondary side of a single dual core 12.47kV/480V transformer. Preference would be for one inverter with a common DC bus serving the PV and Battery system but grounding issues precluded this feature. The Battery System One Line Diagram is shown in Figure 6, below, which details the mater/slave relationship between the PCS and the BESS, which shows the master/slave relationship to the BESS.

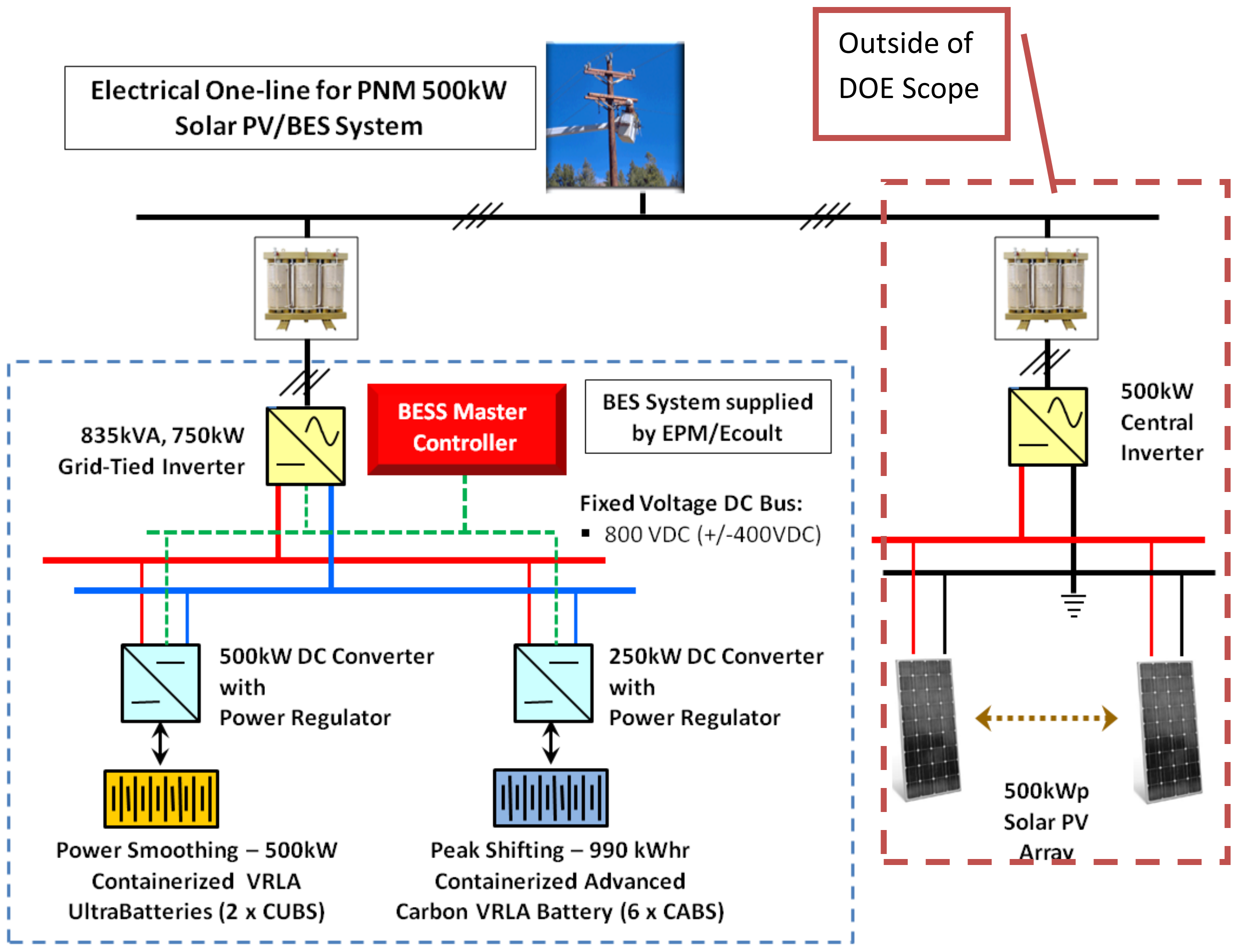


Figure 5 - System One Line Diagram

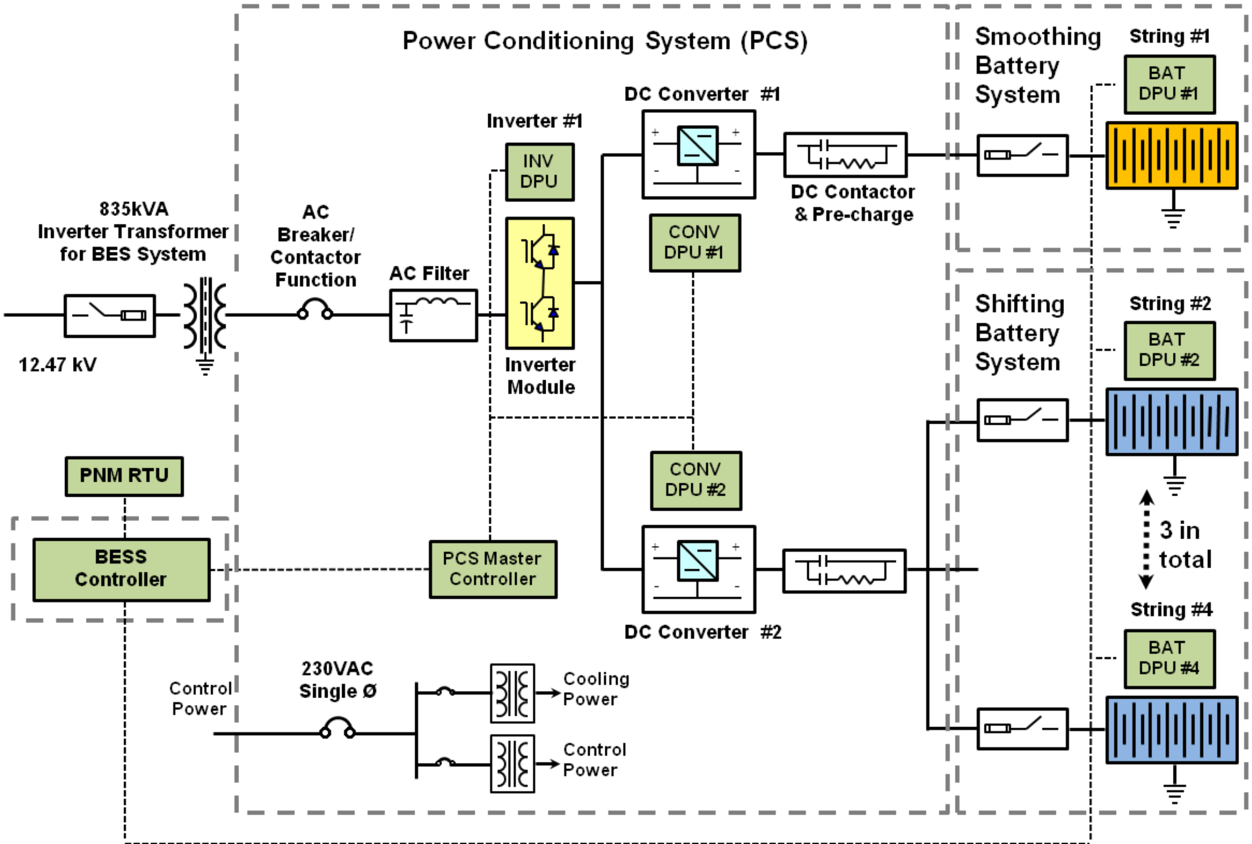


Figure 6 - Battery System One Line Diagram

Figure 7 below shows an aerial view of the plant (looking south) with the battery placed adjacent to the PV system. Note the large parking/staging site. This was required to accommodate the unloading of the battery containers, containers. For details, refer to the Transportation Considerations section below.

Figure 7 - PNM Prosperity Energy Storage Project - Aerial View

2.3 Data Acquisition System

The Data Acquisition system diagram (see

Figure 8) shows the system architecture and devices. The gateway is made up of a Cooper SMP with two Network Interface Cards (NICs). One NIC takes 220 points from each device and sends to the back office for analysis every second with a time stamp from the GPS. The other NIC takes all points available from each device and reads into the gateway at sub-second intervals or when there is a change in value of the signal of each device. The gateway takes the protocol of each device and translates it into DNP3 protocol for back office analysis IEEE C37.118 for the PMUs. The Gateway has the ability to process other protocols such as IEC61850. There are 12 devices on the master side behind the gateway's firewall. Each is described below along with its corresponding sub system.

2.3.1 Master Devices:

1. Intelliruptor (S&C Pulsecloser). Function: 3 Phase protective Device for utility Distribution Operations control for system protection. Media is over fiber to a Dymac converter to RS-232. Data is sent to Gateway over a DNP3 protocol
2. Single Phase Meter (Veris Industries E50C03) Function: To monitor voltage, power, amps, etc. from the Auxiliary load of the energy storage facility. Media is over an RS 485 and data is sent to the gateway over a MODBUS protocol
3. Carlo Gavazzi String Monitors – Function: 6 monitors for 166 string voltage and currents from solar panels. Media is a RS-485 and data is being sent to the gateway over a MODBUS protocol
4. PMU (SEL 451) – Function: Phasor Measurement unit for secondary metering of the sytem (PV & Battery functions). Media is over Ethernet and data is sent to the gateway 30 samples per second to the gateway over a IEEE C37.118 protocol
5. PMU (SEL 351) – Function: Phasor Measurement unit for the Primary Meter data or total system output. Media is over Ethernet and data is sent to the gateway 30 samples per second to the gateway over a IEEE C37.118 protocol
6. ION Meter 8600 meter (PV Meter) – Function: Recording voltage, Amps, KW, Kwh, etc for the PV system output from the inverter (AC). Media is over Ethernet and data is sent to the gateway in DNP3 protocol.
7. ION Meter 8600 meter (Battery Meter) – Function: Recording voltage, Amps, KW, Kwh, etc for the Battery system output from the PCS inverter (AC). Media is over Ethernet and data is sent to the gateway in DNP3 protocol.
8. ION Meter 8600 meter (PM Meter) – Function: Recording voltage, Amps, KW, Kwh, etc for the total system output from 12.47kv side of transformer. Media is over Ethernet and data is sent to the gateway in DNP3 protocol.

9. Advantech. BESS (Advantech UNO-3082) – Function: Battery controller, where the algorithm and control signals (analog) are sent for system functionality. Media is over Ethernet and data is sent and received to the gateway in DNP3 protocol.
10. Subsystem of the BESS: S&C HMI (Matrix MXE-1010). Function: Designed to receive the commands and communicate status to the BESS. Media is over Ethernet between the BESS and HMI in MODBUS protocol.
11. S&C HMI (Matrix MXE-1010). Function: virtual connection for S&C & PNM for system monitoring and remote Diagnostics. Two token authentication and 3 firewall passwords for virtual connection into HMI device. Media is Ethernet and no protocol for data transmission to the gateway.
12. Sunny Webbox (SMA TUS102431): Function: A central communication interface that connects the PV Plant and the operator through a virtual connection for system monitoring. Two token authentication and 3 firewall passwords for virtual connection into Sunny Webbox. Media is over Ethernet and data is sent and received to the gateway in MODBUS protocol.
    a. Micrologger (CR3000 Campbell Scientific. Inc.): Function: take all inputs from Met Station, Pyranometer, and Temperature sensors. (Wind speed, irradiance, temp, etc). Media is over Ethernet and data is sent to the gateway in MODBUS protocol.
    b. Subsystems of Micrologger:
    c. Met Station (RH, Temp, Wind Speed, Irradiance)
    d. 5x LI-COR Pyranometer
    e. 5xTemperatore Sensors

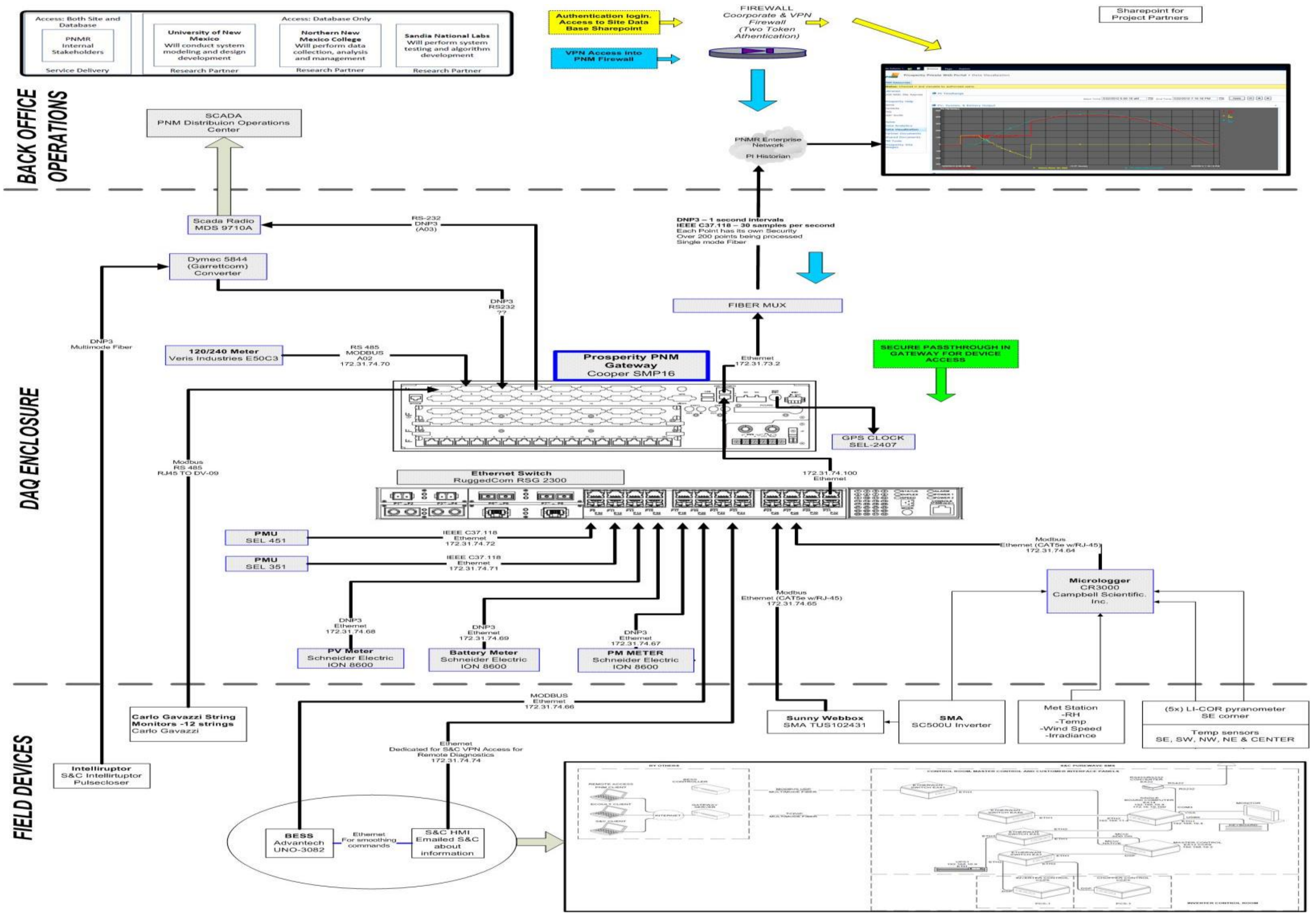


Figure 8 -Data Acquisition system architecture

2.4 Human Machine Interface Systems

2.4.1 PI Data Base

PNM's PI system is a suite of OSI Soft software solutions that support real time information gathering for subsequent analysis. The system can gather information from multiple external data sources, and stores the raw information in the data historian. t PNM's project gathers information from the DNP3 interface that collects all site information using the DNP3 protocol, the IEEE C37.118 interface that collects all site data using the IEEE C37.118 protocol. The system is capable of expanding to collect other data from sources such as internet weather data and system data from PNM operational systems. The PI Interfaces provide high-speed, fault tolerant data links from the field systems to the PI system.

PI data is being shared with project partners using PI to PI interfaces, currently populating OSI Soft PI servers at partner sites in real time. Current interfaces are operational between PNM and Sandia National Labs, PNM and Northern New Mexico College and PNM and the University of New Mexico.

The raw data is being transformed into operational intelligence through other applications in the PI software suite through applications such as PI Process Book, PI DataLink, and PI Webparts. PI Process Book provides a graphical environment in which to display data in real time. PI DataLink automates the retrieval of PI data into Microsoft Excel to use in calculations, analysis, and graphs. PI Webparts provide a tool for visualization in a web environment.

The integration into Microsoft Sharepoint, allows users to view real time data and calculations of multiple applications and data sources into one web environment. Lastly, PI Advanced Computing Engine provides an environment to create complex calculations and schedules with data stored in the PI Server. This allows users to write modules using Visual Basic to provide more capability than is available directly within the core OSI Soft programs, making for a much more powerful and flexible system. The PI suite of software addresses data security as well across the enterprise by allowing specific, administrator-designed permission levels down to the point, asset, or event frame allowing only authorized users access to data that they are authorized to view.

2.4.2 Information Portal

PNM's information portal supports information anywhere, anytime by anybody and enables transition from a data constrained organization to one that is information rich and robust. The portal is the front end of the Project's PI data base.

The Prosperity information portal and operational intelligence platform has been developed in three stages, as outlined below. Proprietary information functionality of the Portal is secure and permissions to project partners are granted and non Proprietary to the Public.

Stage I – Public Outreach

Stage II - Event Processing

Stage III - Situational Awareness

Stage I – Public Outreach

The information portal offers public outreach and educational materials. The portal is used to raise awareness of smart grid opportunities in the region and also informs interested stakeholders about the demonstration project and future deployment efforts applicable to the region. The portal supports static content such as, but not limited to, educational, videos, links, photos, white papers and web publications. Furthermore, the portal supports dynamic information presented as operational intelligence. Operational intelligence is a form of real-time dynamic, operational analytics which delivers visibility and insight into smart grid operations. Operational intelligence translates live information feeds and event data into real-time visualizations and actionable information. This real-time information can be acted upon in a variety of ways – such as executive decisions which can be made using real-time dashboards.

Stage II - Event Processing

Event processing is a method of tracking and analyzing (processing) streams of information (data) about things that happen (events), and deriving a conclusion from them. Complex event processing, or CEP, is event processing that combines data from multiple sources to infer events or patterns that suggest more complicated circumstances. The goal of CEP is to identify meaningful events and respond to them as quickly as possible.

These events may be happening across various layers of operations or they may be news items, text messages, social media posts, economic triggers, weather reports, or other kinds of data. An event may also be defined as a "change of state," when a measurement exceeds a predefined threshold of time, temperature, or other value. CEP will give PNM a new way to analyze patterns in real-time, and help the Distribution Operations Department communicate better with IT and other shared service departments.

Stage III - Situational Awareness

Situational awareness is the perception of environmental elements with respect to time and/or space, the comprehension of their meaning, and the projection of their status after some variable has changed, such as time. It is also a field of study concerned with perception of the environment critical to decision-makers in complex, dynamic areas from power plant operations to command and control, and as well distribution services such as outage management, fault identification, system restoration, field operation and substation operation.

Situational awareness involves being aware of what is happening in the system to understand how information, events, and one's own actions will impact goals and objectives, both immediately and in the near future. Lacking or inadequate situational awareness has been identified as one of the primary factors in accidents attributed to human error. Thus, situational awareness is especially important in work domains where the information flow can be quite high, and poor decisions may lead to serious consequences.

Having complete, accurate and up-to-the-minute situational awareness is essential where technological and situational complexity on the human decision-maker is a concern. Situational awareness has been recognized as a critical, yet often elusive, foundation for successful decision-making across a broad range of complex and dynamic systems.

Features of the portal include

- Visualization of any of the PI Tags, see Figure 9, currently selected variables include,
    - Primary, PV and Battery Meters
    - Irradiance (center of array)
    - Smoothing and Shifting Batteries SoC
    - Battery and Primary meter KVAR
- Data can be visualized and extracted from a wide range of time series, from days to minutes.
- Data can also be exported to Excel from the presented graphs.

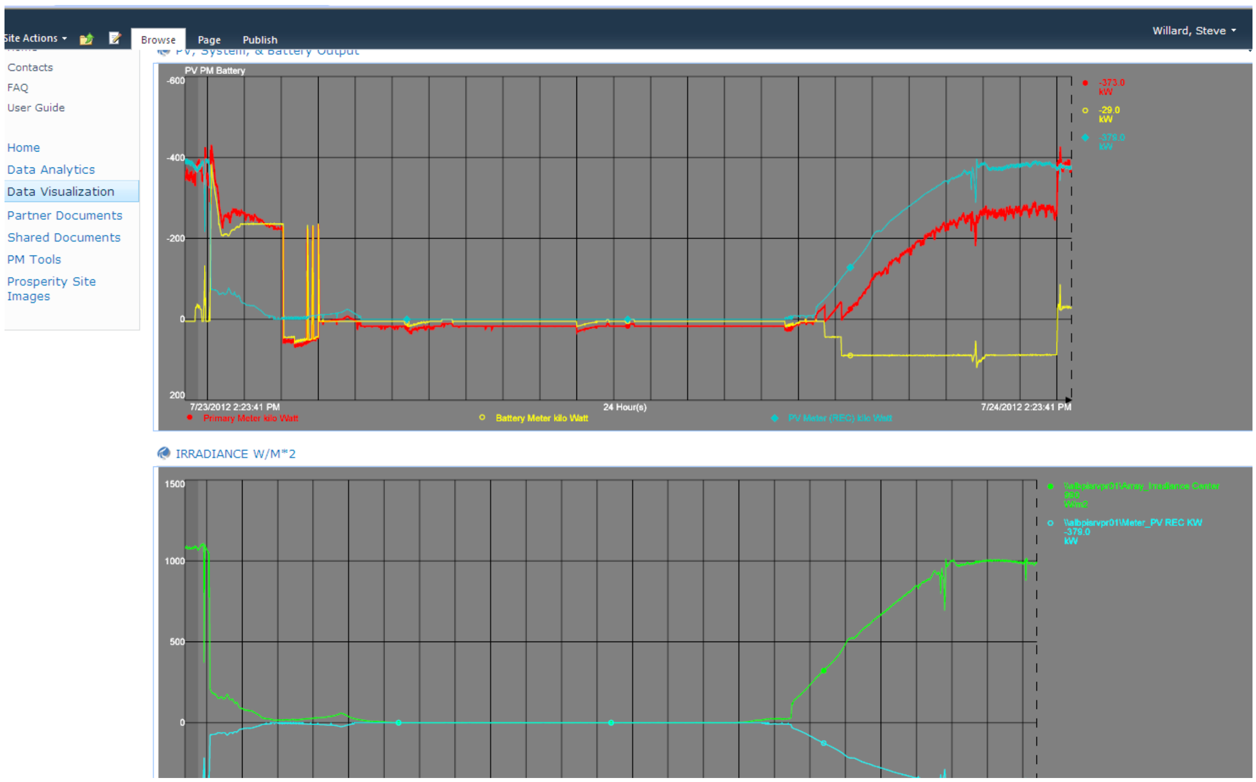


Figure 9 -PNM Sharepoint Data Visualization Screen Shot

2.5 Environmental, Health, and Safety Considerations

2.5.1 Environmental

DOE completed an Environmental Assessment (EA) for the project in August 2010 and DOE issued a Finding of No Significant Impact (FONSI) on Sept 17, 2010. The EA concluded:

“PNM's proposed project could provide a minor reduction of greenhouse gas emissions and have a net beneficial impact on air quality in the region. In addition, there would be a positive socioeconomic benefit resulting from the infusion of $5.8 million into the regional economy.”

2.5.2 Health and Safety

The BESS was designed, manufactured and tested in conformance with the applicable requirements of the latest editions, revisions and addenda of the codes and standards published by the following authorities:

- ANSI American National Standards Institute
- IEEE Institute of Electrical and Electronics Engineers
- NEC National Electrical Code
- NEMA National Electrical Manufacturers Association

- NESC® National Electrical Safety Code®
- NFPA National Fire Protection Association
- OSHA Occupational Safety and Health Administration
- UL Underwriters Laboratories

Door and Panel Safety Features

All electrical power sections/compartments within a battery container that have hinged doors, including the safety barrier described below, are equipped with lockable handles compliant with the National Electrical Code and National Electrical Safety Code®. All sections/compartments that have removable panels fastened with bolts are compliant with the National Electrical Code and National Electrical Safety Code®.

All applicable safety interlocks are in compliance with the National Electrical Code and National Electrical Safety Code®.

Safety Barriers

All live power is behind a safety barrier or within compartments such that the operator may enter the control section within the PCS without having access to live power, excluding control power.

The safety barriers are in compliance with the National Electrical Code and National Electrical Safety Code®.

Safety Features for CUBs and CABs

All CUBs and CABs have VRLA battery safety features specified by National Electrical Code, National Electrical Safety Code®, and IEEE1187. Hydrogen detectors are mounted on the ceiling of the containers, which shall energize explosion proof ventilation fans if hydrogen gas is detected. The detectors are interlocked with the BESS Controller for indication

The following meters, indicating lights, control switches and pushbuttons are mounted within the control section of a container or external to the containers for easy access from the entry door behind a safety barrier that protects the operator from any live power:

- Human machine interface (HMI) terminal to display, as a minimum, the following:
- DC power, voltage and current per DC Converter
- AC voltage, real power and reactive power of the Inverter
- PCS status
- PCS and Battery System fault messages
- Ready light

- AC power on/off status lights
- Cooling System on/off status lights
- UPS healthy light (alarm)
- Remote/Local Selector Switch with indicating lights
- Local on/off pushbuttons for each DC Converter
- Battery Power increase/decrease pushbuttons for each DC Converter
- Two Energized indication lights, one lit when energized, and one lit when de-energized (powered from UPS)
- E-Stop pushbutton

2.6 Transportability Considerations

The containers were transported from the factory assembly site across the U.S. in approximately 5 days. Special consideration was given to the following:

- The gross weight requirements dictated special permitting and adherence to Department of Homeland Security rules preventing overweight transportation at night in certain states.
- The site design accommodated the required crane pick, lift and drop clearances, allowing for efficient unloading and placement
- A detailed staging plan was put into place to ensure the furthest units from the crane were placed first. The plan allowed for a total 2.5 hour unload sequence.

3 Analysis Methodologies

3.1 Goals & Objectives

3.1.2 Project Goals

- Quantify and refine performance requirements, operating practices, and cost versus benefit associated with PV-plus-battery as a firm dispatchable resource
- Achieve 15 percent or greater reduction on distribution feeder peak-load using PV plus battery. Section 3.1 describes current baseline data and detail relating to the 15% target.
- Generate, collect, analyze and share data to quantify the benefit of PV plus battery with respect to grid efficiency, optimization of supply and demand, and increase in reliability
- Validate and support the nationwide effort to develop the next-generation utility systems and Smart Grid technologies and standards that support the full integration renewable, distributed resources and energy efficiency
- Enable distributed solutions that reduce GHG emissions through the expanded use of renewables.

3.1.3 Project and Analysis Objectives

The project objectives are to identify, evaluate and compare various load shifting and peak shaving methods which can be made possible by utilization of a utility-scale battery.

The two main objectives of this demonstration project are:

1. Demonstration of energy shifting to the typical system peak (firming) by planned ("slow") action from the battery, and demonstration of shifting to the typical substation/feeder peak (peak shaving) by planned ("slow") action from the battery, and
2. Simultaneous smoothing of the Photovoltaic plant output by fast-response counter-action from the battery.

Secondary analysis objectives are:

3. Optimization of battery operation for arbitrage purposes, while meeting objectives 1 and 2
4. Optimization of battery operation for longer battery lifetime, while meeting objectives 1 and 2
5. Potential for real-time decision making regarding based on solar and load forecast and utilization of optimization algorithms for objectives 1-4
6. Assess additional system benefits through modeling where physical measurement or demonstration isn't practical. For example, demonstrate PV-plus-battery to mitigate voltage-level fluctuations

3.1.4 Test Plans and Associated Analysis Questions and Research Hypothesis

The following list summarizes planned tests and control strategies identified for PNM's Smart Grid Demonstration project. The smoothing experiments set had the goal of maximizing avoided costs benefits associated with reducing PV intermittency impacts on the utility system while maximizing lifetime of the battery. Peak-shifting experiments had the same goal of maximizing avoided costs benefits and maximizing lifetime of the battery, while at the same time will be responsive to different economic and or/priority signals from utility.

The Test Plans are briefly described below. Test Plans 1 & 2 appear in Appendix A

- Test Plan 1 - Smoothing PV - Demonstrate the effectiveness of battery-based smoothing for various feeder configurations and weather conditions. The goals are to determine the optimal amount of smoothing needed for voltage swing mitigation and the best input signal and control parameters.
- Test Plan 2 - Shifting PV for Firming Purposes - (day ahead) Demonstrate ability to shape PV-battery system output to optimize the value of the PV. energy delivered.
- Test Plan 3 – Peak Shaving– demonstrate a 15% reduction in the feeder peak load through peak shaving
- Test Plan 4 - Energy Arbitrage – demonstrate response to price signals based on set high and low price thresholds.
- Test Plan 5 - Optimized shifting and smoothing – combining and optimizing all functionality.

3.2 Methodologies for Determining Technical Performance

3.2.1 Computer Models

The Interim Technical Performance Report for this project (submitted September 24, 2012) contains detailed information on the methodologies used to model the smoothing and shifting algorithms, as well as cloud cover/PV production simulation and associated utility feeder modeling. Summarized sections of the methodologies contained in the Interim Report appear in Appendix E of this Report. This Report also details the design itself of the smoothing algorithm and describes the fundamentals of the shifting algorithm. Methodologies used subsequent to the Interim Report follow.

3.2.2 Smoothing Algorithm Optimization

This effort targeted determination of the optimal mode of the smoothing algorithm by looking at three different smoothing algorithm structures, lagging Moving Average, centered Moving Average and Low Pass Filter. In order to determine the optimal structure the ramp rate reductions were modeled for each as well as the amount of stress inflicted on the battery, measured by kWh throughput frequency of power flow. This identified the optimal operating parameters that produce maximum ramp rate reduction for the lowest stress on the batteries.

The analysis used a MATLAB platform running the smoothing algorithm developed by Sandia National Labs (SNL). Historical power one second data from the PV and Primary Meters was used to calibrate the model (before and after smoothing) from the Project The pre-smoothing (raw) power data were used to numerically model the theoretical power output which was then calibrated to the Prosperity's historical post-smoothing primary meter (PM) power data. Dead band and system response delays were also calibrated to accurately reproduce historical output data.

3.2.3 SNL Efficiency and Availability Analysis Methodology

SNL has analyzed the efficiency and availability of the BESS. Details are contained in a forthcoming publication. The efficiency calculations were derived utilizing metered data from the primary and battery meters on the Prosperity site. The SNL methodology was staged to include the Balance of Plant loads.[2]

3.2.4 SNL PV Smoothing Effectiveness

In the above mentioned SNL report smoothing effectiveness was also analyzed, separately from UNM based efforts mentioned below. For the SNL effort the following metrics were developed to characterize the degree to which photovoltaic power is effectively smoothed by an energy storage system:

- Percent Reduction in Standard Deviation of Power (RSDP)
- Percent Reduction in Standard Deviation of Ramp-Rate (RSDR)
- Max-Min Reduction

3.2.5 Smoothing Algorithm Optimization Analysis [3]

This analysis was performed using, in part, historical power data (before and after smoothing) from the Prosperity Project. The pre-smoothing (raw) power data were used to numerically model the theoretical power output which was then calibrated to Prosperity's historical post-smoothing primary meter (PM) power data.

[2] PNM Prosperity Electricity Storage Project Evaluation, A Study for the DOE Energy Storage Systems Program, Ellison, J., Roberson, D., Bhatnagar, D., Schoenwald, D., DOE- Sandia National Laboratories, SAND2014-2883

[3] Optimization of solar PV smoothing algorithms for reduced stress on a utility-scale battery energy storage system." Greenwood, W.; Mammoli, A.; Lavrova, O.; Willard, S.; Arellano, B.; Johnson, J. EESAT 2013)

The numerical model used for this analysis was produced by modifying a model used by Sandia National Laboratories. The modifications included introducing a third algorithm which simulates a perfect short term solar power forecast. Running each algorithm for the project's one-second temporal resolution PV power data, theoretical ramp rate distributions and BESS usage characteristics are compared for algorithms using a low pass filter (LPF), lagging moving average (MA), or centered moving average (CMA) simulating a short-term solar forecast). Prior to comparison, parameters such as dead band and system response delays are calibrated to adequately reproduce historical output data from the Prosperity Site for days using either lagging moving average or low pass filter real-time

3.2.6 Smoothing Impact on the Feeder

This effort took a calibrated OpenDSS model from EPRI[4], tuned to the Sewer Plant Feeder, and derived the effect that smoothing has on load tap changer operations at the substation transformer. Clear, low cloud intermittency, high cloud intermittency and overcast data sets were input into the PV portion of the model. Resulting load tap changes were then analyzed for a variety of storage configurations (substation based 250kW, distribution based 250kW and customer based 2kW). These were then compared to historical real world data.

3.3 Methodologies for Determining Economic Performance

EPRI's Energy Storage Valuation Tool (ESVT) was utilized to gauge economics for the shifting applications singularly and in combination. The steps taken in performing this analysis were:

1. Baseline data for specific feeders, PV generation and PNM system were acquired
2. Baseline data sets were cleansed to remove outlier data that affects economic analysis and to bridge null data sets that sometimes appear in SCADA based data (distribution and system)
3. PNM specific system parameters and financial parameters were input into EPRI's ESVT model
4. The above parameters were then run in ESVT to produce similar pro forma dispatch schedules for peak shaving
5. The model was then run with CAISO price history to accommodate arbitrage along with peak shaving (prioritized)
6. Firming (using ESVT System Capacity selection) was then simulated
7. All the above applications were then selected in ESVT and run on a reliability (peak shaving) prioritized basis

[4] OpenDSS is an open source dynamic feeder modeling tool available from EPRI

The DOE ESCT was run to validate the results of the ESVT outputs. These outputs were required in order to input the annual energy levels dedicated to various applications in the ESCT. Similar ESVT emissions, finance and operational inputs were applied to the ESCT.

3.4 Methodologies for Determining Emissions Reduction

This effort utilized the EPA AVERT program. The AVERT RDF 2013 EPABZase (Southwest) data set was utilized to profile the generation fleet and associated baseline emissions. A generalized 500kW PV resource was selected as the offsetting input to the program. Iterations were made to best approximate the firmed PV resource. Emissions offsets were priced at current market pricing and the annual total was used as a base year in a 10 year NPV calculation with a 2% annual degradation to account for reduced PV and Battery output.

4 Technology Performance Results

4.1 Recap of previously presented results – Modeling

The Interim Technology Performance Report (TPR) submitted to DOE in September 2012 presented results on the following computer models (annotated results are contained in Appendix F of this report):

4.1.1 Validation of the Feeder Model

Utilizing OpenDSS , associated feeders in PNM's distribution system were modeled to understand the effects of high penetration PV and the solutions to mitigating effects of PV intermittency.

4.1.2 Smoothing Simulation Test Case #1

In this effort various approaches to the smoothing algorithm were analyzed looking at mover average double moving average and moving median.

4.1.3 Smoothing Simulation Test Case #2

This effort, from SNL, analyzed different gains used in the smooth algorithm

4.1.4 Validation of Shifting Model

In this effort the prediction engines for PV were tested and compared to field data. The shifting algorithm was developed and tested various approaches to the smoothing algorithm which were analyzed looking at moving average double moving average and moving median.

4.2 Smoothing Results

Previous results on initial smoothing tests were presented in the Interim TPR. Following are recaps of major results and further analysis conducted since.

4.2.1 Smoothing Signal Input Results

This effort gauged the effectiveness of different input signals, from the PV meters and Irradiance sensors in driving the smoothing algorithm. The Primary meter was initially tested as an input but was found to present an untenable feedback loop.

For the following figures

- Solar PV Meter data appears in blue
- Primary (Net System) Meter data appears in red
- Battery Meter data appears in yellow

Figure 10 displays four consecutive days of early operation in November 2011. With the input gain set at 0.1 effectively 10% of the battery capacity was used. Little to no smoothing effect are evident on the first and fourth days of the data set where cloud cover was great enough to induce the smoothing. No smoothing was required on the second and third days as no cloud cover was present.

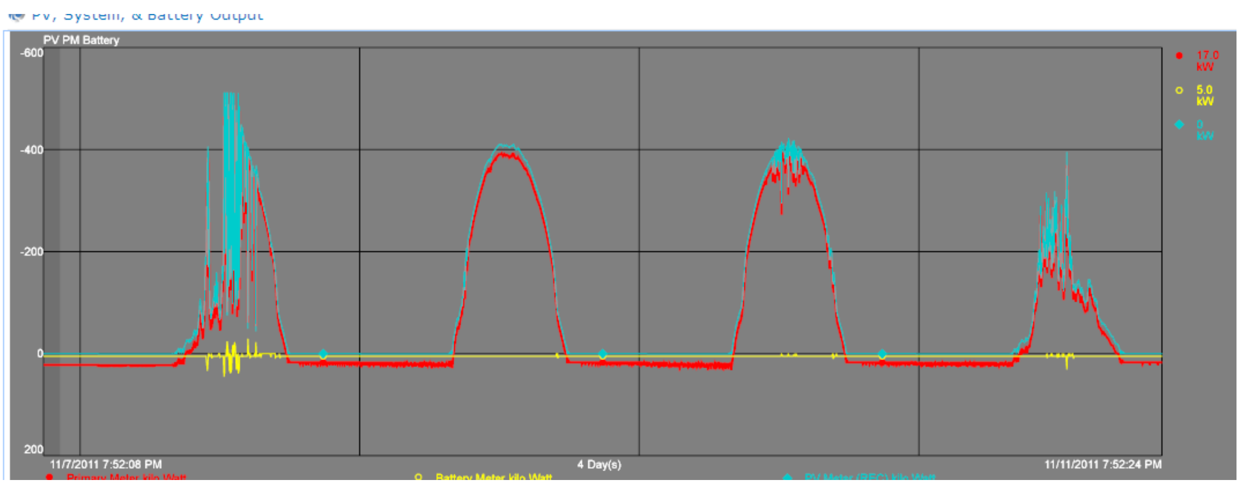


Figure 10 - System Output 1BPV0.1 – 10% of PV Meter

When the System was run at 100% of the PV Meter as an input signal, Figure 11, much more smoothing is apparent. The performance of the smoothing is even more evident in a magnified view of the first day of the data set, 1/15/12, shown in Figure 12. Some spiking occurred because of late response of the smoothing battery, as shown in a magnified view in Figure 13 the magnified view of second day of the data set. This was caused by latency issues from a variety of sources and was resolved, see discussion below.

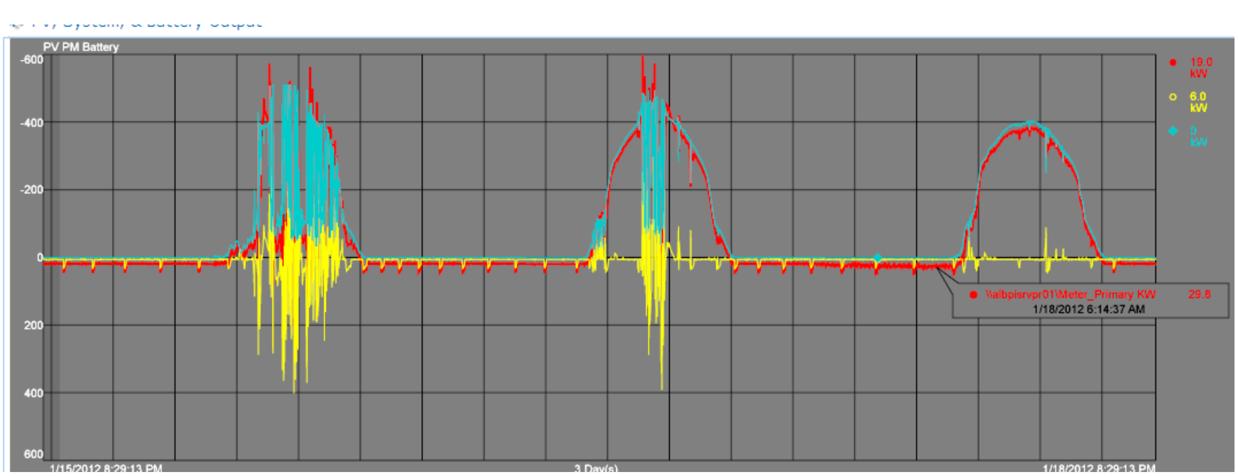


Figure 11 - 1BPV1 100% of PV Meter

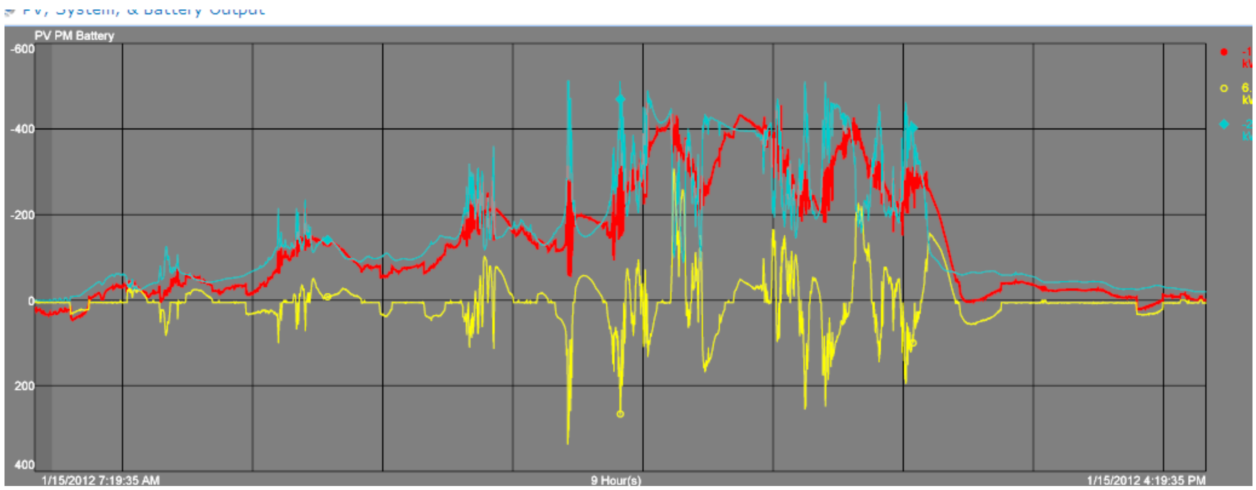


Figure 12 – 1BPV1 - Magnified view of 1/15/12 Smoothing

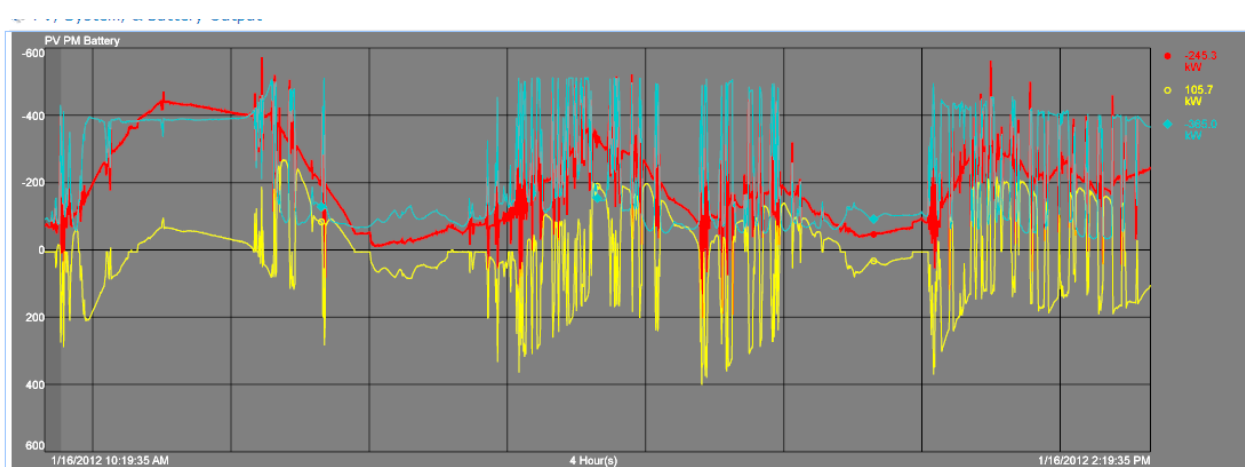


Figure 13 - 1BPV1 - Magnified View of 1/16/12 Smoothing

A subsequent subset of Test Plan 1 utilized the average of the five irradiance sensors as inputs. Figure 14 and Figure 15 shows significant spikes from the battery 6/8/2012. The cause of this unwanted effect and subsequent solution is discussed below.

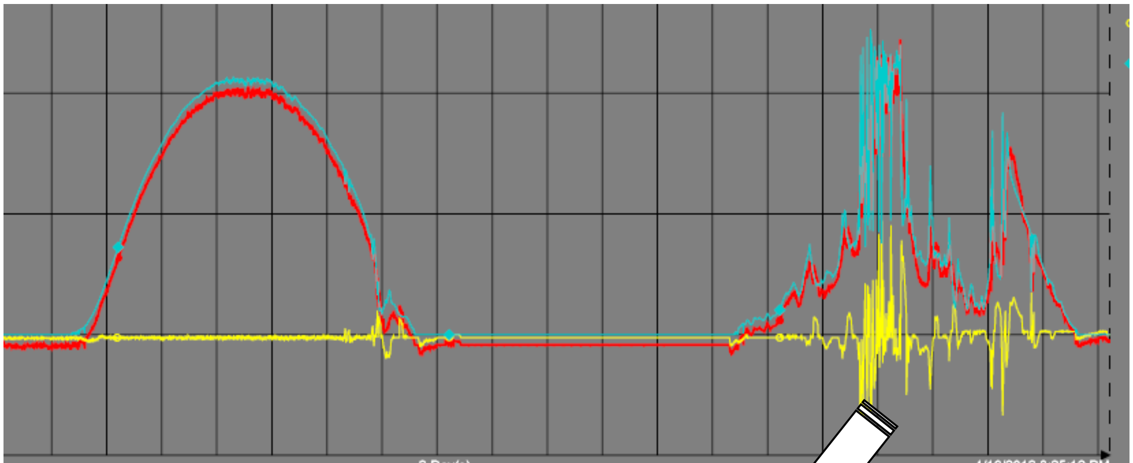


Figure 14 Smoothing with Irradiance Sensor Input

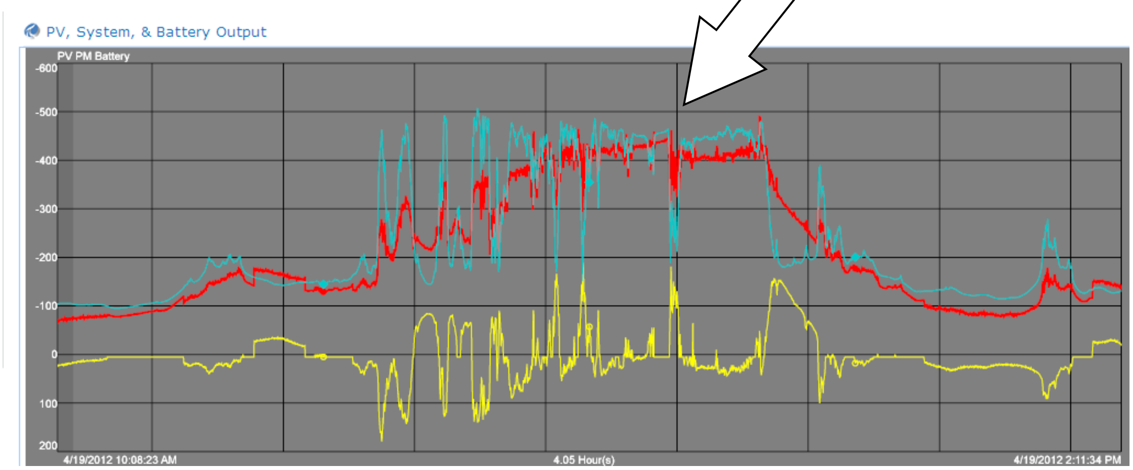


Figure 15 Magnified Smoothing with Irradiance Sensor Input

4.2.2 Quantification of Ramp Mitigation vs. Percent Battery Capacity applied

Previous efforts, presented in the Interim TPR and in Appendix F of this report, contrasted using the smoothing algorithm's Low Pass Filter (LPF) or Moving Average (MA) function. This effort was expanded to further test and compare the effects of ramp mitigation for different battery capacities. Cumulative Distribution Function (CDF) analysis was performed on various data sets utilizing a MATLAB model that was calibrated to field operation. Validation of the model after calibration yields the following correlation in Figure 16 where a strong correlation is evident when predicted output is contrasted to actual field measurements.

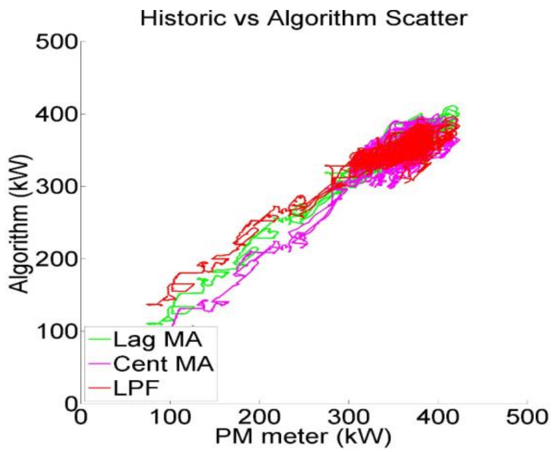
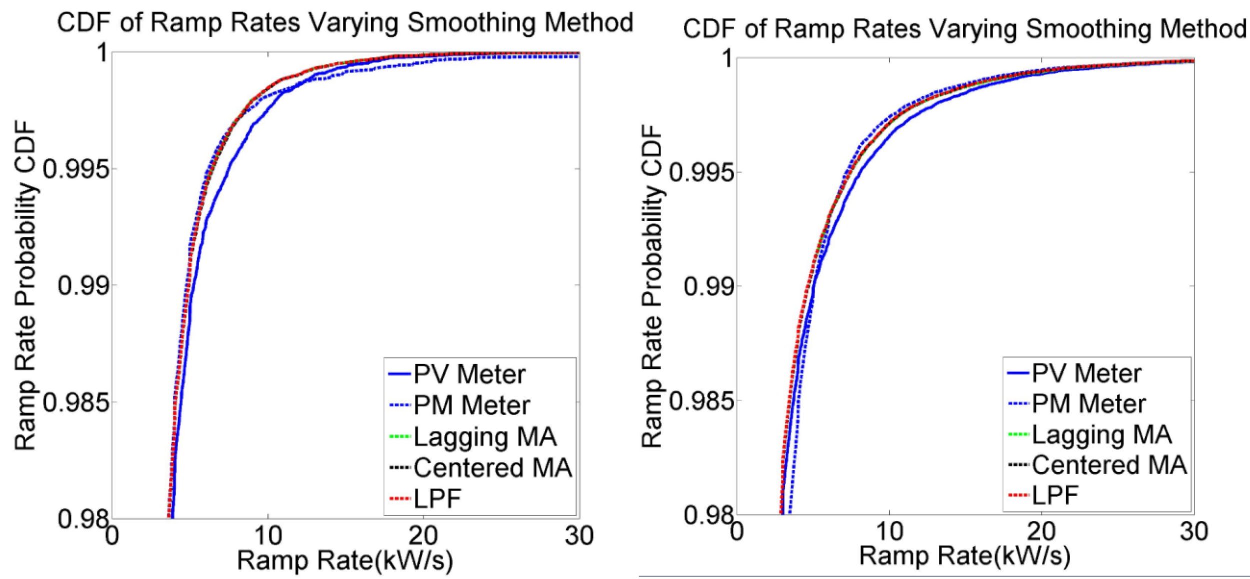


Figure 16   Correlation of Smoothing Model to Primary Meter

Various plots for 40,60, 80 and 100% of battery usage and corresponding ramp mitigation follow in Figure 17, Figure 18,Figure 19, and Figure 20-:

2 Day Comparison of PV Smoothing – 40% Gain on Battery



12-01-13 12-23-13

Figure 17 Ramp Rates for 2 Sampled Days – 40% Gain

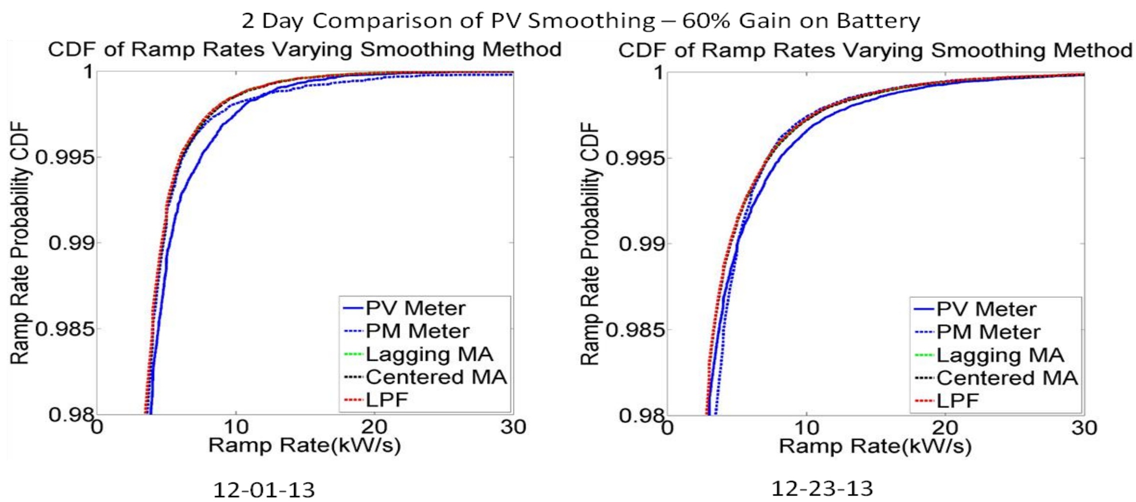


Figure 18 Ramp Rates for 2 Sampled Days – 60% Gain

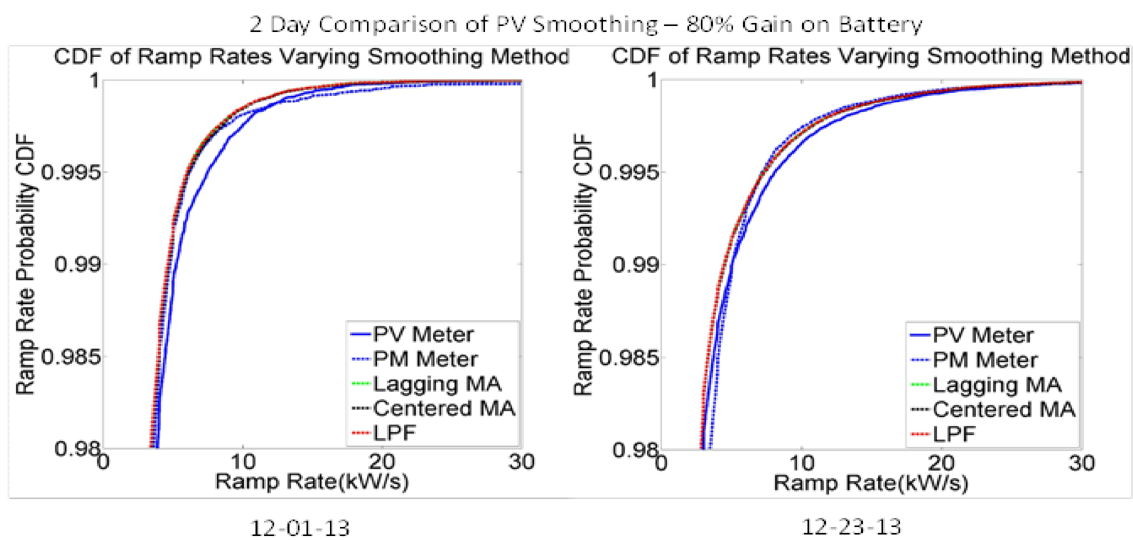


Figure 19 - Ramp Rates for 2 Sampled Days – 80% Gain

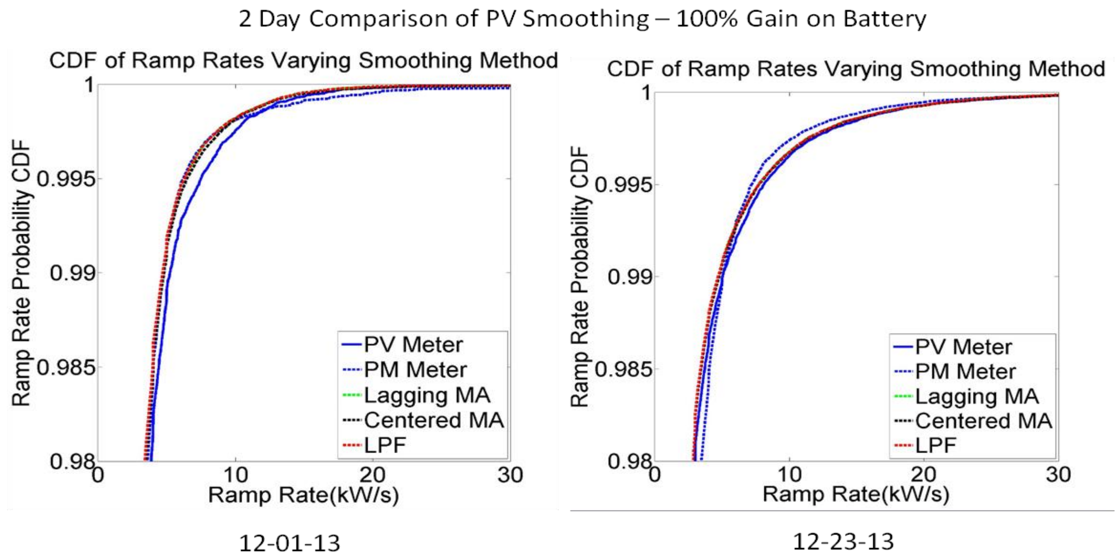
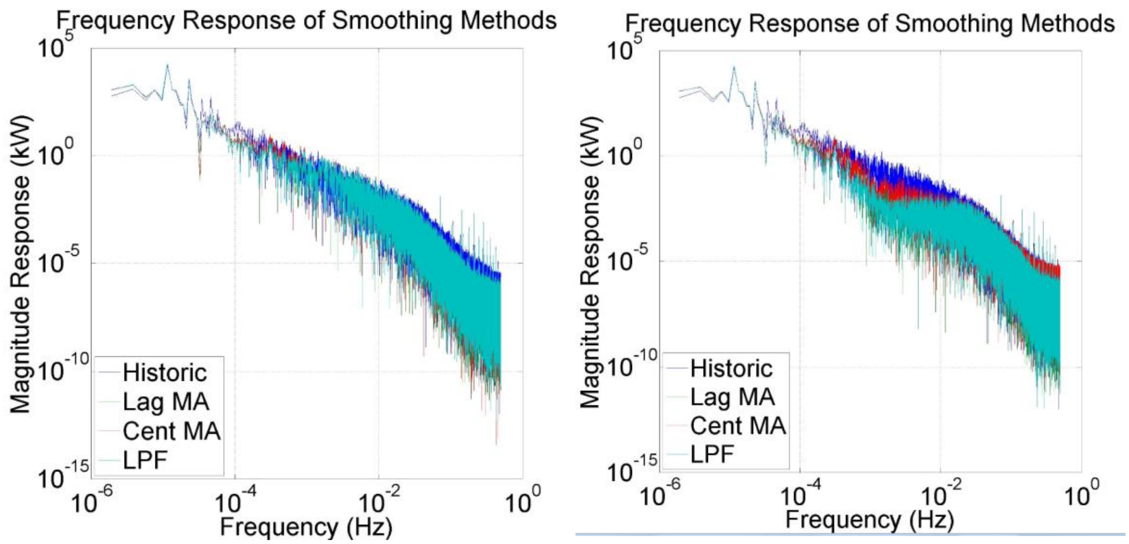


Figure 20 Ramp Rates for 2 Sampled Days – 100% Gain

No discernable difference in ramp mitigation is noted until the 40 and 100% plots are compared in a frequency response analysis in Figure 21. It can be observed that the Low-Pass Filter method with a 100% Gain frequency response does show better (faster) roll-off behavior for frequencies in the range 10^{-4} to 10^{-3} Hz. In Signal Analysis terms, this translates to higher roll-off per octave for the filtering function, which is more desirable for allowing frequencies through the system that are needed, versus filtering out undesirable frequencies. This shows that through Gain and Filter controls, the project was able to tailor the battery smoothing response to specific frequencies ranges. This flexibility is important to show that, for PV resource of varying local intermittency frequency, a best fit frequency response of the battery smoothing can be specifically applied.

Comparison of PV Smoothing – 12-01-13



40% Gain 100% Gain

Figure 21 Frequency Responses for 40 and 100% Gains

4.2.3 Smoothing Algorithm Optimization

Three algorithms, utilizing SNL's smoothing algorithm platform were analyzed. [5] These were 1) low pass filter, 2) lagging moving average, and 3) centered moving average (simulating a short-term solar forecast). The analysis was based on the project's one-second temporal resolution PV power data. Theoretical ramp rate distributions and BESS usage characteristics are compared side by side.

All ramp rates were calculated using an absolute value two-point backwards difference. The ramp rate distribution in Figure 22 shows the three algorithms to be visually identical and this behavior was found to be consistent for all data sets evaluated.

[5] "Optimization of solar PV smoothing algorithms for reduced stress on a utility-scale battery energy storage system." Greenwood, W.; Mammoli, A.; Lavrova, O.; Willard, S.; Arellano, B.; Johnson, J. EESAT 2013.

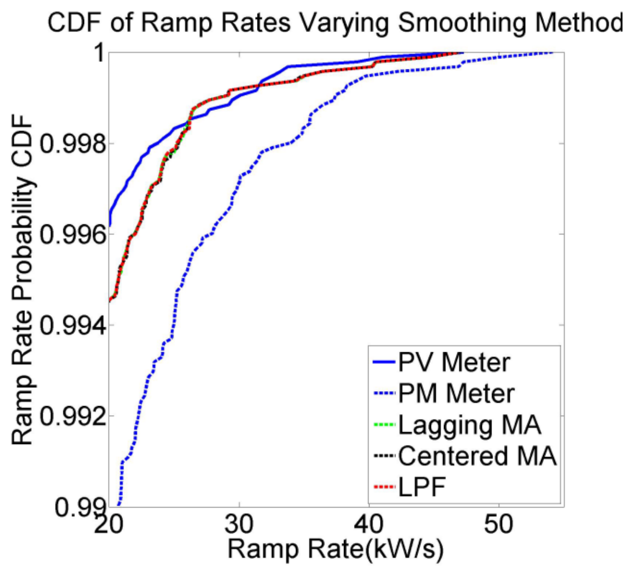


Figure 22 CDF of Ramp Rates for Various Algorithms Filters

The Algorithm Mean Ramp Rate (W/s) were shown to be comparatively similar

- Lagging MA = 508.62
- Centered MA = 513.29
- LPF = 508.20

Note that historical smoothed power data experienced worse ramps after smoothing. This is attributed to noise introduced by the step-up transformer and HVAC cycling on the Station Meter circuit.

The energy displaced, Table 3, through the batteries was calculated for the data sets used. Numerical results show the LPF with the most energy displacement and the centered Moving Average with the least.

01/03/2012 Dataset

Algorithm	Disp. Energy (kWh)	Percent of Worst Case
Lagging MA	89.75	83.51
Centered MA	43.14	40.13
LPF	107.48	100

12/18/2012 Dataset

Algorithm	Disp. Energy (kWh)	Percent of Worst Case
Lagging MA	312.5	88.2
Centered MA	245.6	69.4
LPF	354.3	100

Table 3 Smoothing Model Results

The energy displaced is graphically represented as follows in Figure 23:

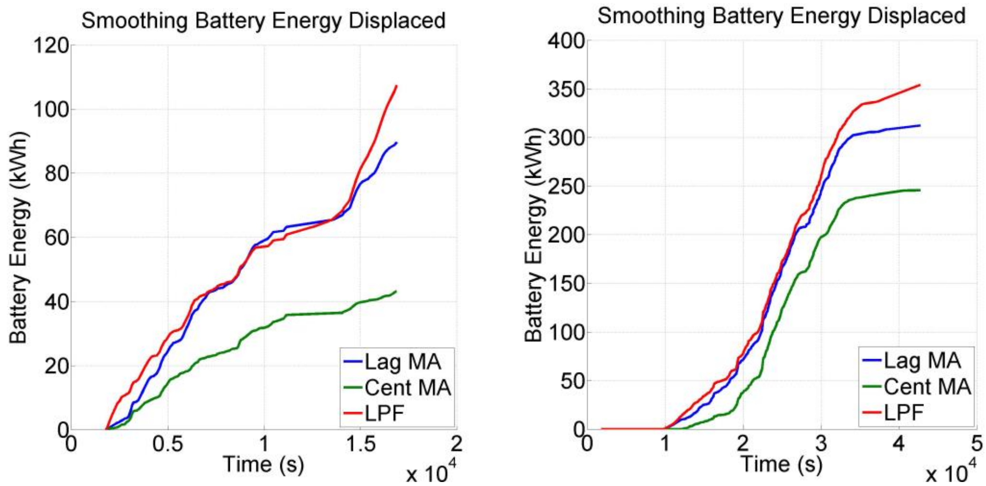


Figure 23 Energy Displacements for Various Smoothing Algorithm Filters

Comparing the three algorithms, the frequency response suggests reduced high-frequency activity for the centered MA.

4.2.4 SNL Analysis of PV smoothing effectiveness [6]

The following metrics were analyzed to assess the effectiveness of the smoothing battery in mitigating PV ramp rates. The variables used to assess the effectiveness were

- Percent Reduction in Standard Deviation of Power (RSDP)
- Percent Reduction in Standard Deviation of Ramp-Rate (RSDR)
- Max-Min Reduction or reduction in the power swing

Three sets of PV variability data sets were analyzed. These are classified as high, moderate and mild variability.

Table 6 shows the results of the analysis. According to SNL, “This implies that the system can smooth the most variable, rapidly changing cloudy days about as well as it can smooth the less

[6] Ellison et al

cloudy or potentially partially cloudy days (i.e. thunderstorm moves in late in the afternoon). Overall, it appears the ESS does its job well."[7]

	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

Table 4 - SNL PV Smoothing Analysis Outputs

4.2.5 Sandia National Laboratories Analysis of BESS Efficiency and Availability[8]

Efficiency Analysis

Site data and manufacturer data for the period of July 2012 through June 2013 were used to calculate efficiency with the parasitic loads and without. The parasitic load labeled by SNL as Balance of Plant (BoP) is labeled by PNM as Station Meter load and in the EPRI ESVT program as Housekeeping Power. Efficiency measures without the BoP present a view of battery system efficiency and measurements with present the efficiency of the entire PV and Battery system along with the associated HVAC and control loads. It is important to note that both inverters (PV and PCS for the battery) contribute to efficiency losses and that additional insulation to the battery containers has preliminarily shown marked improvement in heating system energy use. SNL measured AC-to-AC efficiency using the AC Battery Meter as the point of reference, and included measured BoP (the system meter). This was done because the main goal is to evaluate the efficiency of the battery systems, not the whole Prosperity site. The Primary Meter was not used to avoid blaming the battery systems for losses somewhere else in the facility

Table 5 below, shows the calculated efficiencies, with and without the BoP included:

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

Table 5 SNL Efficiency Analysis Output

[7] ibid
[8] Ibid

AvailabilityAnalysis .

Based on this data supplied by Ecoult and analyzed by SNL , the availability from November 2011 through July 2013 was demonstrated at ~ 91%, see

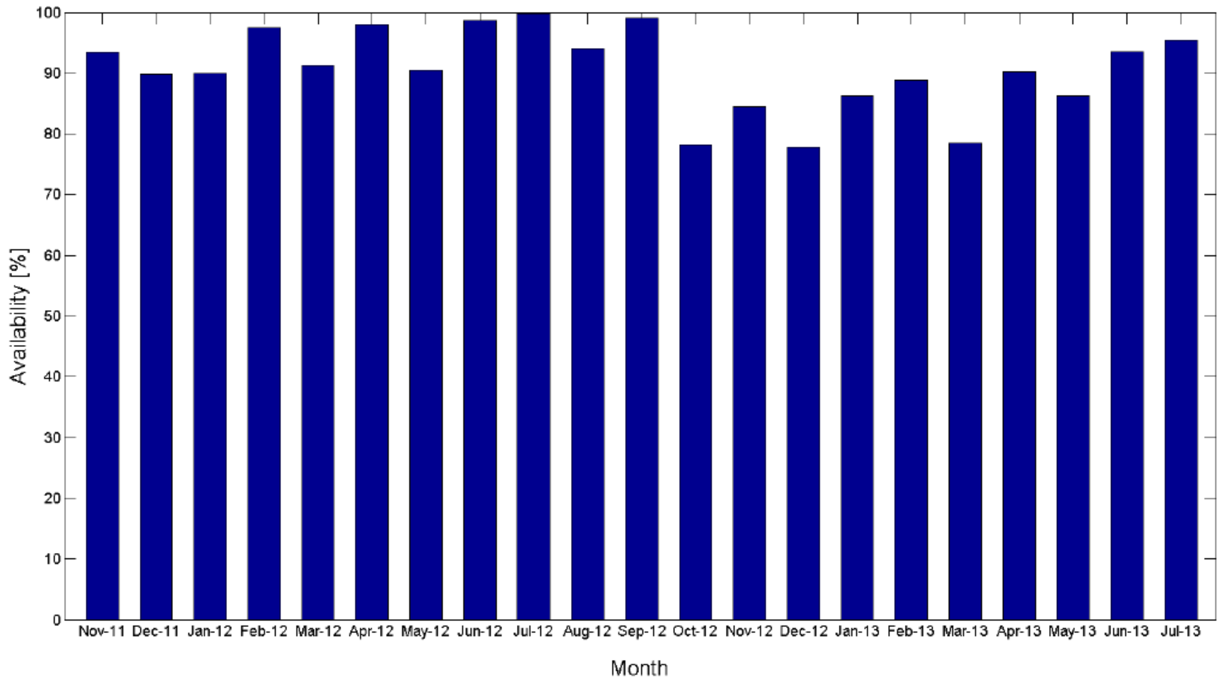


Figure 24 SNL Availability Analysis Figure 24 below. This figure reflects the duration the battery system was on line whether needed or not (this application only dictated need during the day – when the PV was producing. If looking strictly at availability calculated as the percentage of time the battery was needed but was off line the availability figures would be higher.

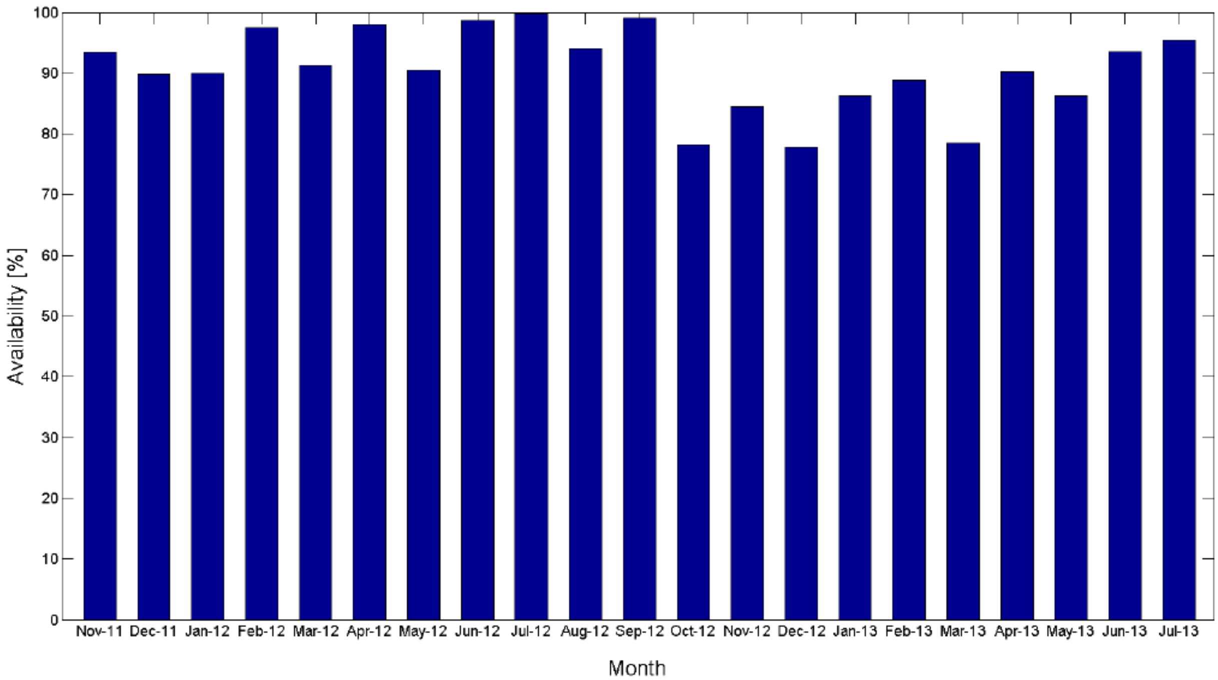


Figure 24 SNL Availability Analysis

4.2.6 Smoothing Impact on the Feeder

The reliability improvements stemming from smoothed PV center on reduced Load Tap Changer (LTC) operations. OpenDSS was used to derive the number of load tap changer operations associated with varying levels of PV intermittency.

A base case model was run with various PV penetration rates for the various levels of intermittency. It can be seen in Table 6 that the number of operations increases with percentage penetration. (Day1 = clear, 2=slightly intermittent, 3 =heavily intermittent, 4=overcast). As observed with field data, the overcast days do not trigger many operations, however, the heavily intermittent day don't trigger as many operations as the slightly intermittent days[9]. The operations were at a maximum for the 100% penetration.

[9] It should also be noted that tap changers can have control delay settings that prevent "hunting" and subsequent tap changes, until a time delay is met. This delay setting could traditionally be at 30 seconds

Case #	Day	PV, %	Operations count
Base	1	0	301
Base	2	0	307
Base	3	0	285
Base	4	0	143
PV 14	1	14	389
PV 14	2	14	381
PV 14	3	14	321
PV 14	4	14	215
PV 100	1	100	393
PV 100	2	100	433
PV 100	3	100	349
PV 100	4	100	145

Table 6 OpenDSS LTC Operations Baseline (no Smoothing) Results

When storage was applied to the OpenDSS model the resulting operations results were inconclusive for the 14% PV penetration feeder modeled. A variety of storage scenarios were applied, intending to approximate 50 % (250kW) of the rated capacity at Prosperity along with scattered customer sited storage (2kW) on the customer side of the meter. The results show that when slight intermittency is introduced the number of operations is not materially affected for any storage scenario. Only when numerous storage devices are utilized does the operations count decline noticeably. The model shows that smoothing storage may be most effective for heavy intermittency (Day 3) when customer and utility side storage are combined (ES2 and ES4 combined cases). See Table 7 and Figure 255 . In other cases smoothing had a negligible effect in either customer side or utility side application. This may indicate that loads are influencing operations more than PV for the modeled feeder.

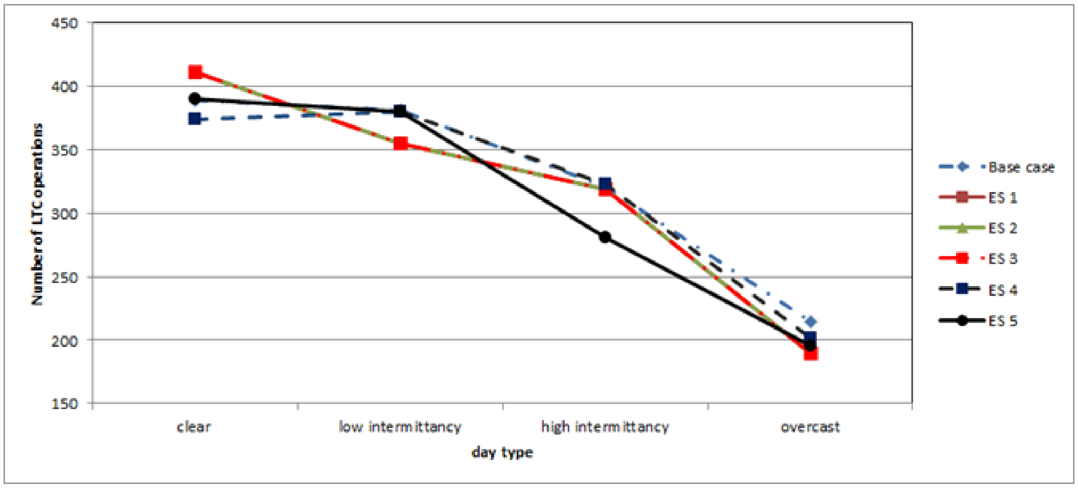


Figure 25 - OpenDSS LTC Operations Counts for Various Days

LTC Operations Result from OpenDSS				
Case #	**Day**	**PV, %**	**Energy Storage Scenario**	**Operations count**
ES 1	1	14	2 of 250kW at feeder head	411
ES 1	2	14	2 of 250kW at feeder head	355
ES 1	3	14	2 of 250kW at feeder head	319
ES 1	4	14	2 of 250kW at feeder head	189
ES 2	1	14	20 of 250kW at secondary	411
ES 2	2	14	20 of 250kW at secondary	355
ES 2	3	14	20 of 250kW at secondary	319
ES 2	4	14	20 of 250kW at secondary	189
ES 3	1	14	200 of 2.5kW behind meter	411
ES 3	2	14	200 of 2.5kW behind meter	355
ES 3	3	14	200 of 2.5kW behind meter	319
ES 3	4	14	200 of 2.5kW behind meter	189
ES 4	1	14	200 of 2.5kW behind meter - smoothing	374
ES 4	2	14	200 of 2.5kW behind meter - smoothing	380
ES 4	3	14	200 of 2.5kW behind meter - smoothing	323
ES 4	4	14	200 of 2.5kW behind meter - smoothing	201
ES 5	1	14	Combined ES 2 and ES 4	390
ES 5	2	14	Combined ES 2 and ES 4	380
ES 5	3	14	Combined ES 2 and ES 4	281
ES 5	4	14	Combined ES 2 and ES 4	195

Table 7 OpenDSS LTC Operations Baseline (with Smoothing) Results

Some results from Prosperity metered data do, however, point to a reduction in operations. Figure 266 below shows two intermittent days where smoothing is disabled (left) and enabled (right). Load tap changer operations are evident 4 times in the left graph with moderate PV intermittency for the measured day and battery smoothing disabled. The evidence of the tap change is the rapid shift in circuit voltage. In the right side, where smoothing is enabled, only 1 tap change is evident when heavy intermittency is experienced.

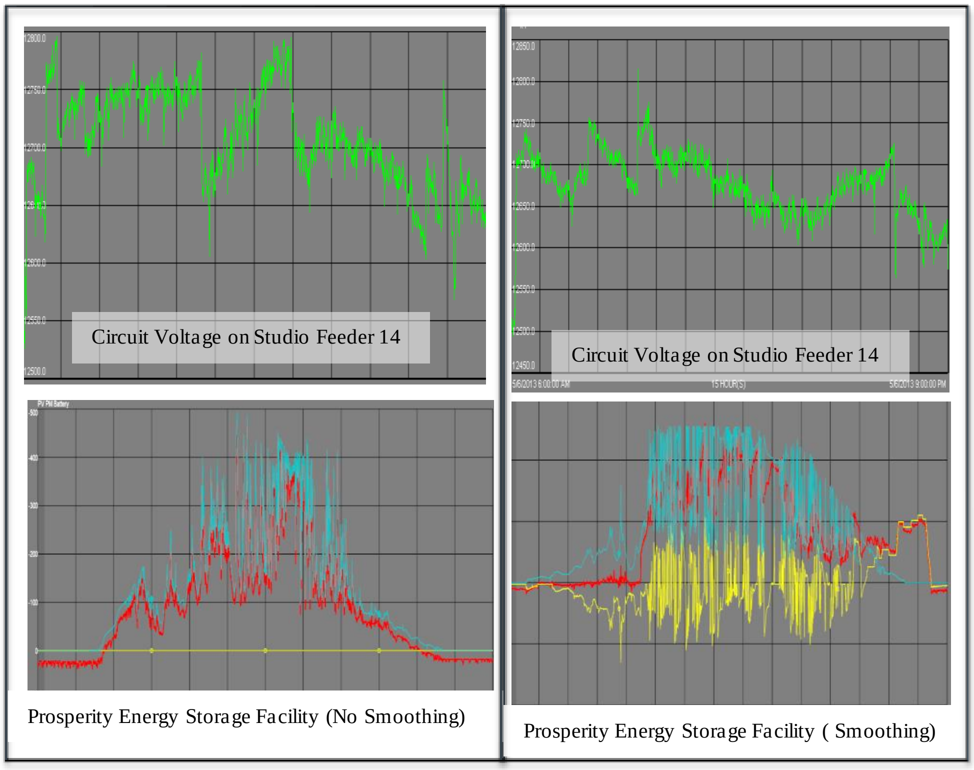


Figure 26 Feeder Voltage Profiles with and without Smoothing

When actual LTC operations for the feeders associated with Prosperity were analyzed no apparent trend of decreasing operations due to PV and smoothing was apparent. See Figure 277 and Figure 29 below highlighting the periods where the individual feeders were switched into the Prosperity system (the site was installed with SCADA switches allowing it to operate on either one or the other feeder). Figure 299 is a magnification of Figure 288 when the Sewer Plant Feeder was switched into the Prosperity Project (normally the Studio feeder was switched in).

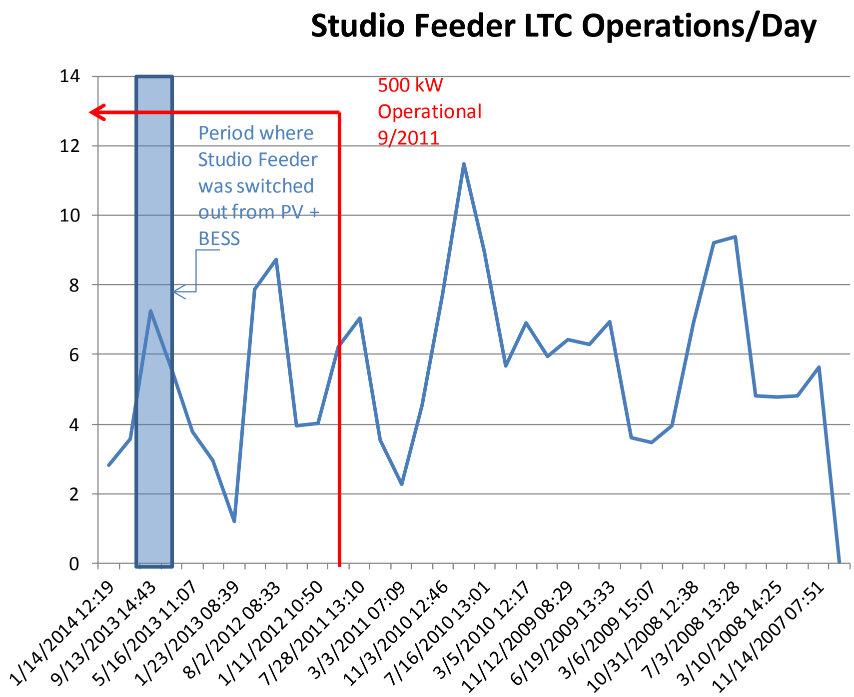


Figure 27 – Historic LTC Operations on Studio Feeder – Highlighting PV Installation

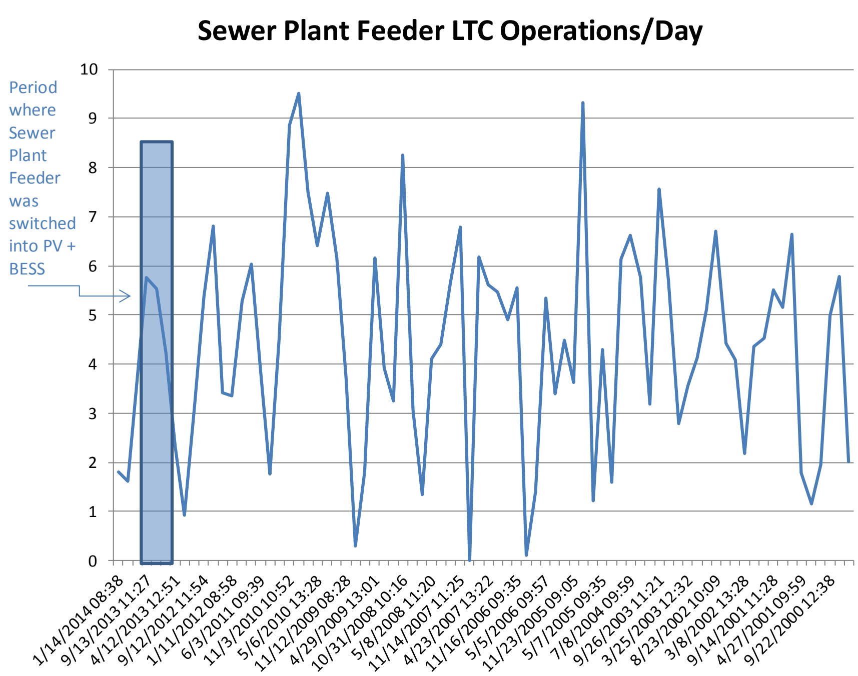


Figure 28 – Historic LTC Operations on Sewer Plant Feeder

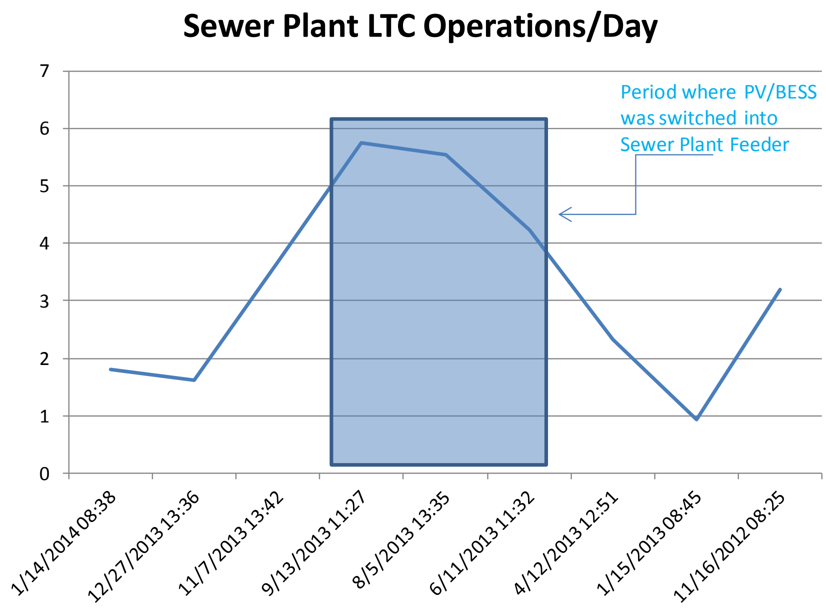


Figure 29 Snapshot of Sewer Plant Data when Switched into PV+BESS

Previously presented data in the Interim TPR (and Appendix F of this report) showed that for the site location, 211 days per year were rated at above 80% irradiance, see Table 8. Utilizing this benchmark for the amount of time per year slight to heavy to overcast intermittency occurs shows that 17 days are predicted overcast, 27 with heavy intermittency, 56 with slight intermittency and 210 with clear to slight intermittency.

Combining these results yields a tenuous conclusion that smoothing in the current configuration on the Prosperity project that only 3 tap change operations per day are relieved by battery smoothing for the slight and heavy intermittency days (40-80% intermittency) per year totaling 83 days per year. This correlates with observed data.

%	days	Persistence
0-20	4	3.8948
20-40	13	2.9400
40-60	27	2.4199
60-80	56	1.4678
80-100	211	1.3696

Table 8 PV Intermittency Bin

Ultimately if the 3 tap change operations per day are saved for 83 days per year then 249 tap changes are prevented annually.

4.2.7 Key Observations – Smoothing

Latency delays in the PCS and BESS software cause the smoothing battery to react too late to severe intermittency. This resulted in upward spikes at the Primary Meter since the battery response happened after the cloud passed and the PV output recovered. The latency was determined by looking at the DAQ gateway. The signal in the DAQ determined control signals are sent a maximum of 37ms, resulting in tuning dead bands in the inverter and battery control system.

- The 10% setting produced no discernible effect, however the 40, 60, 80 and 100% settings had noticeable effects on smoothing
- 40% smoothing has, according to the CDF analysis, similar effects on smoothing compared to 60, 80 and 100%
- The effects have be to analyzed from a strict statistical analysis to screen out variance from clouds, seasonality, ambient temperature and configuration settings – see discussion below on statistical methodology results
- The results presented are particular to this feeder, the amount of PV installed on the feeder as well as the nature of the feeder loads. Other feeders need to be analyzed individually to determine the amount of smoothing needed.
- Dynamic (OpenDSS) and static (Synergee) models will need to be relied upon to understand high penetration PV feeder effects – the Studio feeder in reality doesn't have enough penetration to present a problem
- The irradiance sensors should not be used as an input especially when PV production is close to inverter capacity (shoulder months – especially May). The irradiance may drive upward but the PV output is limited by inverter capacity. The smoothing battery with irradiance as a control signal input ,may, in this case, over respond and cause an upward spike at the Primary Meter Using irradiance sensors to smooth may also conflict with the duties of the Maximum Power Point Tracking function of the PV inverter.
- Ripple effects were introduced to the Primary meter during hotter weather due to battery and PCS air conditioning units cycling. The ripple presents a challenge in analyzing PV vs smoothed output at the Primary Meter
- From SNL 01/14 report "The smoothing battery appears to be effective at reducing PV output volatility. "
- There is still lack of clarity on what standard ramp rate calculations should be used – the smaller the time period the higher ramp and there are no standard definitions available.
- The LTC operations seem to be a lot more load dependent on both feeders analyzed than on PV. Also it should be noted that the LTC operates based on the substation

secondary voltage so the effect of PV on one feeder can be mitigated by loading on all feeders served on the secondary side.

4.3 Shifting Results

The individual and combined results of applications under the shifting realm, including Firming, Peak Shaving, Arbitrage and prioritized delivery of all of the above follow - detailed initial results on firming were presented in the Interim TPR and Appendix F of this report.

4.3.1 Firming Results

The Shifting Algorithm was initially tested in UNM's PI OSI ACE environment, with beta testing complete in January 2012.

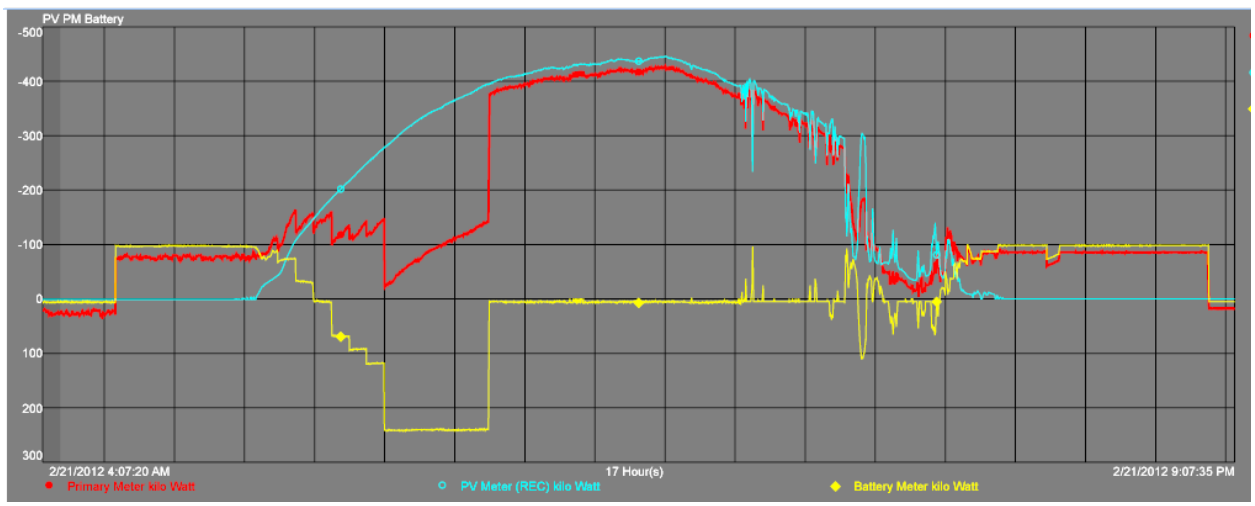


Figure 30 - First Iteration - Manual Shifting – Winter Schedule

The firming production from the battery began at 5am and it can be seen graphically in Figure 3030. When the PV production started later in the morning the algorithm didn't correctly adjust for the PV increase, resulting in an increase in the Primary Meter output rather than a desired flat production. Additionally the time steps associated with manual inputs were not granular enough.

The algorithm was refined to accommodate 1 minute instruction to the BESS from the OSI ACE and modified to better account for the PV production curve. Figure 311 shows a much better flat top production at the Primary Meter.

This is significant in that it demonstrated the ability of the storage system to produce a rectangular shaped energy output, from external utility based commands, by storing sinusoidal shaped PV and producing output on top of the PV output.

Note the ragged nature of the Primary Meter readings in the summer months is due to the cycling of the battery container air conditioner units. The ripple presents an issue for statistical analysis of ramp rate mitigation and mitigation plans will be developed to address this (see Future Plans Section).

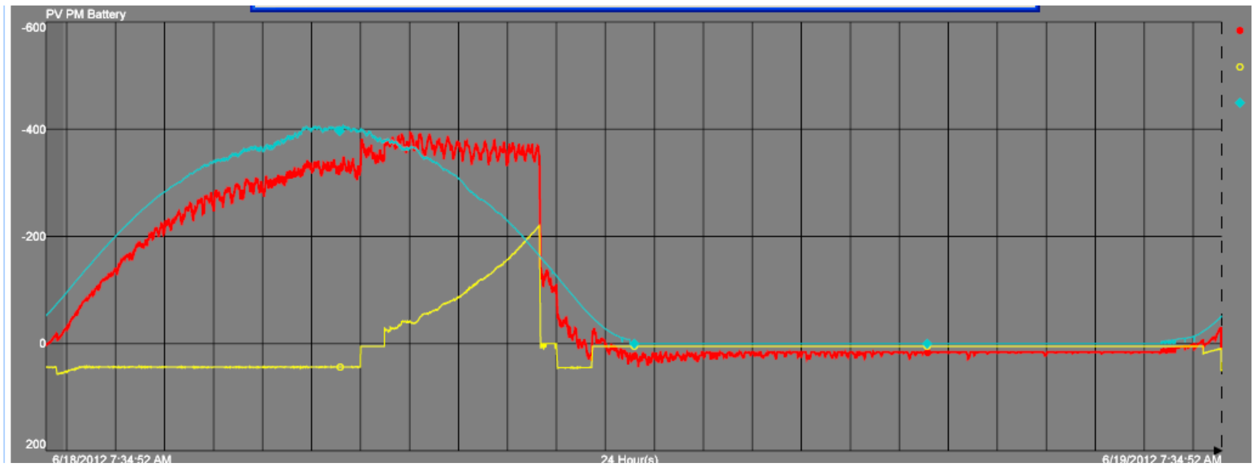


Figure 31 - V1.8 - Automated Shifting – Summer Schedule

Further analysis in the Interim TPR and Appendix F of this report details Firming effects during intermittency and subsequent battery smoothing occurring simultaneously

4.3.2 Key Observations Shifting - Firming

- The shifting algorithm works very well and is quite accurate on clear days. There is lowered confidence in the output on cloudy days.
- SoC limits and rate of charge both limit the amount of morning PV that can be stored, especially in the summer schedule.
- The automation was hindered by software versioning issues.
- Other shapes for firmed output need to be investigated. WSM asked that the sharp drop off in the evening (summer schedule) obvious in Figure 311 be mitigated. This drop off was mitigated in later version to ramp down over 15 minutes.

4.3.3 Peak Shaving

The project data acquisition system has been gathering SCADA based meter data from 3 separate feeders, Tramway, Sewer Plant 14 and Studio 14. The latter two feeders can be fed by the PV Storage system based on the configuration of a SCADA switch. The Tramway feeder was selected because it is currently classified as a high penetration PV feeder. The shifting algorithm was modified to look at recent feeder history and forecast the feeder's next day shape, accounting for the forecast next-day temperature. It then schedules and dispatches battery energy in order to shave a target 15% off of the feeder peak.

Initial attempts at peak shaving showed inaccuracies in the algorithm's forecast and the resulting outcome failed to shave the entire peak. This resulted in a residual peak appearing after the batteries finished discharge obviating any benefit from the batteries. In Figure 322 below the Baseline is the Feeder Meter with the Projects Primary Meter data added back in – representing what the feeder would look like without the PV Storage Project.

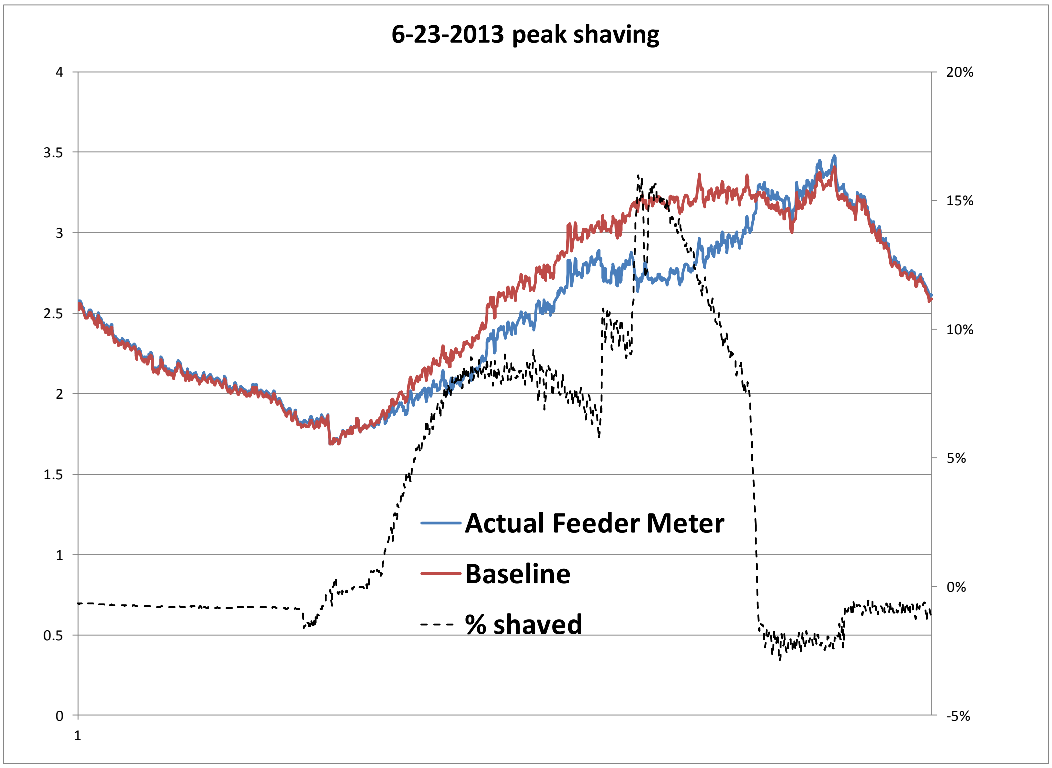


Figure 32 - Peak Shaving prior to Optimization Day Profile

After analysis and tuning of the feeder profile forecast tool in the shifting algorithm, the results improved markedly. In Figure 333 below the batteries are adequately dispatched to shave the peak and the 15% peak reduction goal is met.

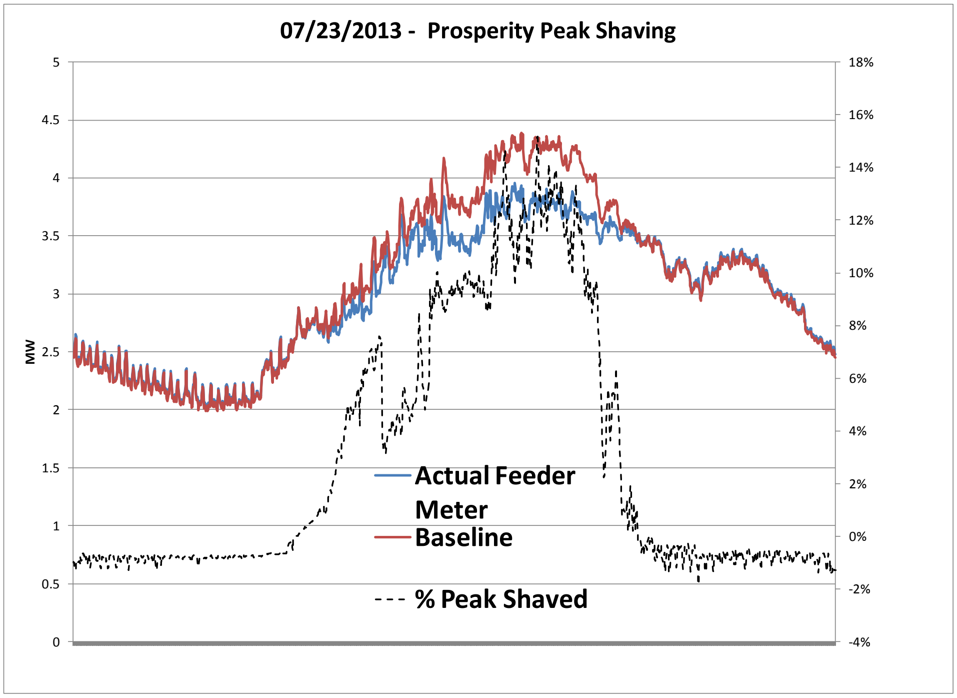


Figure 33 Peak Shaving after Optimization – Day Profile

Another view, via the site share-point portal in Figure 344, shows the output of the battery and PV system for the same day. The Primary Meter is in red, PV in blue and Battery output in yellow.

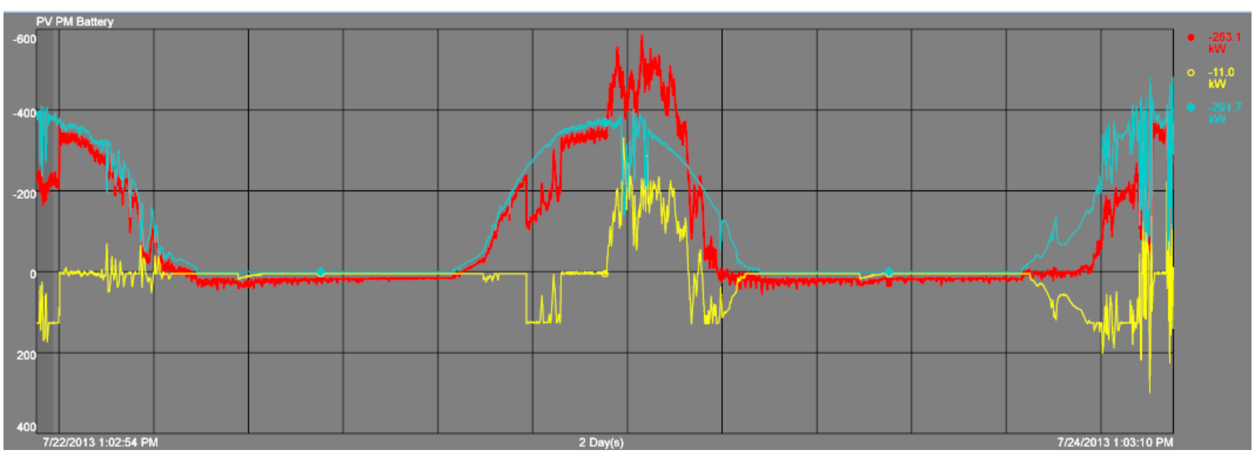


Figure 34 Site Meter Output in Peak Shaving

Figure 355 below shows a similar day where Primary meter data is presented with two different feeders (Tramway and Sewer Plant 14). Note that the Tramway Feeder (not targeted in this example) is in Purple, the Sewer Plant 14 Feeder (targeted in this example) is in Green and the PES Primary Meter is in Red. Not also the multi-scaling on the Y axis.

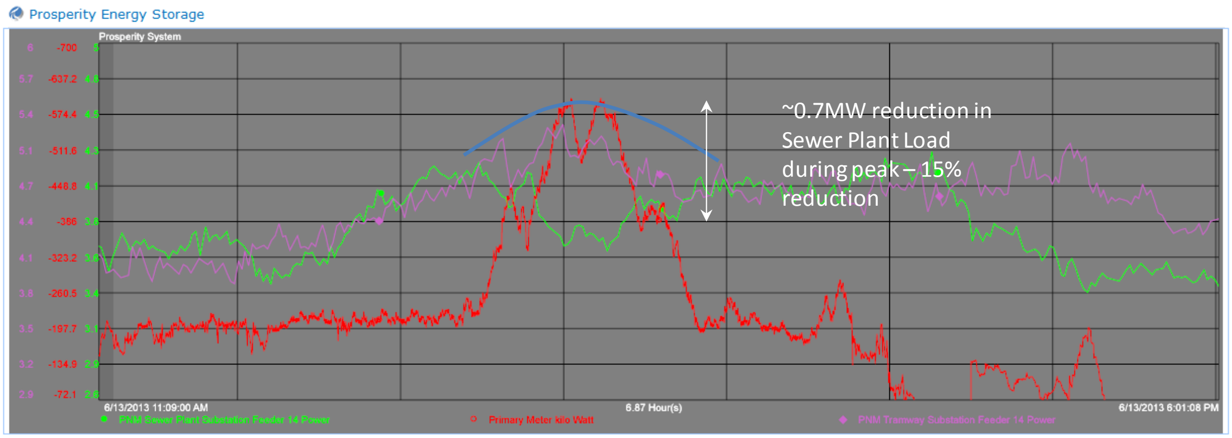


Figure 35 Feeder Voltage Profile in Peak Shaving

4.3.4 Key Observations – Peak Shaving

- The 15% reduction in feeder load goal was met after rigorous study and refinement of feeder profiles and optimization of feeder predictions. It was observed that only on hot days (>92^0 F), when the feeder profile had a sharp predicted peak was the 15% reduction attainable. In cooler periods the load profile was too broad to achieve a 15% reduction – there wasn't enough energy available to achieve the goal in these periods.
- Acquiring the SCADA data into the project PI data base was not a straightforward exercise. Permissions were needed and software modifications were required in order to allow the transfer of PI TAGs from one database to another
- Weather (temperature) forecast data was needed in order to facilitate the prediction of the next day feeder load profile. The forecast profile was created by combining historical patterns, weather forecast and PV production forecast. First attempts had to be tuned to allow for an accurate feeder load profile prediction. First attempts resulted in battery dispatch profiles that ended too soon and allowed the feeder to peak close to status quo patterns.
- Analysis revealed that unless the peak ambient temperature was greater than 92 Deg F the percent of feeder peak shaved was less than 10%. This is because, for this feeder, the peak load profile flattens as the peak temperature drops.

4.3.5 Arbitrage

The following chart shows the system response and corresponding CAISO Real Time (RT) price. The price is extracted directly from the CAISO website on a minute by minute capture.

Thresholds within the shifting algorithm determine if the charge or discharge of the batteries takes place, based on prioritization built within the algorithm.

The data presented below demonstrates the ability of the batteries to respond to price signals. The algorithm thresholds were set at $50/MWH for discharge and $30/MWH for charge. As can be seen in Figure 366 and Figure 377 there are still latency and timing issues – the price signals appear on 5 minute increments but the data pull is on a 1 minute basis and the algorithm responds every minute. Also Battery SoC will over-ride the price signal dispatch if not within set parameters. If the battery SoC is too low, response to high price signals is eliminated until the SoC recovers or waits for appropriate charge timing. Not all price excursions can be pursued.

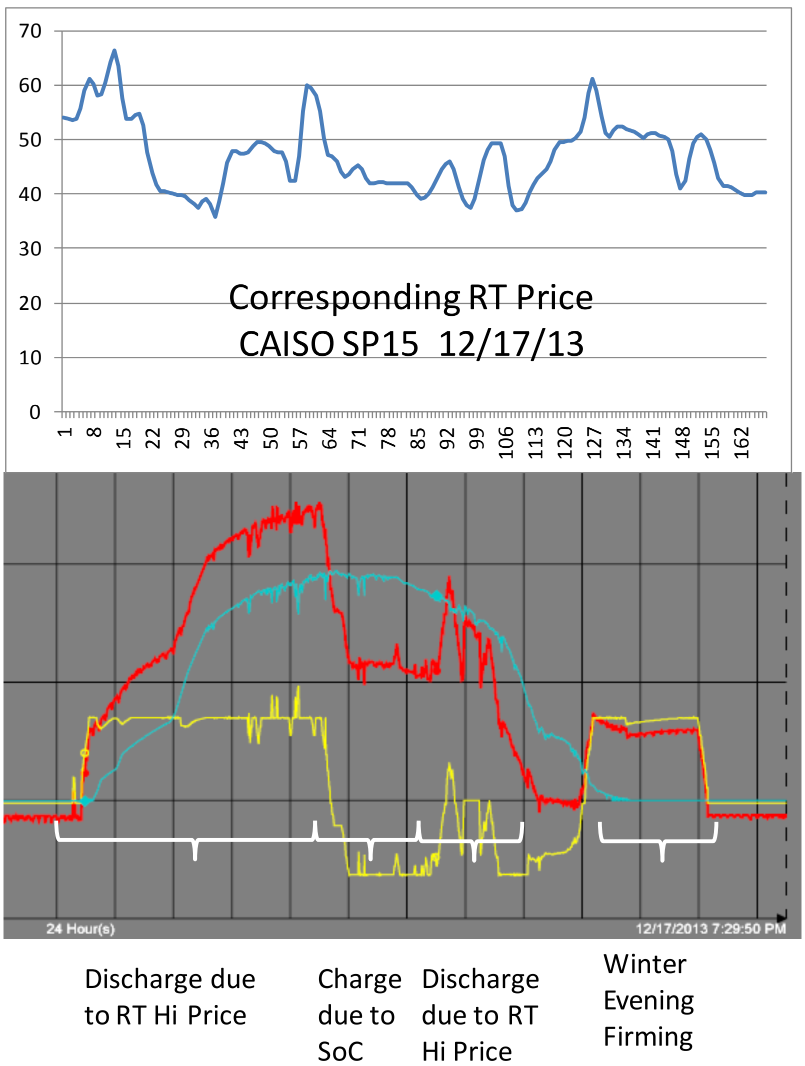


Figure 36 - Arbitrage - Battery Output vs CAISO Price - 1

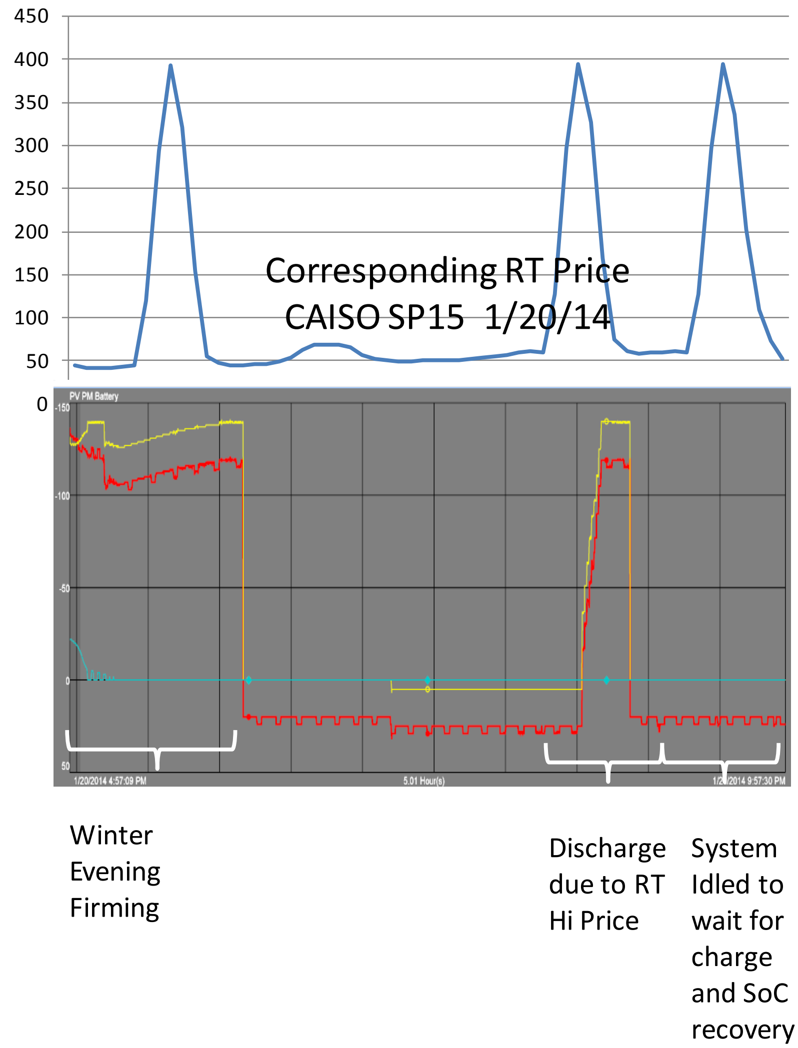


Figure 37 Arbitrage - Battery Output vs CAISO Price - 2

4.3.6 Key Observations - Arbitrage

- CAISO day ahead pricing would be preferable but complications between database types precluded acquisition of day ahead. Real time pricing was substituted as a proxy.
- There are some data integrity issues noticed with the PI tag assigned to the CAISO RT price, this may be due to intermittent connections between the PI server and the internet and associated firewalls.
- The lack of a true wholesale real time market price in the WECC pushed the decision to arbitrage the CAISO RT price. Although PNM does not formally operate in the CAISO there are California influences on the transactions in the WECC.
- The approach used to acquire day ahead pricing was very complicated due to misaligned data base systems. The approach of using Visual Studio and trying to read an Oracle

database points out the need for a mature back office architecture that can take data from disparate systems.

- Duty cycle and SoC have to be understood and economics of arbitrage have to take into account that not all momentary price excursions can be pursued if the battery needs charging
- Coincidence of prices to PNM system peak was not analyzed due to the geographic distance of the CAISO market to local loads.

4.3.7 Prioritized Operation of All Applications

Having established the data inputs and functionality relating to firming, arbitrage and peak shaving, Test Plan 5 was implemented to demonstrate prioritized operation of applications in the shifting algorithm. The algorithm is structured to prioritize reliability based applications over economic based applications. Prioritization is based on thresholds for peak shaving, costs (hi and low prices) for arbitrage. Firming ends up either a medium or low priority, depending on the price and peak shaving thresholds.

Two peak shaving thresholds are established in the algorithm to add to the battery application suite: emergency peak shaving, which is intended to be triggered only in extreme peak events and normal peak shaving, which is triggered on days were forecast peak temperature is greater than 92 deg F.

In order to test the prioritization capabilities of the shifting algorithm, the thresholds were changed to drive requests for applications. In Figure 388 below emergency peak shaving threshold was lowered, price thresholds attenuated (meaning the low price threshold was raised and high price threshold was lowered) in order to force emergency peak shaving. Since the price thresholds weren't violated the system also firmed on the same day. Note that the red line indicates the primary meter (net meter of PV and Battery), the blue line is the associated feeder metered load (labeled: swr plant) and the green line represents the baseline feeder load (what the feeder would look like without the battery and PV associated with this project). Note also that the primary meter corresponds to the right vertical axis measurements and the other meters to the left axis. Note also that simultaneous smoothing took place in the evening.

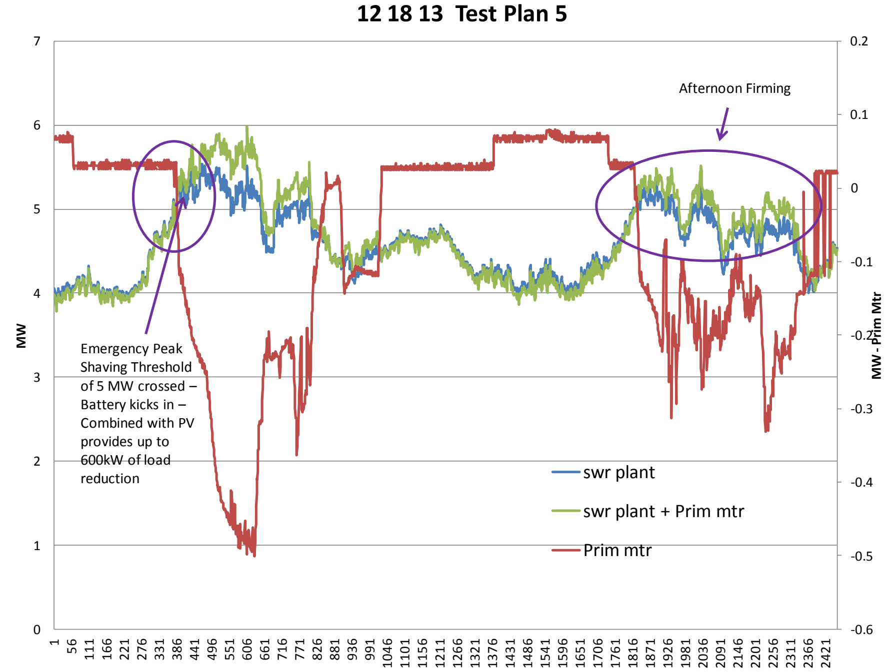


Figure 38 - Optimized Operation showing a variety of Applications in one day

A more detailed few of this operation, for the same day, follows in Figure **39**9

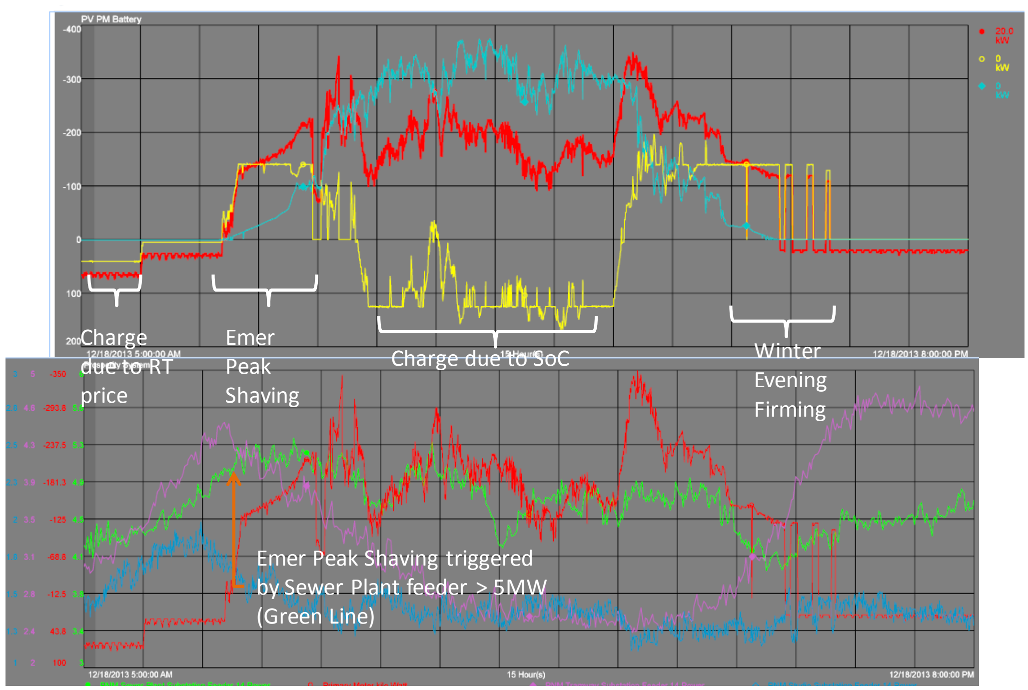


Figure 39 Sharepoint Output of 12 18 2013 Optimized Operation (images shifted to align time)

4.3.8 Key Observations – Prioritized Operation of All Applications

- There are now five distinct applications that can run on a prioritized basis on a given day: Emergency Peak Shaving (threshold based), Peak Shaving (temperature based), Arbitrage, Wind Firming (assumes RT Price<$20MWH indicates a wind dominated system) and PV Firming.
- The adaptability of the control system could easily tackle new, unforeseen applications
- Understanding the thresholds used to prioritize applications may very well be site and feeder specific in terms of peak shaving based applications. Each feeder will have a different profile and its shape will be both load and DR driven.
- The optimization required may be complicated depending on the number of variables. The optimization will require good knowledge of throughput effects on battery life.
- A good valuation on costs of operation vs. the monetized benefit gained will prevent operation on days where costs are greater. This requires a day ahead forecast posture on most of the shifting applications which in turn dictates that accurate feeder and PV resource day-ahead predictions are a necessity. On some days it's probably better to not operate the batteries as the value attained is less than the associated cost of operation.

4.4 Environmental Modeling Results

The EPA AVERT model was used to derive emission reductions. The MWH energy production was built from a 500kW PV input. This allows for a conservative estimate of emissions since the firming of PV would be more aligned with system peak. The system power profile output is presented in Figure 4040 below and the emissions offset are presented in Table 9.

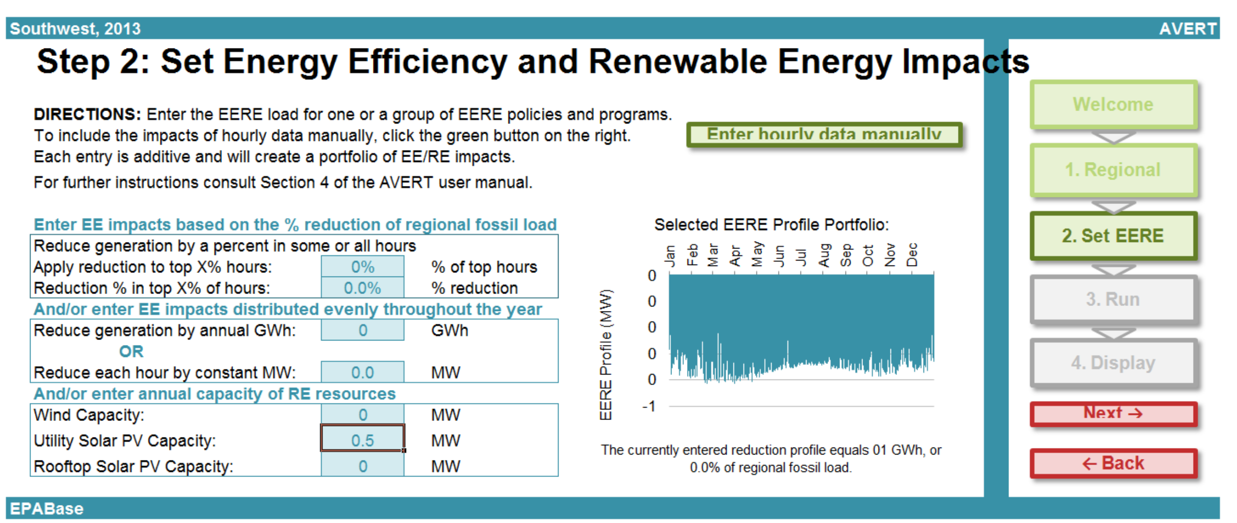


Figure 40 EPA AVERT Output Screen

The emissions avoided are presented below in Table **9** as the “Delta”. These reductions are nominal due to the small size of the project (500kW) however when scaled to larger or numerous systems they become substantial.

Total Emissions	Pre	Post	Delta
SO2 (lbs)	96,560,400	96,560,100	300
NOx (lbs)	228,134,400	228,133,500	800
CO2 (tons)	103,612,700	103,612,000	600
Emission Rates			
SO2 (lbs/MWh)	0.715	0.715	
NOx (lbs/MWh)	1.69	1.69	
CO2 (tons/MWh)	0.768	0.768	

Table 9 EPA AVERT Emissions Reduction Results

4.3.9 Control –Communication System Latency

Figure 411 below shows the GPS clocked speeds for segments of the entire control system from field devices to the back office data base hosting the Advanced Calculation Engine.

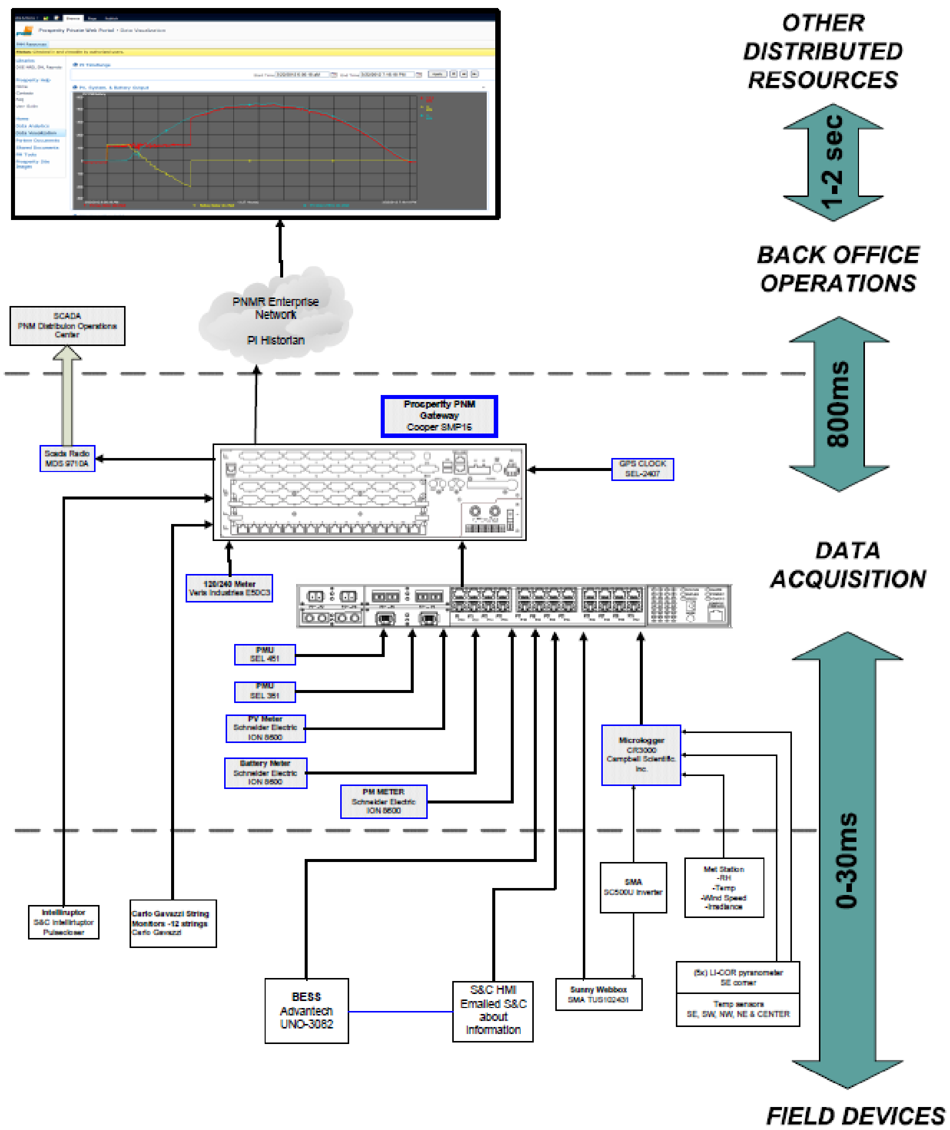


Figure 41

5 Grid Impacts and Benefits

5.1 Economic Benefits Summary

PNM has utilized EPRI's Energy Storage Valuation Tool (ESVT) to calculate grid impacts and quantified shifting benefits for peak shaving, arbitrage and firming (system capacity)–

individually and in combination. Smoothing benefits were derived through simple OpenDSS models. Smoothing benefits were calculated separately and were added to the shifting benefits since the system has demonstrated the ability to simultaneously pursue both shifting and smoothing applications.

The main benefits expected from the demonstration include deferred generation capacity investments and deferred distribution capacity investments. Benefits can be derived through the avoided costs of substation or feeder expansion due to peak shaving and avoided cost of capacitor banks and voltage regulators by smoothing PV ramp rates and minimizing voltage fluctuations. Creation of a reliable, dispatchable renewable resource is also intended to account for pollutant emission avoidance.

5.2 ESVT Inputs

The variable inputs to the ESVT are presented in Appendix B. PNM specific baseline data was used for the overall utility system profile, distribution feeder profile and loss percentage, distributed generation profile (associated Prosperity 500kW PV farm), financial parameters and battery system inputs. CAISO pricing history was used for arbitrage calculations since there is no real established market pricing in the WECC, where PNM operates. EEI sourced market prices were used for environmental offset calculations. ESVT default inputs were used for distribution upgrade costs and number of years deferred.

5.3 Peak Shaving Results

Peak shaving benefits are mostly reliability based. The ESVT calculates these benefits based on distribution investment deferral and distribution losses reduction. With only these two services selected the NPV output was:

.

Peak Shaving Only ESVT Results			
		Cost	Benefit
	Utility Rev. Requirement (Variable)	$ -	$ -
	Utility Rev. Requirement (Fixed)	$ 2,929,123	$ -
	Electricity Sales	$ -	$ -
	Distribution Investment Deferral	$ -	$ 333,987
	Distribution Losses Reduction	$ -	$ -
	Total	$ 2,929,123	$ 333,987

Table 10 Peak Shaving Financials

Sensitivity analysis around the capital cost for peak shaving follows:

Peak Shaving Sensitivity Analysis Inputs		
	Capital Cost ($M)	
	Base	2.66
	Low	1.5
	High	3
Peak Shaving Resulting Benefit/Cost Ratio		
	Base	0.114
	Low	0.198
	High	0.100

Table 11 Peak shaving Sensitivity

5.4 Arbitrage Results

CAISO 2012 real time data was selected from the ESVT library, producing the following results:

Arbitrage Only ESVT Results			
		Cost	Benefit
	Utility Rev. Requirement (Variable)	$ 52,723	$ -
	Utility Rev. Requirement (Fixed)	$ 2,929,123	$ -
	Electricity Sales	$ -	$ 120,276
		$ 2,981,846	$ 120,276

Table 12 Arbitrage Financials

Sensitivity analysis around the capital cost for arbitrage follows:

Arbitrage Only Sensitivity Analysis Inputs		
	Capital Cost ($M)	
	Base	2.66
	Low	1.5
	High	3
Arbitrage Only Resulting Benefit/Cost Ratio		
	Base	0.040
	Low	0.069
	High	0.035

Table 13 Arbitrage Sensitivity

5.4 PV Firming Results

The ESVT System Capacity application was selected as a proxy for firming, producing the following results:

System Capacity (Firming) Only ESVT Results		
	Cost	Benefit
Utility Rev. Requirement (Variable)	$ 52,898	$ -
Utility Rev. Requirement (Fixed)	$ 2,929,123	$ -
Electricity Sales	$ -	$ 120,464
System Electric Supply Capacity	$ -	$ 201,526
Total	$ 2,982,022	$ 321,990

Table 14 - Firming Financials

Sensitivity analysis around the capital cost for System Capacity (Firming) follows:

System Capacity Only Sensitivity Analysis Inputs	
Capital Cost ($M)	
Base	2.66
Low	1.5
High	3
System Capacity Only Resulting Benefit/Cost Ratio	
Base	0.210
Low	0.361
High	0.184

Table 15 - Firming Sensitivity

5.5 Combination of Prioritized Peak Shaving, Arbitrage, System Capacity Results

Results of ESVT output for combination of arbitrage, peak shaving and system capacity follow. Note that the ESVT prioritizes, similar to the Prosperity Shifting Algorithm on reliability based service (peak shaving – distribution deferral).

	Cost	Benefit
Utility Rev. Requirement (Variable)	$ 51,576	$ -
Utility Rev. Requirement (Fixed)	$ 2,929,123	$ -
Electricity Sales	$ -	$ 114,736
Distribution Investment Deferral	$ -	$ 333,987
Distribution Losses Reduction	$ -	$ 16
System Electric Supply Capacity	$ -	$ 177,036
Total	$ 2,980,700	$ 625,775

Table 16 - Prioritized Operation Financials

Sensitivity analysis around the Prioritized Application follows:

Prioritized Application (All) Sensitivity Analysis Inputs		
	Capital Cost ($M)	
	Base	2.66
	Low	1.5
	High	3
System Capacity Only Resulting Benefit/Cost Ratio		
	Base	0.114
	Low	0.361
	High	0.184

Table 17 Prioritized Operations Sensitivity

A detailed financial pro-forma for this case appears in Appendix C.

5.6 Sensitivity Analysis of Combination of Prioritized Applications

Further sensitivity analysis was performed to identify the break-even cost given the base line inputs (i.e., what is the breakeven cost needed to produce a cost benefit ratio of 1 given the $625,755 benefit stream produced?). Results show that the capital cost would have to drop to $450k to achieve a C/B ratio >1.

Prioritized Application (All) Sensitivity Analysis Inputs

Capital Cost ($M)

Base	2.66
Low	**0.45**
High	3

Base	0.114
Low	1.101
High	0.184

Table 18 - Breakeven Cost Analysis Financials

Further Sensitivity Analyses were run to test the effect of higher efficiency on the break even cost. Raising the overall AC/AC efficiency to 80% from 60% nominally increased the break even cost.

Prioritized Application (All) Sensitivity Analysis Inputs
Hi efficiency
Capital Cost ($M)

Base	2.66
Low	**0.5**
High	3

Base	0.222
Low	1.027
High	0.195

Table 19 Break Even Cost Analysis – Hi Efficiency Case Financials

Sensitivity analyze were also run to test the effect of Fixed O & M costs however these did not greatly influence the Benefit/Cost Ratio results. Corresponding sensitivity analysis appears in Appendix C.

5.7 Smoothing Benefits

The reliability improvements stemming from smoothed PV center on reduced Load Tap Changer (LTC) operations. For the associated feeder studied on this project only an estimated annual 83 Load Tap Changer operations were obviated due to battery smoothing. If one operation is valued at $1.50[10] then only nominal benefits are attributable to smoothing, in the order of $374 annually using the calculated 249 annual saved operations. This approach, however, neglects numerous realities discussed in Section 6 Conclusions.

5.8 Environmental Benefits

The benefits estimated for PNM's demonstration project are based on the following metrics:

Reduced Carbon Dioxide Emissions (society) Substitution of fossil fuel based generation with PV may reduce carbon dioxide emissions. Establishing the amount of such reductions requires: 1) tracing the load profile of the load change attributed to the project back to ascertain how the generation dispatch was affected, 2) determining which generation units had their output reduced (and which had their output increased, if appropriate), and 3) associating with each affected generation unit a CO_2/kWh emission rate.

Reduced SO_X, NO_X, and PM-2.5 Emissions (society) - Establishing these emissions effects involves tracing the load profile to the generation origin method, as is required for CO2 impact, but in this case the effected generation output is associated with an SO_X, NO_X, and PM-2.5

[10] Reference EPRI email on LTC from J. Simmons – Tuesday, June 11, 2013 11:34 AM

Emissions rate were evaluated using the EPA AVERT program. PM Emissions aren't calculated in AVERT nor are they traded or priced currently, hence they were precluded from the analysis. Calculations were based on the following rates quoted from evomarkets [11]

CAIR SO2 Spot Market, 2014 vintage: Bid, $0.70; Offer $0.75
CAIR NOx Seasonal, 2014 vintage: Bid, $15; Offer, $22
CAIR NOx Annual, 2014 vintage: Bid, $43; Offer, $45
RGGI Spot Market, 2014 vintage: Bid $3.50; Offer, $3.70
CCA ICE V13 Dec 14 Delivery: Bid, $12.20; Offer, $12.30

The following annual benefits accrue due to emissions reductions:

Total Emissions	Pre	Post	Delta	Benefit
SO_2 (lbs)	96,560,400	96,560,100	300	$ 210.00
NO_x (lbs)	228,134,400	228,133,500	800	$36,000.00
CO_2 (tons)	103,612,700	103,612,000	600	$ 7,380.00
Emission Rates				
SO_2 (lbs/MWh)	0.715	0.715		
NO_x (lbs/MWh)	1.69	1.69		
CO_2 (tons/MWh)	0.768	0.768		
			Total	$43,590.00

Table 20 Environmental Benefits Results

If these are monetized using the same discount rate in previous ESVT runs the annual benefit NPV is $45,583 and the new resulting cost benefits streams are presented below. Accounting for the emissions credits does not substantially affect the cost benefit ratios previously presented.

Base Case	Utility Rev. Requirement (Variable)	$ 51,576.11	$ -
	Utility Rev. Requirement (Fixed)	$ 2,929,123.43	$ -
	Electricity Sales	$ -	$ 114,735.61
	Distribution Investment Deferral	$ -	$ 333,987.30
	Distribution Losses Reduction	$ -	$ 15.80
	System Electric Supply Capacity	$ -	$ 177,036.26
	Emission offset		$45,583.56
	Total	$ 2,980,699.54	$ 671,358.53

Table 21 Prioritized Operation with Environmental Benefits Financials

[11] http://www.evomarkets.com/environment/emissions_markets

5.9 Comparison to Energy Storage Calculation Tool (ESCT)

An attempt to cross check and validate both the ESVT and AVERT models was attempted through the ESCT. The results aligned with the ESVT outputs on the benefits streams and after further analysis an adjustment of Fixed Charge % rate input aligned the cost results were also aligned with ESVT cost outputs.

6 Conclusions

6.1 Peak Shaving

The peak shaving application produced the highest level of individual application benefits. This was due to the high level of deferment assumed in the ESVT model ($2.387M). The initial project proposal envisioned that the feeder and substation associated with the project would experience high penetrations of PV and that substantial upgrades would be necessary to accommodate the high levels of variability introduced. In order to analyze the proposed high penetration scenario it makes sense to utilize and defer the similar upgrade costs in order to establish and economic framework, even though the economic recession precluded the envisioned PV and load growth.

The key challenges associated with peak shaving centered on 1) acquiring the feeder substation meter SCADA points and 2) accurately predicting the approaching next day peak shaving profile. Its rather important that the peak shaving effort not miss and allow spikes to occur after discharge is completed; this would obviate the day’s efforts and remove the benefit stream.

Success in this effort stemmed from thorough analysis of the historic feeder profiles and development of an accurate feeder load profile prediction engine. This engine was coupled with the PV prediction engine to allow for accurate dispatch of the battery system and success in achieving the 15% feeder load reduction goal.

Any control algorithms aimed at peak shaving will require granular, feeder specific historic and temperature data and rigorous analysis to effectively and consistently clip the peaks. Ambient temperature correlations need to be understood for the specific feeder to identify associated temperature thresholds below which peak shaving may not be beneficial.

6.2 Arbitrage

The initial project scope called for importation of historic spreadsheet base pricing in order to test the battery’s response capabilities. The project team instead chose to import true real time prices from the closest active wholesale market, namely CAISO. This was a much more sophisticated and useful approach compared to the proposed approach in that it demonstrated the capability of securely importing real world data into a back office platform. There were many software interface challenges that had to be overcome but the functionality was greatly enhanced through this development.

There appears to be some latency in the battery response to changes in the real time CAISO price. This could be due to the latency of the price coming over the internet and the speed of response. Given the market dispatches every 5 minutes this shouldn’t be an issue. Another possible source for the apparent slight misalignments could be due to the way data is being pulled from the PI database, with non corresponding time stamps

Arbitrage economics stem from the CIASO 2012 price history. Future years may see more volatility as renewable resource impacts become greater – hence increasing the potential benefit gained form arbitrage.

Further optimization analysis would be required to maturely establish high and low price thresholds above and below which charging and discharging takes place. This analysis would need to accommodate local node pricing history, storage type and cost of energy throughput along the benefits available from other applications.

Correlation analysis of wind generation during light load periods and the corresponding real time price history could further identify a good low price threshold that indicates a wind dominated system. If the battery responds by charging to this it would in a sense be firming wind which adds to the list of functionality and applications for a multi-purpose storage system.

6.3 Firming

It is important to understand the difference between Peak Shaving and Firming. Firming is an economic based dispatch of the storage resource while dispatch for Peak Shaving is reliability based. Firming is done to benefit the market or control area in general while Peak Shaving benefits the local substation and feeders. The System Capacity function was therefore selected in the ESVT to mimic PV Firming. This was the best approximation available as it in essence dispatches the storage based on system economics.

This firming application centered on a desired scheduled output from PNM's WSM group for both summer and winter load conditions. Although there are morning and evening peaks in PNM's winter load shape, firming for the PM peak was deemed to be more valuable since gas units are typically taken off line during this period but are available for the AM peak.

Firming during periods of PV intermittency did introduce a less than square output load profile from the batteries. Logic could be built into the BESS smoothing function to limit spikes but the combined smoothing and shifting functions were able to work together during these periods and produce actable dispatch shapes.

Noise on the primary (system output) meter was evident during firming, especially in summer periods. This was due to HVAC cycling. This could be addressed by putting load control features on the HVAC units to limits coincident cycling but was beyond the scope of this project.

6.4 Combination of Prioritized Peak Shaving, Arbitrage, System Capacity Results

The shifting storage system has demonstrated the capability of performing prioritized operation of a variety of applications. Emergency peak shaving, peak shaving, arbitrage, and wind and PV firming have all been demonstrated.

The emergency peak shaving application was a late feature add on that simply looks at for an "emergency " threshold to be met at the feeder substation meter. If this threshold is met the battery discharges to it low SoC limit. No attempt was made to quantify the benefits of this application as it is simply thought of as an add-on "bell & whistle". Its ability points to how numerous applications can be packaged and pursued, making storage an even more effective and valuable tool.

Optimization is a key element of the shifting algorithm; not only do the applications have to be prioritized but the impact on battery life due to energy throughput has to also be accounted for. Thresholds used to establish application triggers need to be thoroughly analyzed for local and system conditions. This allows for a wider selection and implementation of a variety of applications accounting for battery life impact. In some cases conditions may dictate that no charge or discharge activity is needed for a given day. In other days, as demonstrated in this project, multiple applications can be pursued in a given day.

Having proven the capabilities of an isolated storage system performing multiple applications future focus should center on operating numerous distributed resources, with each capable of tackling local issues but al having the ability to act in concert to benefit the overall system. This project has taken a key step in developing a scalable architecture with a single back office calculation engine importing data from numerous sources (tabular weather forecasts, feeder/substation meter data, ISO real time prices and local project weather, BESS and meter data). It has demonstrated a successful development of a sophisticated and automated storage system.

6.5 Smoothing

The economic valuation of smoothing produced marginal results. This is not to say that smoothing is not beneficial it simply reflects that the feeder being treated is still stiff and not incurring wide voltage swings due to lack of PV installation. The original project proposal assumed the feeder would be in a high PV penetration mode, however economic realities prevented this situation.

The OpenDSS modeling tool is the only accessible tool to the project that can really tackle the impacts of high PV penetration. It is a dynamic model and when applied to the feeder in question it only produced marginal effects of smoothing through a small limitation of Load Tap

Changer operations at the substation. Models of other feeders in true high penetration environments do show more substantial benefits of smoothing at other utilities, however modeling of these feeders was outside the project scope. Never-the-less the benefits to industry are evident through the lessons learned and models developed through this project. The work done here can now easily be translated.

6.6 Combined Smoothing and Shifting System

The benefits of smoothing and shifting have been bifurcated and the identified smoothing benefits are nominal. This is the result of a lack of originally envisioned high penetration PV appearing on the project associated feeders. Applications of smoothing on high penetration feeders through separate efforts shows there is a benefit to smoothing but even in these cases it is difficult to assign a monetized benefit to increased reliability.

Of note is the projection by the project's battery partner that the smoothing batteries could potentially perform the duties currently assigned to the shifting batteries. This would present a considerable cost reduction by simplifying the power conditioning circuit and associated DC BESS circuit. Additionally the smoothing batteries have shown exceptional field performance.

Original project designs called for a single inverter to handle both the PV and battery systems. At the time no PCS product was available to handle both due to grounding circuit design differences. Manufacturers are now claiming that his hurdle has been overcome. If true this would drive a further cost reduction and a~3% gain in efficiency.

The success of the communication/control architecture used in this project is one of its biggest achievements. It points to a bigger need for integrated platforms such DERMS operating in a DMS environment that facilitates sharing of pertinent data between systems. The traditional isolated operating system environment where individual systems do not interact will limit the adoption of distributed resources and of energy storage systems.

While this system was successful in meeting all project goals many of the developed applications are site specific while others are market or system oriented. Future storage systems will require multiple benefits streams to justify costs and the control systems need to have the capability of directing local applications from a central location as well as aggregated applications where many distributed resources act in concert to achieve system benefits.

Prioritization of the applications will be necessary in order to facilitate the highest benefit stream possible. Storage is one of the most flexible assets on the grid since it can look like a controllable load as well as a controllable source depending on system needs. How to prioritize those needs in a dynamic system (i.e. market, reliability, etc.) is a key decision.

The ability to securely access the appropriate data to make the decisions is as important as the battery technology itself. The battery can appropriately respond to the information that it is given. The ability to bring this information together with a home grown system is probably not the mature path forward. This will require more development on the storage control side including both back office control systems as well as control systems at the storage itself. Also, some standardization of what that information can and/or should be needs to be discussed in the industry in general. Without this discussion, things that have proven useful in this project such as smoothing gain factors, moving average window sizes, etc. would probably not be thought of in terms of functionality that needs to reside in a DERMS, DMS, or similar control system. Even the need to put that functionality in the battery controller may not be apparent.

There needs to be a realization that some of the functionality is bleeding across the traditional “distribution” and “transmission” silos. Distributed storage can have some value to the transmission system even though it may be controlled at the distribution system level. System operators at the transmission level may not be well equipped to monitor multiple small distributed systems, and distribution system operators may not be in a position to understand what is needed in terms of support to the bulk electric system. These are issues that will need to be addressed over time in terms of storage (as well as other technologies such as demand response).

6.7 Communications/Controls

The project has operated successfully from the communications/control perspective from day 1 This is due to rigorous front end Requirements Definition and underlying Use Case developments that took place before any equipment was purchased. Key elements of these processes target evolving interoperability and cyber-security requirements.

Control Signals

The implementation of the DAQ system to host multiple devices was a crucial component to implement autonomous control. In respect to implementing the smoothing test plans, the communication system needed to address fast intermittent behavior of solar PV. This intermittent behavior required Device to Device control signals that were traced at less than 30ms (source to BESS) in order to effectively command the battery response.

DAQ to back office PI System

Site devices report to PI within 800ms. Parameters defined by Algorithm can make decisions in seconds to determine a control set point to be sent back to BESS for type of dispatch according to priority. Analysis by Algorithm for dispatching is implemented in a few seconds. These speeds may be a bit sophisticated and expensive for energy based algorithms that make minute to minute decisions.

Energy vs. Power Controls

Creating the back office environment was challenging since our existing enterprise architecture was not readily set up to get information from the multitude of sources that the project ultimately implemented. This project utilized information from markets, distribution system, as well as other resources such as weather and CAISO pricing, and in the future Area Control Error. These are all data sources that are influencing a distributed resource, and have not really been pulled together in this type of application in the past.

Field or Back Office Hosting

Storage is an interesting tool given the possible location on the distribution system, but the mature model potentially supports transmission and generation also. It is evident that power based controls should be autonomous and field based due to potential latency issues. However energy based controls, especially if mature and requiring numerous data inputs are best based in the back office with simple commands sent from there to distributed units. However, this brings into consideration where this resource would be controlled in the future. Currently the distribution control center may not accurately account for economics (markets, etc.). The transmission operator may not be able to accurately account for the needs of the local distribution system, and due to the size may not be able to fully integrate into the area control. Wholesale Marketing cannot take into account any reliability implications due to rules of Standards of Conduct.

7 Next Steps

- Use the PCS/Battery System to source/sink VARs, aligning project with smart inverter concepts that optimize the amount of storage needed
- Using the existing batteries, install an improved software and hardware configuration
- Import the PNM Area Control Error signal as an AUX input to the smoothing algorithm to test the smoothing battery capabilities. Goal would be to prove the ability to respond in a fast frequency response (FFR) mode per the directives of NERC BAL-003.
- Further the FFR capability by testing simultaneous PV smoothing and FFR through outside/inside loop control
- Link Prosperity to other activities at Mesa del Sol (former NEDO project) and other proximate research, pursuing demonstrations related to micro-grids and smart distributed resources.
- Demonstrations aligned to Economic Development   associated with for the Mesa del Sol Smart Grid effort
- Further analysis and development of back office coordination of distributed resources, development of a smart Grid based Distributed Energy Resource Management System (DERMS),
- Further advanced OpenDSS models and research correlation of load and PV penetration vs. need for voltage control and use of batteries. Align OpenDSS with ESVT
- Implement a low cost Si Camera/Analysis System with minute ahead cloud forecasting output in the smoothing algorithm and verify 50% reduction in energy use.

8 Appendices

8.1 Appendix A - Test Plans

Test Plan 1

1. Objectives
   a. Primary
      i. determine the optimum size of a Battery Energy Storage (BES) system vs amount of PV ramp rate mitigation provided for smoothing the power output of a 500kW PV system
      ii. determine the optimum algorithm for smoothing with respect to irradiance sensor versus PV and primary meters as the input control signal
      for maximum ramp rate mitigation

   b. Secondary

i. Translate findings to UNM GridLAB and OpenDSS models to further optimize smoothing in high penetration feeders
ii. Establish control path for sending ACE signal to BESS
iii. Establish methodology of automatically polling NOAA website for cloud cover prediction and incorporating into a database for algorithm use
iv. Correlate NOAA predictions to associate % cloud cover with cloud types
v. Balance battery capacity used vs. optimized voltage regulation for various cloud types

2. Scope/Requirements
   a. In Scope – East Penn CUBs smoothing function and CUB BESS, 500kW PV system, beginning and end of 12.47kV distribution feeder configurations
   b. Out of Scope –, East Penn CABs shifting function
3. Roles & Responsibilities
   a. Ecoult/East Penn – trigger battery operation, establish and refine control settings, provide UNM battery model parameters, provide optimized algorithm through continual feedback of test results
   b. PNM – provide operational system, data and system access
   c. Sandia National Labs– monitor demonstration and provide technical input
   d. UNM – provide modeled results and modify models as needed to match actual recorded demonstration data, assist in creating ability to strip NOAA data from forecasts and load into database – calibrate models based on actual data
   e. NNMC –
      i. capture and package pertinent data - separated for the individual steps depicted in the methodology,
      ii. correlate actual PV variability with NOAA % cloud cover forecast from day before,
      iii. perform optimization calculation for each test.
4. Assumptions
   a. Demonstration will isolate smoothing function of BESS system in order to demonstrate this smoothing function independently
   b. Test plan can be modified to accommodate shifting in later stages – 10 day window per subset assumes clouds will appear
   c. Irradiance sensors serve as baseline data, Primary kW serves as response to algorithm
   d. Increments of available BESS power capacity can be adjusted in order to demonstrate various output levels
   e. Demonstration period November 2011 to December 2014 will feature a wide variety of cloud types in each test period
   f. NOAA % cloud cover predictions are a good indicator of cloud types
   g. Feeder is stable and voltage stability from smoothing arises from mitigating ramp rates – this approach is translatable and applicable to high PV penetration feeders and will stabilize voltage in these situations
   h. Optimized regulation is based on ANSI Range A parameters

5. Constraints
    a. Not demonstrating on a high penetration feeder – results need to be translated via modeling
    b. Weather - Cloud types – demonstrations will need to correlate the % cloud cover with irradiance variation and cloud type is not a controlled variable
6. System Schematic
7. Use up to date system schematic for all demonstrations
8. Smoothing Algorithm - is revised iteration from SNL Memo 09 06 11
    a. Will be adjusted once per test period - current start version is _________
9. Equipment Requirements
    a. Points list alignment
        i. all Ion meters
        ii. field irradiance sensors
        iii. All met points
        iv. Data Acquisition System
        v. PI Data Base
        vi. Sharepoint portal
        vii. GridLAB
        viii. OpenDSS
    b. External data tags (data needed but not measured by DAQ)
        i. NOAA % cloud cover predictions
    c. 12.47kV Distribution System Configuration needs
        i. End of feeder
        ii. Beginning of feeder
10. Methodology
    a. Ensure BESS is receiving Primary Meter Voltage and kW, Irradiance values (averaged and sw sensor only)
    b. Ecoult keeps log of algorithm version and associated configurations within algorithm and associated dates of implementation
    c. Ecoult programs into BESS the increment of energy capacity for the dates and values in table below
    d. Capture data for the test period from PI, segregate for each test period and associate with NOAA predicted cloud cover data file for the dates of the test period
    e. Analyze each data set for each test period immediately after test period ends and assess the impact of smoothing for various battery capacities applied vs. mitigation of ramp rate –
        i. Assess test period data set – derive ramp rate from irradiance sensor change per second
        ii. Assess Primary meter kW for mitigation of ramp rate –
        iii. Graph irradiance sensor ramp rate vs primary meter ramp rate
        iv. Report data to PMO

f. Demonstration of ACE signal following will be intermittent and targeted to later phases in the project

g. Procedure – following table dictates parameters demonstrated and duration of each, if adequate

		Test Plan 1 Smoothing Control Source				4/7/2014 14:04				
test label	period	Feeder Configuration	irradiance sensor	PV Meter	ACE from PNM	Low Pass Filter or Moving Average	Increment of Battery Capacity	Maximum Duration (days)	Start Date	End Date
1BPV0.1	**1**	B		**x**		**MA**	10%	10	10/31/2011	11/10/2011
1BPV0.4	**1**	B		**x**		**MA**	40%	10	11/16/2011	11/26/2011
1BPV0.7	**1**	B		**x**		**MA**	70%	10	12/9/2011	12/28/2011
1BPV1	**1**	B		**x**		**MA**	100%	10	1/3/2012	1/13/2012
2BIRRA0.4	**2**	B	**averaged**			**MA**	40%	20	1/19/2012	2/8/2012
2BIRRA0.7	**2**	B	**averaged**			**MA**	70%	15	2/14/2012	2/29/2012
2BIRRA1	**2**	B	**averaged**			**MA**	100%	18	3/6/2012	3/24/2012
3BIRRSW0.4	**3**	B	**sw corner**			**MA**	40%	15	3/30/2012	4/14/2012
3BIRRSW0.7	**3**	B	**sw corner**			**MA**	70%	15	4/20/2012	5/5/2012
3BIRRSW1	**3**	B	**sw corner**			**MA**	100%	10	5/14/2012	5/24/2012
4BPV0.6	**4**	B		**x**		**MA**	60%	10	5/30/2012	6/9/2012
4BPV0.8	**4**	B		**x**		**MA**	80%	10	6/15/2012	6/25/2012
4BPV1	**4**	B		**x**		**MA**	100%	10	7/1/2012	7/11/2012
5BPV0.6	**5**	B		**x**		**MA**	60%	10	7/17/2012	7/27/2012
5BPV0.8	**5**	B		**x**		**MA**	80%	10	8/2/2012	8/12/2012
5BPV1	**5**	B		**x**		**MA**	100%	10	8/18/2012	8/28/2012
6BPV0.6	**6**	B		**x**		**MA**	60%	10	8/31/2012	9/10/2012
6BPV0.8	**6**	B		**x**		**MA**	80%	10	9/12/2012	10/7/2012
6BPV1	**6**	B		**x**		**MA**	100%	31	10/12/2012	11/12/2012
7BPV0.4	**7**	B		**x**		**LPF**	40%	20	11/18/2012	12/7/2012
7BPV0.6	**7**	B		**x**		**LPF**	60%	20	12/8/2012	1/7/2013
7BPV0.8	**7**	B		**x**		**LPF**	80%	20	1/11/2013	1/31/2013
8BPV0.8	**8**	B		**x**		**LPF**	80%	16	2/1/2013	2/17/2013
8BPV0.4	**8**	B		**x**		**LPF**	40%	6	2/18/2013	2/24/2013
8BPV0.6	**8**	B		**x**		**LPF**	60%	7	2/25/2013	3/4/2013
9EBEST0.8	**9**	B		**x**		**LPF**	80%	15	3/5/2013	3/20/2013
9EBEST1	**9**	B		**x**		**LPF**	100%	5	3/21/2013	4/2/2013
9EBEST0.4	**9**	B		**x**		**Best = MA**	40%	5	4/3/2013	4/8/2013
10EBEST0.6	**10**	B		**x**		**Best = MA**	60%	5	4/14/2013	4/19/2013
10EBEST0.8	**10**	B		**x**		**Best = MA**	80%	103	4/25/2013	8/6/2013
10EBEST0.8	**10**	B		**x**		**Best = MA**	80%	3	8/6/2013	8/9/2013
11EBEST0.8	**11**	B		**x**		**Best = MA**	80%	190	8/15/2013	2/21/2014

7/16/2012

a. For each test measure – all available in PI database
   i. PV Irradiance (all 6 points and average)
   ii. Primary meter Volts

iii. Primary meter kW
iv. PV meter Volts
v. PV meter kW
vi. Battery Meter kW
vii. Associated cloud prediction (via NOAA predicted % cloud cover)

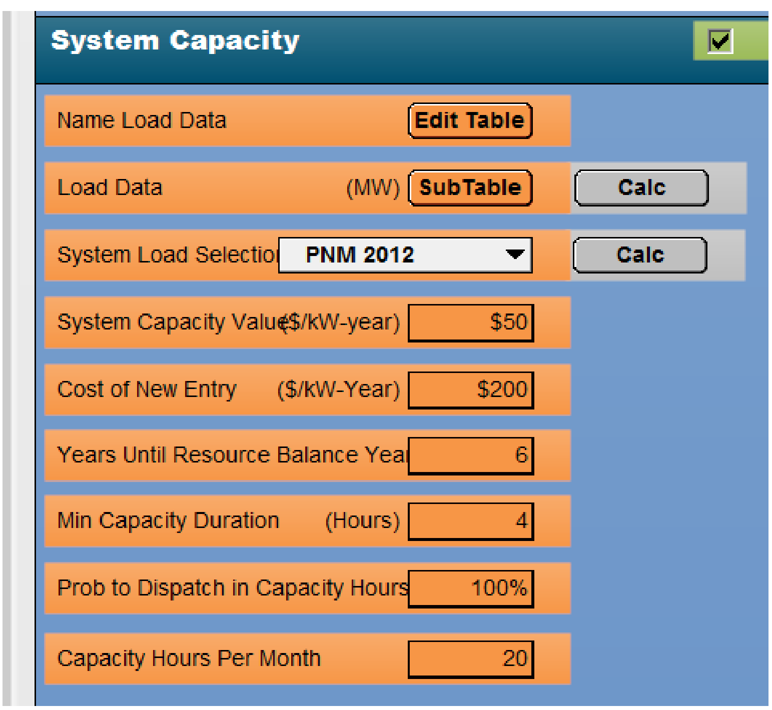
11. Deliverables
    a. For each subset period set (labeled test label) an analysis of ramp rate (change in output) derived from irradiance sensor average vs. associated ramp rates on primary meter kW – graphed for each day in test period with associated data set in excel file (NNMC) – 1 second intervals
    b. For each subset period a correlation analysis of NOAA predicted % cloud cover for a given day vs. actual irradiance average (NNMC)
    c. For each subset period in above table an optimization analysis graph showing the ramp rate mitigation for each configuration in the test plan (NNMC)
    d. For the overall test plan (excluding ACE input) an optimization analysis graph showing the ramp rate mitigation for all configurations tested (NNMC)
12. Reports
    a. Correlation analysis between NOAA cloud cover prediction and actual irradiance (NNMC)
    b. Optimization analysis for each subset (test label) (NNMC)
    c. Optimization analysis for overall test plan (NNMC)
    d. Overall test report for incorporation into DOE TPR periodically 12/11, 6/12/, 12/12, 6/13, 12/13,6/14, 12/14 (PNM)
    e. Inclusion of above reports in DOE Final Report (PNM)

Test Plans 2 – 5 Modified Versions

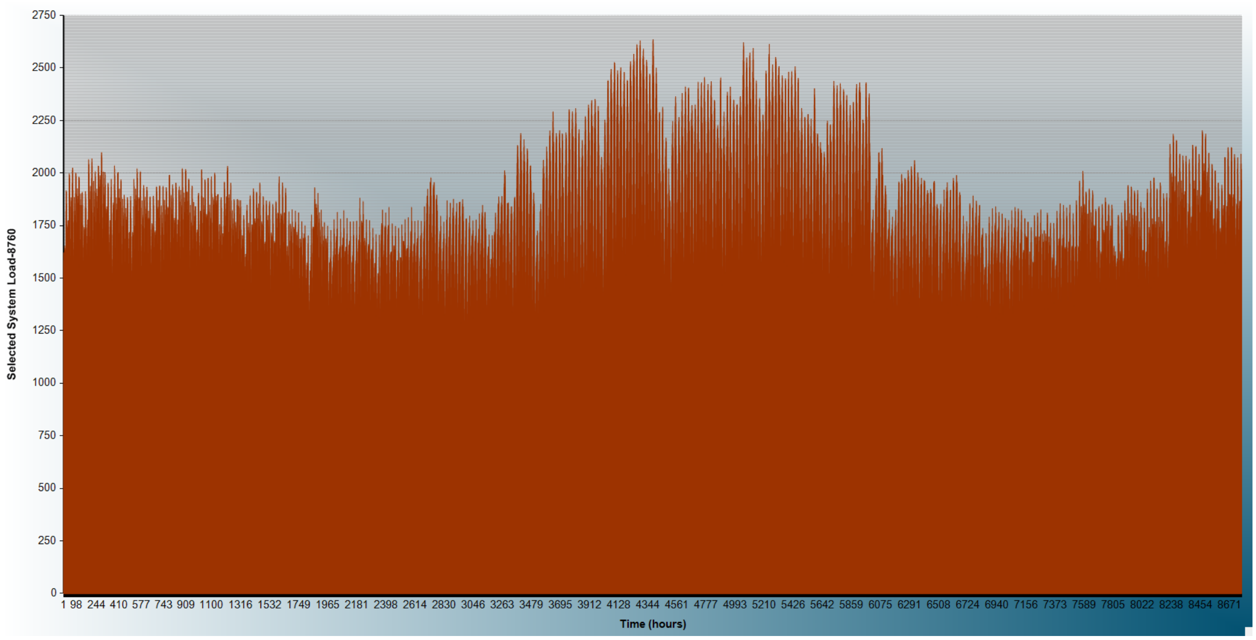
Redacted for Proprietary Considerations

8.2 Appendix B- ESVT Base Case Inputs

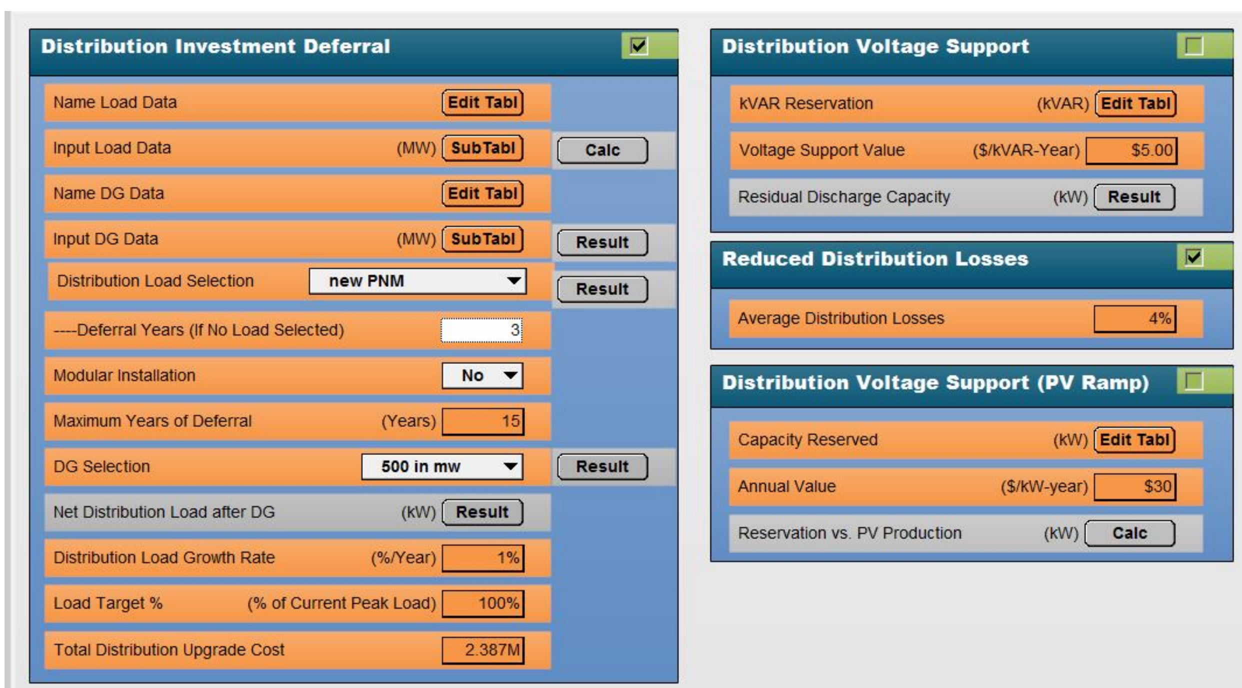
Screen Shot of System Services Selection



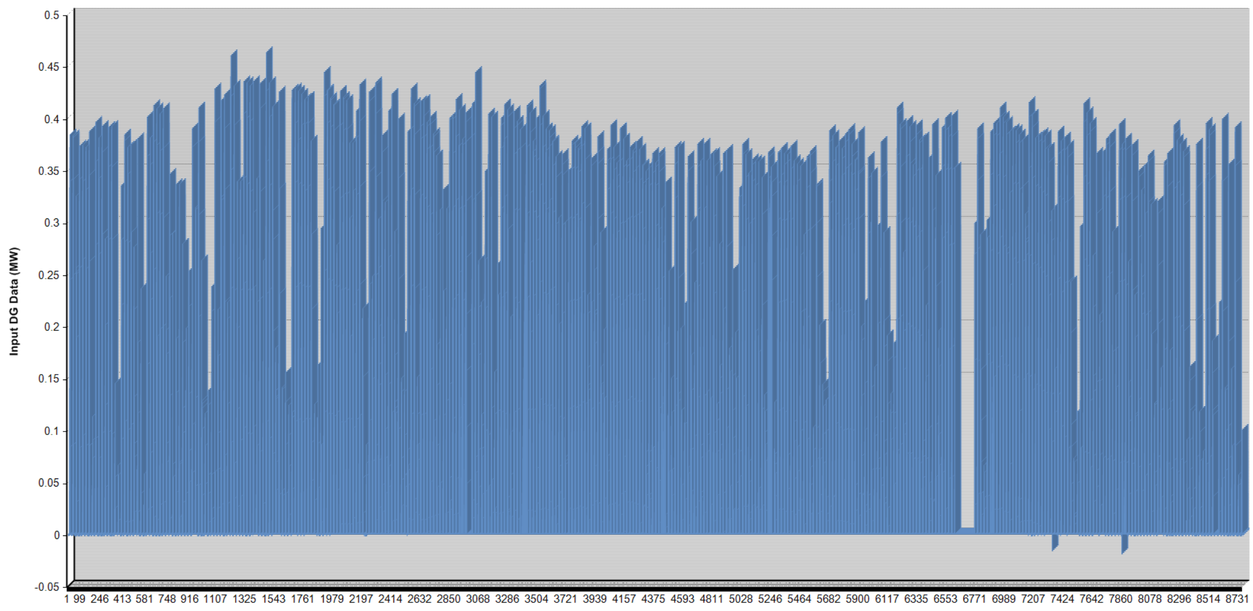
PNM 2012 System Profile



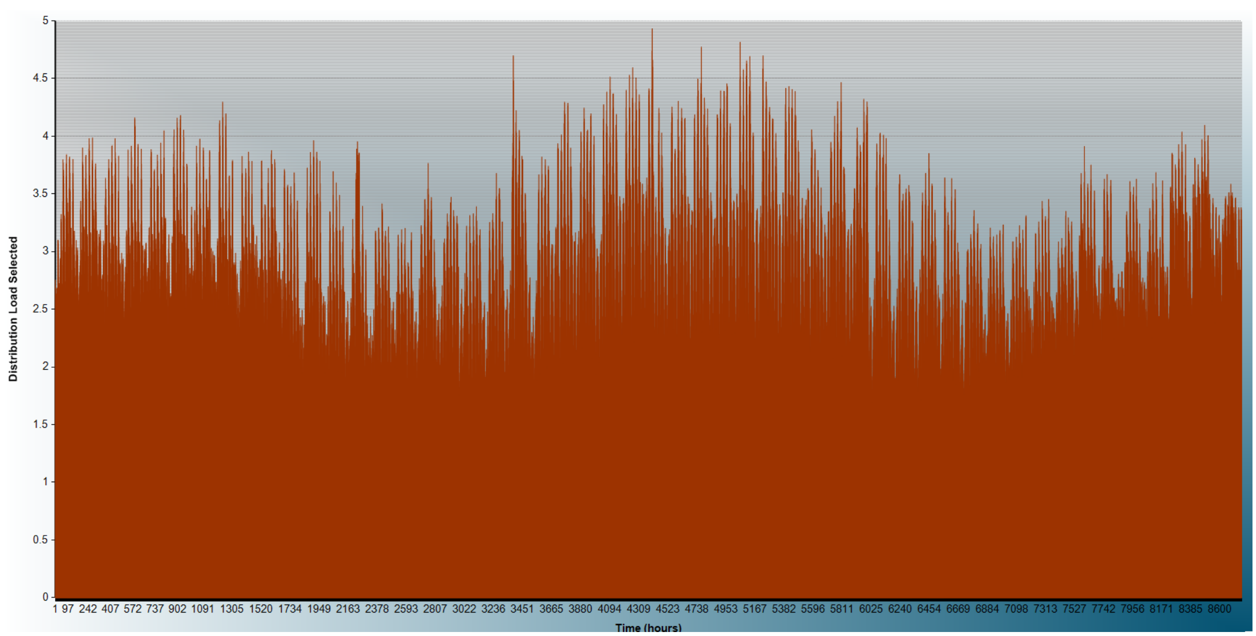
Distribution Inputs



Sewer Plant 14 Distribution Feeder 2012 Load Profile



Prosperity 500 kW PV Profile 2012



Financial Inputs

Financing Inputs

Ownership Type	IOU
% Debt	50%
Debt Rate	6.35%
% Equity	50%
Equity Rate	10%

Economic Inputs

Inflation Rate	(%/Year)	2.50%
Fuel Escalation Rate	(%/Year)	2.50%

Tax Inputs

Federal Income Tax Rate		35%
State Income Tax Rate		7.6%
Property Tax Rate		3.5%
MACRS Term	(Years)	5
Federal Investment Tax Credit	(%)	0%
% of Capital Cost Eligible for ITC	(%)	100%

Battery System Inputs

Maximum Plant Life	(Years)	10
Discharge Capacity	(kW)	215
Apparent Power Rating	(kVA)	225
Charge Capacity	(kW)	225
AC/AC roundtrip efficiency	(%)	85%
Discharge Duration	(Hours)	4
Maximum Depth of Discharge	(%)	80%
Installed Energy Storage	(kWh)	Calc
Housekeeping Power	(% dis. cap.)	5%

Capital Costs	($)	$2.622M
Capital Costs	($/kWh)	$0
Capital Costs	($/kW)	$0
System Capital Costs	($)	:$2,622,000
Variable O&M	($/MWh)	$0
Fixed O&M	($/kW-Year)	$10
Battery Replacement Costs	($/kWh)	$0
Replacement ...	(Reduction %/Year)	2%
Years Between Battery Replacement		3

8.3 Appendix C – ESVT Results & Financial Outputs

Base Case Pro Forma

Base Case Pro Forma										
Years	1	2	3	4	5	6	7	8	9	10
Utility_Pro_Forma2										
Capital Cost	$2,622,000	$0	$0	$0	$2,622,000	$0	$0	$0	$0	$2,622,000
Technology Replacement Fund	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Starting Rate Base	$2,622,000	$2,255,077.32	$1,762,487.42	$1,403,942.56	$1,125,824.71	$847,706.86	$629,909.28	$472,431.96	$314,954.64	$157,477.32
Accumulated Deferred Income Tax	($104,722.68)	($335,112.58)	($431,457.44)	($447,375.29)	($463,293.14)	($418,890.72)	($314,168.04)	($209,445.36)	($104,722.68)	($0.00)
Accumulated Depreciation	($262,200)	($524,400)	($786,600)	($1,048,800)	($1,311,000)	($1,573,200)	($1,835,400)	($2,097,600)	($2,359,800)	($2,622,000)
Ending Balance Rate Base	###########	$1,762,487.42	$1,403,942.56	$1,125,824.71	$847,706.86	$629,909.28	$472,431.96	$314,954.64	$157,477.32	$0
DEBT										
Beginning Balance	$1,311,000	$1,127,538.66	$881,243.71	$701,971.28	$562,912.36	$423,853.43	$314,954.64	$236,215.98	$157,477.32	$78,738.66
Interest	$83,248.50	$71,598.70	$55,958.98	$44,575.18	$35,744.93	$26,914.69	$19,999.62	$14,999.71	$9,999.81	$4,999.90
Principal	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100
EQUITY										
Beginning Balance	$1,311,000	$1,127,538.66	$881,243.71	$701,971.28	$562,912.36	$423,853.43	$314,954.64	$236,215.98	$157,477.32	$78,738.66
Equity Return	$131,100	$112,753.87	$88,124.37	$70,197.13	$56,291.24	$42,385.34	$31,495.46	$23,621.60	$15,747.73	$7,873.87
Return of Invested Equity	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100	$131,100
Book Equity Return	$262,200	$243,853.87	$219,224.37	$201,297.13	$187,391.24	$173,485.34	$162,595.46	$154,721.60	$146,847.73	$138,973.87
TAXES										
Equity Return	$131,100	$112,753.87	$88,124.37	$70,197.13	$56,291.24	$42,385.34	$31,495.46	$23,621.60	$15,747.73	$7,873.87
Tax on Equity Return	$52,361.34	$45,033.89	$35,196.87	$28,036.73	$22,482.72	$16,928.71	$12,579.29	$9,434.47	$6,289.64	$3,144.82
Amortized ITC	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Tax Grossup	$34,820.38	$29,947.61	$23,405.98	$18,644.47	$14,951.05	$11,257.62	$8,365.25	$6,273.94	$4,182.62	$2,091.31
REVENUE REQUIREMENT										
Variable O&M	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Charging Costs	$3,831.18	$3,966.81	$4,165.15	$4,373.41	$4,592.08	$4,821.69	$5,045.80	$5,277.52	$5,680.30	$5,964.32
Housekeeping Power	$2,667.97	$2,667.97	$2,667.97	$2,667.97	$2,667.97	$2,667.97	$2,667.97	$2,667.97	$2,667.97	$2,667.97
Fuel Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Fixed O&M	$2,150	$2,203.75	$2,258.84	$2,315.31	$2,373.20	$2,432.53	$2,493.34	$2,555.67	$2,619.57	$2,685.06
Interest Earned on Technology Replaceme	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Interest	$83,248.50	$71,598.70	$55,958.98	$44,575.18	$35,744.93	$26,914.69	$19,999.62	$14,999.71	$9,999.81	$4,999.90
Equity Return	$131,100	$112,753.87	$88,124.37	$70,197.13	$56,291.24	$42,385.34	$31,495.46	$23,621.60	$15,747.73	$7,873.87
Depreciation	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200
Tax on Equity Return-before grossup	$52,361.34	$45,033.89	$35,196.87	$28,036.73	$22,482.72	$16,928.71	$12,579.29	$9,434.47	$6,289.64	$3,144.82
ITC	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Tax Grossup	$34,820.38	$29,947.61	$23,405.98	$18,644.47	$14,951.05	$11,257.62	$8,365.25	$6,273.94	$4,182.62	$2,091.31
Total Revenue Requirement	$569,711.40	$527,704.64	$471,310.20	$430,342.24	$398,635.22	$366,940.57	$342,178.76	$324,362.91	$306,719.68	$288,959.28
ACCUMULATED DEFERRED INCOME TAX										
Book Depreciation	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200
MACRS Schedule	$0.20	$0.32	$0.19	$0.12	$0.12	$0.06	$0	$0	$0	$0
MACRS Depreciation	($524,400)	($839,040)	($503,424)	($302,054.40)	($302,054.40)	($151,027.20)	$0	$0	$0	$0
Deferred Tax-depreciation related	($104,722.68)	($230,389.90)	($96,344.87)	($15,917.85)	($15,917.85)	$44,402.42	$104,722.68	$104,722.68	$104,722.68	$104,722.68
ADIT-depreciation related	($104,722.68)	($335,112.58)	($431,457.44)	($447,375.29)	($463,293.14)	($418,890.72)	($314,168.04)	($209,445.36)	($104,722.68)	($0.00)
ITC-initial balance	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
ITC-amortization	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
ITC-ending balance	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
ADIT-total-for rate base adjustment	($104,722.68)	($335,112.58)	($431,457.44)	($447,375.29)	($463,293.14)	($418,890.72)	($314,168.04)	($209,445.36)	($104,722.68)	($0.00)
CHECK OF BOOK TAXES										
Revenue	$569,711.40	$527,704.64	$471,310.20	$430,342.24	$398,635.22	$366,940.57	$342,178.76	$324,362.91	$306,719.68	$288,959.28
Expenses	$5,981.18	$6,170.56	$6,424.00	$6,688.73	$6,965.28	$7,254.21	$7,539.14	$7,833.20	$8,299.87	$8,649.37
Operating Profit	$563,730.22	$521,534.08	$464,886.20	$423,653.51	$391,669.94	$359,686.36	$334,639.62	$316,529.71	$298,419.81	$280,309.90
Interest	$83,248.50	$71,598.70	$55,958.98	$44,575.18	$35,744.93	$26,914.69	$19,999.62	$14,999.71	$9,999.81	$4,999.90
Book Depreciation	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200	$262,200
Income	$218,281.72	$187,735.37	$146,727.22	$116,878.33	$93,725.00	$70,571.67	$52,440	$39,330	$26,220.00	$13,110.00
Taxes	$87,181.72	$74,981.51	$58,602.85	$46,681.21	$37,433.77	$28,186.32	$20,944.54	$15,708.40	$10,472.27	$5,236.13
ITC	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
After-Tax Income	$131,100.00	$112,753.87	$88,124.37	$70,197.13	$56,291.24	$42,385.34	$31,495.46	$23,621.60	$15,747.73	$7,873.87
CHECK OF BOOK EQUITY RETURN										
Earnings	$131,100.00	$112,753.87	$88,124.37	$70,197.13	$56,291.24	$42,385.34	$31,495.46	$23,621.60	$15,747.73	$7,873.87
Book Equity	$1,311,000	$1,127,538.66	$881,243.71	$701,971.28	$562,912.36	$423,853.43	$314,954.64	$236,215.98	$157,477.32	$78,738.66
ROE	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10

Sensitivity Analysis Summarized Output

Base Case	Utility Rev. Requirement (Variable)	$ 51,576.11	$ -
	Utility Rev. Requirement (Fixed)	$ 2,929,123.43	$ -
	Electricity Sales	$ -	$ 114,735.61
	Distribution Investment Deferral	$ -	$ 333,987.30
	Distribution Losses Reduction	$ -	$ 15.80
	System Electric Supply Capacity	$ -	$ 177,036.26
	Total	$ 2,980,699.54	$ 625,774.97
	assumes 60% AC/AC		
		Cost	Benefit
peak only	Utility Rev. Requirement (Variable)	$ -	$ -
	Utility Rev. Requirement (Fixed)	$ 2,929,123	$ -
	Electricity Sales	$ -	$ -
	Distribution Investment Deferral	$ -	$ 333,987
	Distribution Losses Reduction	$ -	$ -
	Total	$ 2,929,123	$ 333,987
arbitrage c	Utility Rev. Requirement (Variable)	$ 52,723	$ -
	Utility Rev. Requirement (Fixed)	$ 2,929,123	$ -
	Electricity Sales	$ -	$ 120,276
		$ 2,981,846	$ 120,276
4C System	Capacity Only	Benefit_Cost_Ra	Benefit_Cost_Ratio
		Selected Result	Sensitivity Outputs
		Cost	Benefit
	Utility Rev. Requirement (Variable)	5.29E+04	$0
	Utility Rev. Requirement (Fixed)	2.93E+06	$0
	Electricity Sales	$0	1.20E+05
	System Electric Supply Capacity	$0	2.02E+05
	Total	2.98E+06	3.22E+05

ESVT Sensitivity Outputs

		Base Case		Cap Cost	AC/AC eff	Fix O&M
1A	Low	0.209942318	0.360791817	1.5M	60%	10
All Aplications	High	0.209942318	0.184021186	3M	60%	10
	Total	0.419884636	0.544813003			
1B	Low	0.209942318	1.101383818	450k	60%	10
All Applications	High	0.209942318	0.184021186	3M	60%	10
Breakeven Cap Target	Total	0.419884636	1.285405004			
2A	Low	0.419884636	0.568379198	1.5M	55%	10
hi eff, low cost	High	0.419884636	0.408054514	3M	80%	10
combination sensitibvity (1)	Total	0.839769271	0.976433711			
2B	Low	0.419884636	0.584825144	1.5M	80%	10
hi eff, low cost	High	0.419884636	0.391608567	3M	55%	10
combination sensitibvity (2)	Total	0.839769271	0.976433711			
2C	Low	0.216248869	0.370509003	1.5M	70%	10
medium efficiency	High	0.216248869	0.18964766	3M	70%	10
	Total	0.432497737	0.560156663			
2D	Low	0.207307132	0.356708819	1.5M	55%	10
lo efficiency	High	0.207307132	0.18167236	3M	55%	10
	Total	0.414614263	0.538381179			
3A	Low	0.2105343	0.362543691	1.5M	60%	5
Low O & M Cost	High	0.2105343	0.184475853	3M	60%	5
	Total	0.4210686	0.547019543			
3B	Low	0.209353655	0.359056792	1.5M	60%	15
High O & M Cost	High	0.209353655	0.183568755	3M	60%	15
	Total	0.418707311	0.542625547			
4A	Low	0.114022953	0.198462597	1.5M	60%	10
peak shaving only	High	0.114022953	0.09972797	3M	60%	10
	Total	0.228045907	0.298190567			
4B	Low	0.040336087	0.06929956	1.5M	60%	10
arbitrage only	High	0.040336087	0.035357554	3M	60%	10
	Total	0.080672173	0.104657115			
1C	Low	0.222413501	1.027123504	500k	80%	10
hi efficency	High	0.222413501	0.195174772	3M	80%	10
target breakeven cost	Total	0.444827002	1.222298277			
4C	Low	0.108	0.185502361	1.5M	60%	10
system capacity	High	0.108	0.094650456	3M	60%	10
	Total	0.216	0.280152817			

EPA AVERT Environmental Emissions Valuation

Assume these are $/ton
Market prices emissions 2/20/14

CAIR SO2 Spot Market, 2014 vintage: Bid, $0.70; Offer $0.75
CAIR NOx Seasonal, 2014 vintage: Bid, $15; Offer, $22
CAIR NOx Annual, 2014 vintage: Bid, $43; Offer, $45
RGGI Spot Market, 2014 vintage: Bid $3.50; Offer, $3.70
CCA ICE V13 Dec 14 Delivery: Bid, $12.20; Offer, $12.30

Total Emissions	Pre	Post	Delta	Benefit
SO_2 (lbs)	96,560,400	96,560,100	300	$ 0.11
NO_x (lbs)	228,134,400	228,133,500	800	$ 18.00
CO_2 (tons)	103,612,700	103,612,000	600	$ 7,380.00
Emission Rates				
SO_2 (lbs/MWh)	0.715	0.715		
NO_x (lbs/MWh)	1.69	1.69		
CO_2 (tons/MWh)	0.768	0.768		
			Total	$ 7,398.11

	1	2	3	4	5	6	7	8	9	10
yr	1	2	3	4	5	6	7	8	9	10
	$ 7,398.11	7250.143	7105.14	6963.037	6823.776	6687.301	6553.555	6422.484	6294.034	6168.153
NPV	$45,583.56									
dis rate	8.2%									

Base Case	Utility Rev. Requirement (Variable)	$ 51,576.11	$ -
	Utility Rev. Requirement (Fixed)	$ 2,929,123.43	$ -
	Electricity Sales	$ -	$ 114,735.61
	Distribution Investment Deferral	$ -	$ 333,987.30
	Distribution Losses Reduction	$ -	$ 15.80
	System Electric Supply Capacity	$ -	$ 177,036.26
	Emmission offset		$45,583.56
	Total	$ 2,980,699.54	$ 671,358.53
	assumes 60% AC/AC		
		change in benefits	7%

8.4 Appendix D - Energy Storage Computational Tool

Inputs Screen – Asset Characterization Cost Parameters

Please enter the cost parameters for the energy storage deployment.

What is the expected lifetime (years) of this deployment?	10	years	Use Default Value	
Please enter the average inflation rate (%) that will be used in the economic calculations.	2	%	Use Default Value	Definition
Please enter the discount rate (%) that will be used in the net present value analysis.	8.2	%	Use Default Value	Definition
Please enter the total installed cost ($) of the deployment.	2,660,000	$	Use Default Value	
Please enter the fixed charge rate (%) that will be used to annualize the cost of the deployment.	9	%	Use Default Value	
Please enter the average yearly operating and maintenance costs ($/year) not related to energy. These costs may include may include fixed and variable operations and maintenance costs as well as replacement costs.	5,000	$/year	Use Default Value	
If you would prefer to enter a custom operating and maintenance cost schedule please check the box to the right.	☐			
Please enter the expected decommissioning and disposal costs ($) in current nominal dollars.	0	$	Use Default Value	
Please enter the initial year (20xx) of this analysis.	2011	Year		

Previous Exit Next

Run CM with Sensitivity Case Inputs | View Sensitivity Results | Reset all values to 100%

		Select % using toggle			2011 Values		
Input Name	**Unit**	**Low**	**Reference**	**High**	**Low**	**Reference**	**High**
Average Variable Peak Generation Costs	$/MWh	100%	100%	100%	$ 70	$ 70	$ 70
CO2 Emissions Factor for Generation on the Margin	lbs/MWh	100%	100%	100%	1,536	1,536	1,536
SOx Emissions Factor for Generation on the Margin	lbs/MWh	100%	100%	100%	0.715	0.715	0.715
NOx Emissions Factor for Generation on the Margin	lbs/MWh	100%	100%	100%	1.69	1.69	1.69
PM Emissions Factor for Generation on the Margin	lbs/MWh	100%	100%	100%	-	-	-
Value of CO2	$/ton	100%	100%	100%	$ 12	$ 12	$ 12
Value of SOx	$/ton	100%	100%	100%	$ 1	$ 1	$ 1
Value of NOx	$/ton	100%	100%	100%	$ 15	$ 15	$ 15
Value of PM	$/ton	100%	100%	100%	$ -	$ -	$ -
Distribution Capacity Deferred	kVA	100%	100%	100%	50	50	50
Annual Fixed Charge Rate for Distribution Capital Investment	%	100%	100%	100%	0	0	0
Capital Cost of Deferred Distribution Capacity	$/kVA	100%	100%	100%	$ 50,000	$ 50,000	$ 50,000
Yearly O&M Costs of Deferred Distribution Capacity	$/year	100%	100%	100%	$ 10,000	$ 10,000	$ 10,000
Initial Year of Distribution Deferral	year	100%	100%	100%	2013	2013	2013
Final year of Distribution Deferral	year	100%	100%	100%	2015	2015	2015
Average Variable Renewable Generation Costs	$/MW	100%	100%	100%	$ 2	$ 2	$ 2
Total Renewable Energy Discharged for Arbitrage	MWh	100%	100%	100%	100,000	100,000	100,000
Total Renewable Energy Discharged for Energy Time-Shift	MWh	100%	100%	100%	500,000	500,000	500,000
Capital Cost of Conventional Electric Service Reliability Solution	$/kW	100%	100%	100%	$ 1	$ 1	$ 1
Annual Fixed Charge Rate for Electric Service Reliability Capital Investment	%	100%	100%	100%	1	1	1

Output Screens

Reference Case Output: Annual and Cumulative Results Tables

The tables below display the annual and cumulative project benefits and costs. The benefits are organized by category. The total gross benefit, total cost, and net benefit are also displayed at the bottom of each chart. All values are present value terms. To calculate additional benefits navigate to the additional benefits worksheets from the Additional Benefits tab.

Annual Benefit and Cost

	Benefits	Additional Benefits - Total Present Value over the Deployment Period	+	Primary and Secondary Benefits - Total Present Value over the	=	Total Benefit - Present Value over the Deployment	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Market Revenue	Arbitrage Revenue	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Capacity Market Revenue	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Ancillary Services Revenue	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Improved Asset Utilization	Optimized Generator Operation (Non-Utility	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Optimized Generator Operation	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Deferred Generation Capacity Investments	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced Congestion Costs (Non-Utility Merchant)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced Congestion Costs (Utility/Ratepayer)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
T&D Capital Savings	Deferred Transmission Investments	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Deferred Distribution Investments	$ -		$ 84,600		$ 84,600	$ -	$ -	$ 25,300	$ 30,900	$ 28,400	$ -	$ -	$ -	$ -	$ -
Energy Efficiency	Reduced Electricity Losses	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Electricity Cost Savings	Reduced Electricity Cost (Consumer)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced Electricity Cost (Utility/Ratepayer)	$ -		$ 506,000		$ 506,000	$ 58,900	$ 58,000	$ 56,900	$ 55,500	$ 54,000	$ 50,600	$ 47,400	$ 44,300	$ 41,500	$ 38,900
Power Interruptions	Reduced Outages (Consumer)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced Outages (Utility/Ratepayer)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Power Quality	Improved Power Quality	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Air Emissions	Reduced CO2 Emissions	$ -		$ 57,400		$ 57,400	$ 8,000	$ 7,300	$ 6,700	$ 6,200	$ 5,700	$ 5,300	$ 5,000	$ 4,700	$ 4,400	$ 4,100
	Reduced SOx Emissions	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced NOx Emissions	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced PM Emissions	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Total Gross Benefit	**$ -**		**$ 648,000**		**$ 648,000**	**$ 66,900**	**$ 65,300**	**$ 88,900**	**$ 92,600**	**$ 88,100**	**$ 55,900**	**$ 52,400**	**$ 49,000**	**$ 45,900**	**$ 43,000**
	Costs															
	Capital Cost of Deployment (fixed charge rate)					$ 1,678,500	$ 239,400	$ 219,800	$ 201,700	$ 185,200	$ 170,000	$ 156,100	$ 143,300	$ 131,500	$ 120,700	$ 110,800
	Operating and maintenance costs not related to energy (labor for operation, plant maintenance, equipment wear leading to loss-of-life)					$ 35,100	$ 5,000	$ 4,600	$ 4,200	$ 3,900	$ 3,600	$ 3,300	$ 3,000	$ 2,700	$ 2,500	$ 2,300
	Decommissioning and Disposal Costs					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Total Annual Cost of Deployment					**$ 1,713,900**	**$ 244,400**	**$ 224,400**	**$ 206,000**	**$ 189,100**	**$ 173,600**	**$ 159,300**	**$ 146,300**	**$ 134,300**	**$ 123,300**	**$ 113,200**
	Total Net Benefit					**$ (1,065,900)**	**$ (177,500)**	**$ (159,100)**	**$ (117,100)**	**$ (96,500)**	**$ (85,500)**	**######**	**$ (93,900)**	**$ (85,300)**	**$ (77,400)**	**$ (70,200)**

Cumulative Benefit and

	Benefits	Additional Benefits - Total Present Value over the Deployment Period	+	Primary and Secondary Benefits - Total Present Value over the	=	Total Benefit - Present Value over the Deployment	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Market Revenue	Arbitrage Revenue	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Capacity Market Revenue	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Ancillary Services Revenue	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Improved Asset Utilization	Optimized Generator Operation (Non-Utility	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Optimized Generator Operation	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Deferred Generation Capacity Investments	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced Congestion Costs (Non-Utility Merchant)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced Congestion Costs (Utility/Ratepayer)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
T&D Capital Savings	Deferred Transmission Investments	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Deferred Distribution Investments	$ -		$ 84,600		$ 84,600.00	$ -	$ -	$ 25,300	$ 56,200	$ 84,600	$ 84,600	$ 84,600	$ 84,600	$ 84,600	$ 84,600
Energy Efficiency	Reduced Electricity Losses	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Electricity Cost Savings	Reduced Electricity Cost (Consumer)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced Electricity Cost (Utility/Ratepayer)	$ -		$ 506,000		$ 506,000.00	$ 58,900	$ 116,900	$ 173,800	$ 229,300	$ 283,300	$ 333,900	$ 381,300	$ 425,600	$ 467,100	$ 506,000
Power Interruptions	Reduced Outages (Consumer)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced Outages (Utility/Ratepayer)	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Power Quality	Improved Power Quality	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Air Emissions	Reduced CO2 Emissions	$ -		$ 57,400		$ 57,400.00	$ 8,000	$ 15,300	$ 22,000	$ 28,200	$ 33,900	$ 39,200	$ 44,200	$ 48,900	$ 53,300	$ 57,400
	Reduced SOx Emissions	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced NOx Emissions	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Reduced PM Emissions	$ -		$ -		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Total Gross Benefit	**$ -**		**$ 648,000**		**$ 648,000.00**	**$ 66,900**	**$ 132,200**	**$ 221,100**	**$ 313,700**	**$ 401,800**	**$ 457,700**	**$ 510,100**	**$ 559,100**	**$ 605,000**	**$ 648,000**
	Costs															
	Capital Cost of Deployment (fixed charge rate)					$ 1,678,500.00	$ 239,400	$ 459,200	$ 660,900	$ 846,100	$ 1,016,100	$ 1,172,200	$ 1,315,500	$ 1,447,000	$ 1,567,700	$ 1,678,500
	Operating and maintenance costs not related to energy (labor for operation, plant maintenance, equipment wear leading to loss-					$ 35,100.00	$ 5,000	$ 9,600	$ 13,800	$ 17,700	$ 21,300	$ 24,600	$ 27,600	$ 30,300	$ 32,800	$ 35,100
	Decommissioning and Disposal Costs					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Total Annual Cost of Deployment					**$ 1,713,900.00**	**$ 244,400**	**$ 468,800**	**$ 674,800**	**$ 863,900**	**######**	**######**	**######**	**######**	**######**	**######**
	Total Net Benefit					**$ (1,065,900.00)**	**$ (177,500)**	**######**	**######**	**######**	**######**	**$(739,100)**	**######**	**######**	**######**	**######**

8.5 Appendix E - Annotated Methodologies for Determining Technical Performance - Extracted from PNM Interim TPR

Smoothing Algorithm Modeling

Smoothing Modeling – Moving Average and Moving Median Algorithms

The PV output ramp rate depends greatly on cloud cover and cloud type conditions. For a partly cloudy day, the PV system output could fluctuate significantly and rapidly. An important concern with the control of BESS is the charge/discharge rates (or `ramping' rates) capability that the battery needs to have to effectively smooth out the ramp of PV output.

The purpose of smoothing algorithm is to mitigate abrupt changes in PV power output due to clouds moving over the footprint of the PV array. Figure 42 below shows an example of such smoothing.

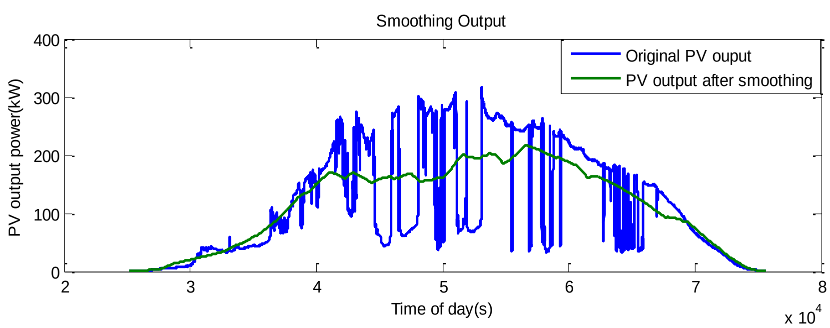
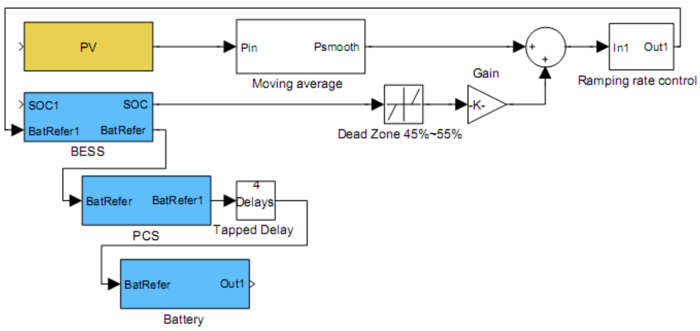


Figure 42 - Example of Modeled Smoothing.

Four different smoothing algorithms are being investigated in the scope of this project: moving average, double moving average, moving median and double moving median. A flowchart for a moving average smoothing algorithm is shown in the Figure 43 below.



.

Figure 43 – Modeled Smoothing

The smoothing battery will see short duration charges and discharges. Its performance is best characterized by its ability to supply rated power (+/-) while maintaining its SoC within upper and lower limits such that when averaged over a 1 hour period its SoC remains at the nominal rating. Several smoothing battery real-time control algorithms have been modeled and are currently being implemented at the test site.

For each of these algorithms, the following parameters are being evaluated as a metric: PV output variance, battery SoC, battery ramping rates, number and depth of battery cycles. A restoring power function is used to slowly drive the battery to the nominal SoC.

The restoring power needs will change dynamically with the change of SoC every second. First, the true restoring power is calculated according to the difference between the real time SoC and a set value. Then available battery capacity is calculated based on battery size, also setting different power rates to offset the difference. If the power rate is too big, it may lead to oscillation of the SoC. If it's too small, it may not offset the difference in a timely fashion. Here, we choose a factor: a, which refers to the weight of restoring power. Different values of : 3, 4, and 5 were iterated for this variable. Secondly, a moving average is used to make the restoring power smooth and not affecting the smoothing operation of the battery.

Smoothing Modeling – Moving Average and Low Pass Filters Algorithms - SNL Analysis

This algorithm was designed to be implementable in a real-time controller. The algorithm can switch between moving average (MA) and low-pass filter (LPF) modes. The operating schema is as follows: A separate battery energy storage system (BESS) commands the battery power level based on a power reference computed by the smoothing algorithm. The smoothing algorithm can be configured to compute the reference signal that the control system is trying to track, either a moving average (MA) of the PV power, or the PV power processed through a low pass filter (LPF). The control system has a supervisory function that tracks the state of charge (SoC) and slowly drives it to a reference SoC, thus maintaining the control range of the battery. To improve the robustness and minimize battery cycling, a dead band function was added to the battery control system. The dead band function will prevent the battery from responding to small excursions that are too small to warrant control action. The control structure has two additional inputs to which the battery can respond. For example, the battery could respond to PV variability, load variability, area control error (ACE) or a combination of the three. Figure 44 below shows the general control algorithm.

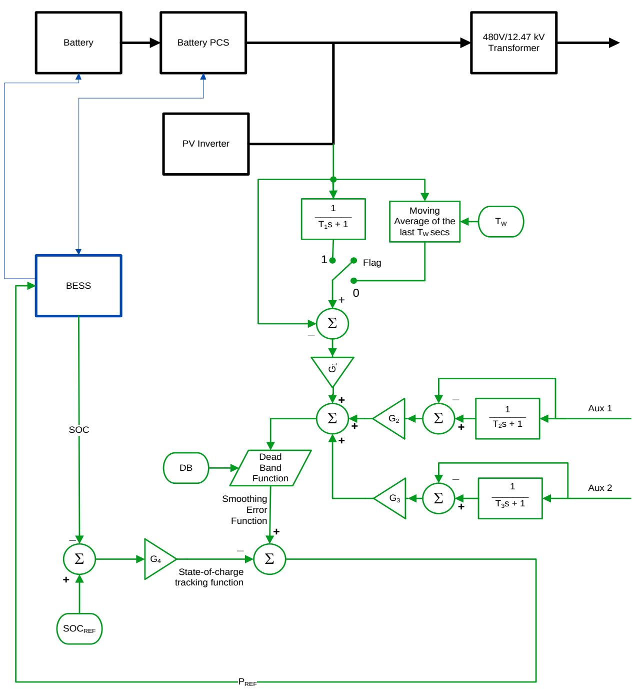


Figure 44 Diagram of PV smoothing control algorithm

The initial condition of the accumulator is set to the desired reference SoC value within the allowable range. For this application, a point in the middle of the range was chosen. A time delay was used as a simple way to represent the response time of the BESS and controls in the power electronic devices. The delay is represented by a time constant TBESS. In this specific application, it is assumed that the delay is on the order of 1 sec. The power rating of the power electronics are modeled with a simple power limiter, set to +/- 500 kW, in this particular case.

The BESS ultimately commands the battery power level based on a power reference computed by the smoothing algorithm. The BESS takes the desired battery power computed by the smoothing algorithm and updates the battery reference power. The battery is assumed to respond to the time constant TBESS. A saturation function is applied to limit the requested battery power to no more than the rating of the power electronics interface (+/-500 kW). The default parameters in Table 1 were derived assuming a control system sampling rate of 1 second, and for the specific application considered during testing.

Symbol	Name	Units	Default Value
TW	PV Moving Average Time Window	Seconds	3600 (1 hour)
T1	PV Low Pass Filter Time Constant	Seconds	3600 (1 hour)
T2	AUX1 (load) Low Pass Filter Time Constant	Seconds	3600 (1 hour)
T3	AUX2 (ACE) Low Pass Filter Time Constant	Seconds	0
Flag	Switch between LPF and MA	0 or 1, 0=use MA, 1=use LPF	1 (use LPF)
G1	PV Smoothing Error Gain	unit less	1 (for 100% compensation)
G2	AUX1 (load) Scaling Factor	unit less	depends on magnitude of AUX1 signal
G3	AUX2 (ACE) Scaling Factor	unit less	Depends on magnitude of AUX2 signal
G4	SoC Tracking Gain	unit less	1000
DB	Dead Band Width	kW	+/- 50 (in models)
SoCREF	Reference State of Charge	unit less (within defined SoC limits)	

Table 22 - Parameters for PV Smoothing Algorithm.

Feeder Modeling

Feeder modeling is a key element of the project. The feeder models help validate control algorithm implementation but also serve as a platform for extending the field results to actual high penetration feeders as well as providing a basis for determining status quo equipment requirements which will be used in optimization and cost/benefit analysis.

The project feeder modeling effort utilizes OpenDSS from EPRI and Gridlab-D™ by Pacific Northwest National Lab (PNNL). Both are open source software packages developed mainly to provide tools for modeling distribution systems which are not necessarily balanced.

OpenDSS is a power flow solver which has various capabilities such as fault analysis, harmonic analysis and time based analysis in snap shot, daily or longer term modes. It can be used as a COM object to provide more versatility for other software to be used for further analysis.

Gridlab-D is agent based software which provides numerous analysis and decision making options to the user. In Gridlab-D detailed properties of different types of loads could be modified to make a better match with the real system. Both software tools have the ability to perform time series analysis as opposed to simply solving power flow problem sequentially. This allows for daily, weekly and annual analyses. The process used models of the feeders for both software packages to take better advantage of the individual model capabilities of each and to compare the results as a calibration and verification effort.

PNM data, relating to the feeder's topology, was provided in an unprocessed comma-separated values (CSV) file format. Conductors, transformers, switches, capacitors and other assets are extracted as circuit features into separate files. The data was extracted from PNM's GIS databases, which are not designed to provide standard output to be fed directly into the modeling software. Therefore, the circuit's information had to be translated from CSV files to an interpretable script. The very first step was to develop translator software. Translator applications were developed for both software packages that are capable of building the basic model of each feeder under study.

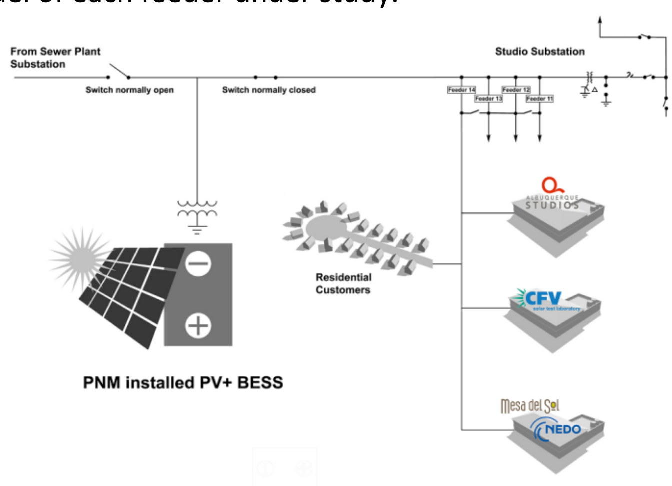


Figure 45 - PNM Smart Grid Demonstration Project – highlighting the associated feeders

Figure 45 above details the layout of the system with respect to feeders served. SewerPlant14 and Studio14 are two of the distribution feeders of the city of Albuquerque, New Mexico serving the site and being subsequently modeled. Those feeders were expected to have different characteristics as they connect to the Smart Grid Demonstration site, due to :

- SewerPlant14 serves a fully developed residential/commercial area while Studio14 is still under development.
- PNM PV system could be connected to SewerPlant14's end point while it could be connected to the beginning of Studio14

A mixed number of residential and commercial customers comprise the load connected to SewerPlant14 feeder. Due to limited information about each individual customer's consumption behavior, an exact load model was not able to be determined for each customer. However, load seen at the substation, but not individual loads was of primary interest. Therefore it was concluded that total load seen at the substation transformer could be a good base case for building load shapes that could be expected to be seen at each customer's service drop. This feeder's total demand and energy consumption, recorded every 15 minutes, was the primary data to develop load models. Feeder's load shape was generated by normalizing 15-minutes demand data based on the feeder's nominal rating and is shown in Fig. 46..

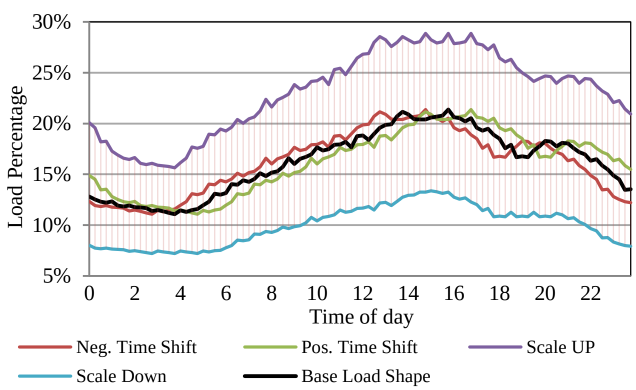


Fig. 46. SewerPlant14 Base Load Shape (Thursday, Sep., 2, 2010)

One heuristic approach for approximating each customer's load shape was to shift the base load shape randomly for a limited time, while randomly changing the load shape's magnitude within a certain percentage of the base load shape, i.e. if basic load percentage at any given time t was $l_b(t)$ load percentage for customer i at that time would be:

$\boldsymbol{l_i(t) = l_b\big(t + \alpha_i(t)\big).\beta_i(t)}$ Equation 1

$\boldsymbol{\alpha_i(t) = G1(\Delta)_i}$ Equation 2

$\boldsymbol{\beta_i(t) = G2(\sigma, t)_i}$ Equation 3

Visual representation of equation resulted in upper and lower boundaries which are shown in Fig. 46. Upper and lower bounds show the maximum and minimum possible load percentages for the each load while any point in the hashed area is a possible point for a load shape. Δ and σ are distribution function's parameters.

In order to properly analyze the feeder's behavior with required resolution, the load shapes must have an equal or higher resolution than metered data. Feeder demand data, from the existing SCADA system, was recorded every 15 minutes, while at least 1-minute interval data was desired for analysis. Missing data points were found by extrapolation between available load data points, assuming that feeder load has a smooth transition between every 2 consecutive points. Finer time steps could easily be generated when necessary but higher resolution must be balanced with the required processing burden. In the future, shorter step analysis may be needed for generation intermittency effects studies.

Different levels of scaling and time shifting has been studied. In Figure 47, a randomly selected customer's load shape after ±1 hour time shift and ±65% magnitude scaling is presented.

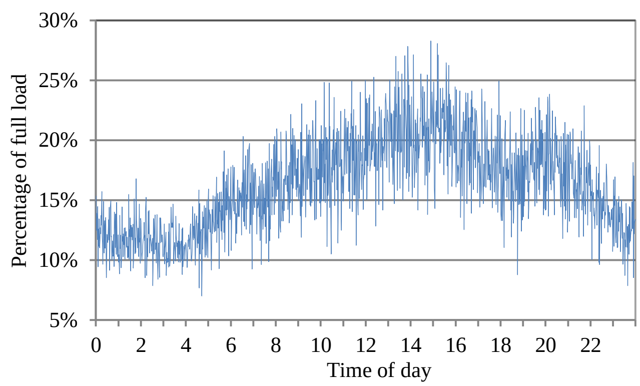


Figure 47 - Generated load shape for a random customer (scaled to service transformer's rating)

Adding Loads to the Model

Having developed those load shapes, the next step was to add loads to the model. Loads, associated with a load shape, represent customers in the model. For that purpose, PNM has provided a detailed list of premises, which was used to define load objects in the models. Each premise came with an identifier plus the identity of the transformer, supplying that load. Although adding loads to the models looked to be a trivial job, because of many constraints, it was almost impossible to assign nominal load capacity to each customer. Service nominal amperage (capacity) was known but normally that value could give a sense of maximum load, not actual values. An allocation method is used to find each customer's allocated load versus its supplying transformer's rating. The allocation procedure was performed by OpenDSS, which has a built-in function which could optimize load multipliers to meet a specific load at specific zone. All loads were allocated with respect to maximum feeder capacity to serve .

$$\boldsymbol{Feeder\ Nominal\ Capacity} = \sum_{i=1}^{n} \boldsymbol{m_i.T_i} + \boldsymbol{Full\ Load\ Loss} \qquad \text{Equation 4}$$

m_i: *load multiplier for customer i*

T_i: *nominal transformer rating feeding customer i*

According to Figure 47 the developed load shape has a high frequency of variation which is not a realistic assumption for loads expected at the distribution level. Loads usually don't exhibit such a high frequency of variations. For this reason, a metric was defined to depict average time duration between two consecutive changes in the load level and named it load response times (LRT). Several case studies to see effects of different LRTs on the cumulative load seen at the feeder source were conducted.

PV Ramp Rate Analysis Methodology

Methodology Overview

For this analysis, ramp rate is defined as the instantaneous rate of change in power. In the case of a solar array, the ramp rate (in power/time) can be taken from either total array output power (in W) or nominalized to effective array area by using irradiance (in W/m2). For this analysis and applicability to solar arrays of all sizes, ramp rates will be expressed in W/m2/s.

Statistical Comparison of Ramp Rate Analysis

In order to gauge the effectiveness of the smoothing battery it is necessary to understand the ramp rates produced by the PV system and the effect of varied input signals and corresponding output levels applied by the smoothing battery.

The first question that needs to be addressed is a working definition of ramp rate. These can range from a simple differencing of consecutive measurements to, e.g., an averaging of these differences over some *a priori* specified time range. The approach taken is to use smoothing splines that interpolate the data first. By controlling a single parameter in the spline definition the degree of smoothing of the raw data can vary from minimal (the data is perfectly interpolated, so there is no smoothing) to maximal (a linear regression line is fit to the day's measurements). Taking the derivatives of the splines at specified points will give an estimate of the ramp rate. Comparison of this method to the simple differencing method shows that they give similar results when the splines are not smoothed. However, being able to conveniently control the degree of smoothing is a distinct advantage of using splines.

When considering the effects of various independent variables on smoothing efficacy the first question to answer is how to measure the overall level of smoothing. One possible measure is the largest ramp rate observed both before and after smoothing. However this would place all of the analysis on a single, potentially isolated, event and would likely not give a good picture of what occurred over the whole day.

The measurements being compared are the magnitudes of all of the observed daily ramp rates before smoothing and after smoothing. Empirical Cumulative Distribution Functions (ECDFs) are then formed for each of these collections. These are denoted as ECDFs as $ECDF_{PV}$ for the ramp rates observed with the PV meter measurements and $ECDF_{PM}$ for the ramp rates observed with the Primary Meter measurements. Given these two ECDFs the final scalar value we find is the area between 1 and $ECDF_{PM}$ as a percentage of the area between 1 and $ECDF_{PV}$:

$$A = \frac{\int_0^\infty \left(1 - ECDF_{PM}\right) dr}{\int_0^\infty \left(1 - ECDF_{PV}\right) dr} \qquad \text{Equation 5}$$

This is a dimensionless quantity that helps to compare the effects of smoothing while cancelling out, to some extent, variations from day to day in the $ECDF_{PV}$. A value of *A* close to 0 indicates good performance on smoothing. As *A* nears or exceeds 1 the smoothing was less effective for that day.

With *A* as the dependent variable the following are the independent variables considered:

- Smoothing control source (a categorical independent variable)
- Cloud cover (an ordinal or a ratio independent variable)
- Increment of battery capacity (an ordinal or a ratio independent variable)
- Potentially season (an categorical variable)

Note that the type of variable for each independent variable is included. For cloud cover and increment of battery capacity we will likely treat these as ratio variables. Seasonality effects will initially be ignored. Other independent variables may be included as appropriate.

The dependent variable *A* is itself a ratio variable. By ignoring things like smoothing source then a standard regression analysis would suffice. If the ratio independent variables can be ignored then a standard ANOVA (ANalysis Of VAriance) would suffice. Neither of these is the case however, so the appropriate statistical tool is ANCOVA (ANalysis of COVAriance). This allows us to investigate the effects of both categorical and ratio independent variables on a ratio dependent variable. This is initial test that will is being pursued to investigate smoothing.

Ultimately the question of what is a good definition of ramp rate is a question of how to effectively estimate the derivative of a function. The use of splines for this is tentative though well motivated. The area of numerical differentiation is a subject with a long history. These various procedures will be investigated. Downstream efforts are described further in Section 7

Ramp Rate Specific Methodology

To investigate ramp rate behavior and interpretation, two different numerical methods of varying order of accuracy were tested using a known function for which a derivative is calculated. This was then used to find the numerical derivatives' error depending on sample rate (time interval). The methods are then used to calculate ramp rates using theoretical clear-day fixed-plate collector irradiance data to establish a typical clear-day ramp rate distribution. Finally, historical irradiance data were purposefully selected for cloudy days to examine the effects of high variability.

Correlation of Percent Cloud Cover Weather Forecast to Actual Irradiance

It is important to understand the accuracy of the weather forecast used by the shifting algorithm. The goal of this initial analysis is to compare measured irradiance from the Prosperity Project's solar array at Mesa del Sol in Albuquerque, New Mexico to predicted irradiance. Predictions are based on known methods for calculating clear day terrestrial irradiance in combination with National Weather Service (NWS) percent cloud cover predictions. First, the direct irradiance on a south-facing surface with 25˚ tilt was calculated. The model was to calculate the global irradiance for clear-day conditions in Albuquerque, New Mexico.

A computer program was written in modules which were assembled after individual testing for accuracy. These modules included data loading and organizing, curve fit or interpolating, and theoretical annual irradiance calculation codes. The code was designed for varying sample rates and mathematical anomalies such as infinite or undefined terms. While the code is customized to the Mesa del Sol site, the underlying method could be reproduced for other locations and conditions.

The measured data loading and organizing code takes advantage of MATLAB's built-in Excel data loading function. Providing the layout of data is known (i.e. which columns contain what), the data are loaded into the workspace in matrix form. The irradiance data are saved in a matrix of size "day of year" X "samples per day" through a series of loops and filters. For example, the tested data had a sample rate of every minute which yielded a [365 X 1440] matrix.

Memory locations associated with all days where no data were recorded are set to zero to provide easy filtering later. A visual representation of irradiance data recorded for the month of September 2011 is shown in Figure 48. It is apparent that the typical arc of a clear day's irradiance is disrupted by clouds. Clear days maintain a relatively smooth curve and cloudy days cause a jagged profile.

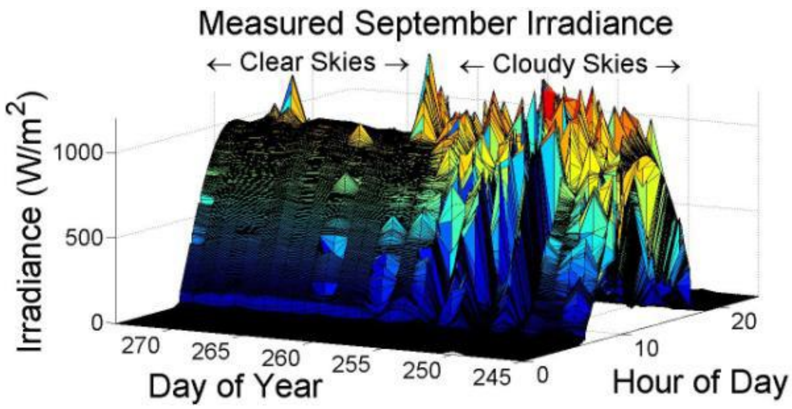


Figure 48 - Measured Irradiance Data (Sept. 2011); displays variability in power due to clouds

A sliding average was taken for this data to provide easier comparison to the prediction method. The same data shown in Figure 48 then appears below in Figure 49

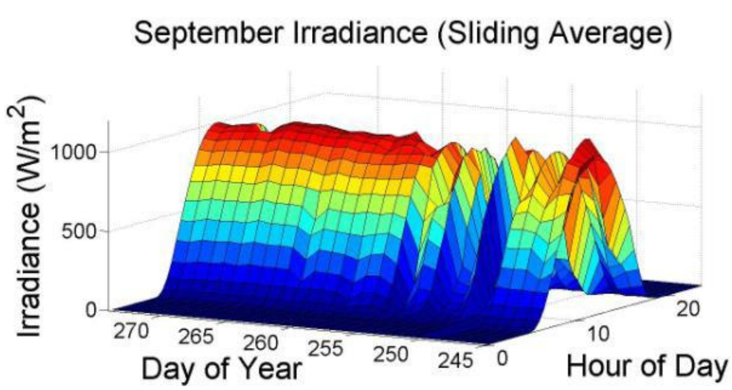


Figure 49 - Average Sept. 2011 Irradiance Data; used to compare to prediction

Methodologies for Determining Grid Impacts and Benefits

As the project progresses and data accumulates, optimization analysis will be required to determine the optimal smoothing battery size as well as the optimal shifting output strategy.

Smoothing Optimization

In order to determine an adequate amount of smoothing battery capacity needed, an optimization routine will look at status quo distribution equipment normally used to mitigate

PV intermittency. The feeder models will be used to simulate high penetration scenarios calibrated to actual operation. The target will be the highest avoided cost of status quo equipment needed to mitigate effects of high penetration PV intermittency contrasted to the lowest amount of smoothing battery capacity. The methodology will involve statistically comparing the ramp rate mitigation from various capacities and settings (Test Plan 1), determining the best combination and then modeling this in a high penetration feeder. Then a economic comparison will be made to determine monetized benefits.

Shifting Optimization

Firming –Utilizing the shifting batteries to produce a known quantity of energy based on day ahead forecasts is labeled in this project as firming. The objective here is to create a known rectangular shape of energy output from the combination of the shifting batteries and the PV resource with a known start and end time and a know output. Based on the discussions with PNMs Wholesale Marketing Department, it was established that the PNM's high demand times can be categorized as following segments in time versus seasons:

Nov: HE5-8 and 18-21

Dec-Feb: HE6-9 and 18-21

Mar: HE 5-8 and 18-21

April -October: HE 14-18

(HE = hour ending)

Optimization will involve investigating different known shapes, see **Error! Reference source not found.** below, to determine over a course of time which approach eliminates or offsets the most peaking period energy. The cost benefit analysis will then calculate an associated LCOE for the firming battery compared to a proxy gas peaking unit.

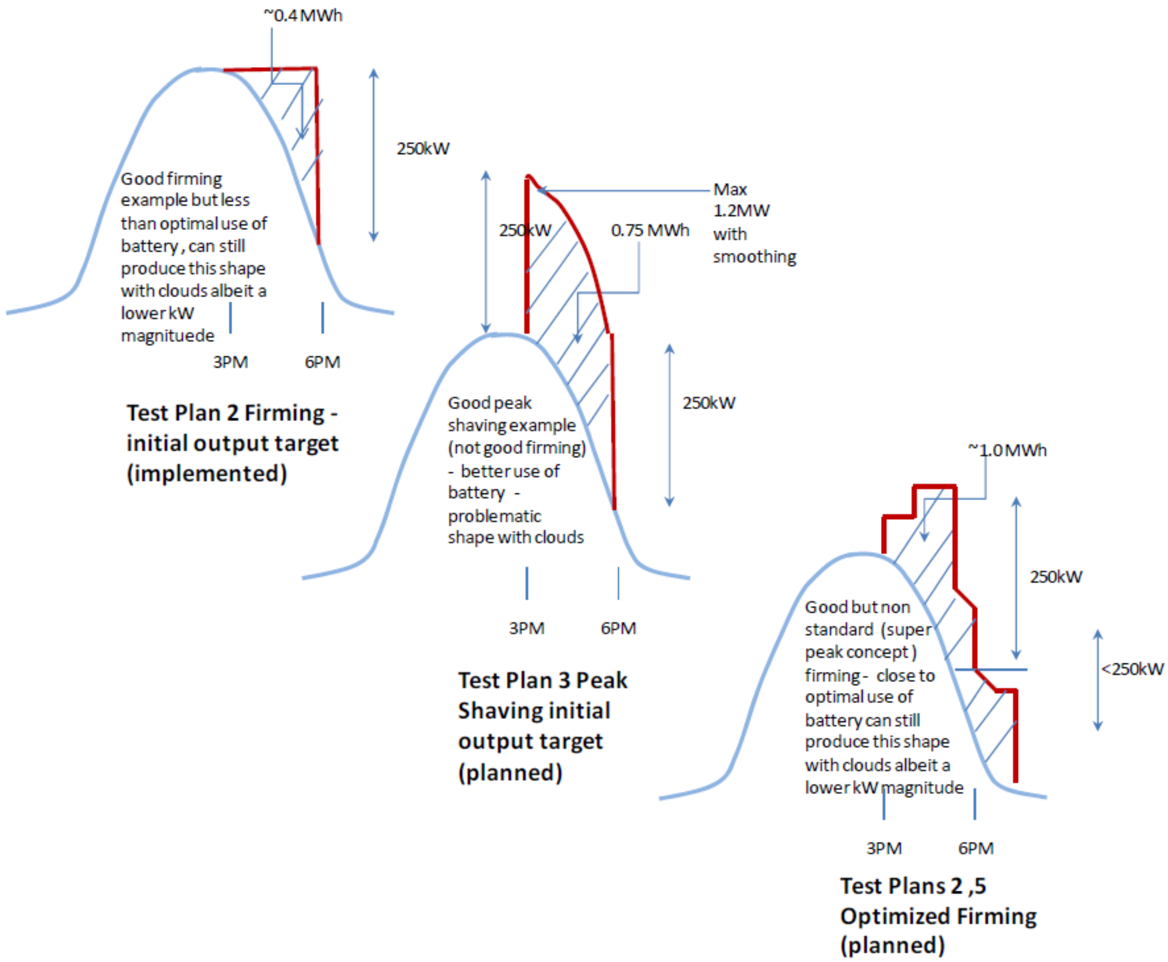


Figure 22 Firming and Peak Shaving Target Shapes

Peak Shaving - Utilizing the shifting batteries to offset loads at a substation or feeder is labeled in this project as peak shaving. A similar approach will be utilized to study the effects of peak shaving. The difference will lie in offsetting upgrade costs in a high penetration PV modeled for a loaded feeder. Here the costs of the deferred upgrade will be compared to the cost of the shifting batteries.

8.6 Appendix F - Annotated Performance Results - Extracted from PNM Interim TPR

Smoothing Field Results

The smoothing test has been conducted via Test Plan 1 (see Section 3 Appendix B) utilizing the variable sets in Table 23.

			Test Plan 1 Smoothing Control Source							
test label	period	Feeder Configuration	irradiance sensor	primary meter	PV Meter	ACE from PNM	Increment of Battery Capacity	Maximum Duration (days)	Start Date	End Date
1BPV0.1	**1**	B			**x**		10%	10	10/31/2011	11/10/2011
1BPV0.4	**1**	B			**x**		40%	10	11/16/2011	11/26/2011
1BPV0.7	**1**	B			**x**		70%	10	12/9/2011	12/28/2011
1BPV1	**1**	B			**x**		100%	10	1/3/2012	1/13/2012
2BIRRA0.4	**2**	B	**averaged**				40%	20	1/19/2012	2/8/2012
2BIRRA0.7	**2**	B	**averaged**				70%	15	2/14/2012	2/29/2012
2BIRRA1	**2**	B	**averaged**				100%	18	3/6/2012	3/24/2012
3BIRRSW0.4	**3**	B	**sw corner**				40%	15	3/30/2012	4/14/2012
3BIRRSW0.7	**3**	B	**sw corner**				70%	15	4/20/2012	5/5/2012
3BIRRSW1	**3**	B	**sw corner**				100%	10	5/14/2012	5/24/2012
4BPV0.6	**4**	B			**x**		60%	10	5/30/2012	6/9/2012
4BPV0.8	**4**	B			**x**		80%	10	6/15/2012	6/25/2012
4BPV1	**4**	B			**x**		100%	10	7/1/2012	7/11/2012
5BPV0.6	**5**	B			**x**		60%	10	7/17/2012	7/27/2012

Table 23 - Test Plan 1 Test Configuration

To date the control signal inputs have consisted of the PV Meter, an average of the 5 irradiance field sensors (1 on each corner and 1 in the middle of the array) and the SW corner irradiance sensor. The feeder configuration has remained in Beginning of Feeder. The following graphs show the Primary Meter (red), PV Meter (blue) and the Smoothing Battery output (yellow) . The % battery capacity refers to the % gain used in variable in the G1 variable for the control algorithm (see **Error! Reference source not found.** below).

For the following figures

- Solar PV Meter data appears in blue
- Primary (Net System) Meter data appears in red
- Battery Meter data appears in yellow

Figure 10 displays four consecutive days of early operation in November 2011. With the input gain set at 0.1 effectively 10% of the battery capacity was used. Little to no smoothing effect are evident on the first and fourth days of the data set where cloud cover was great enough to induce the smoothing. No smoothing was required on the second and third days as no cloud cover was present.

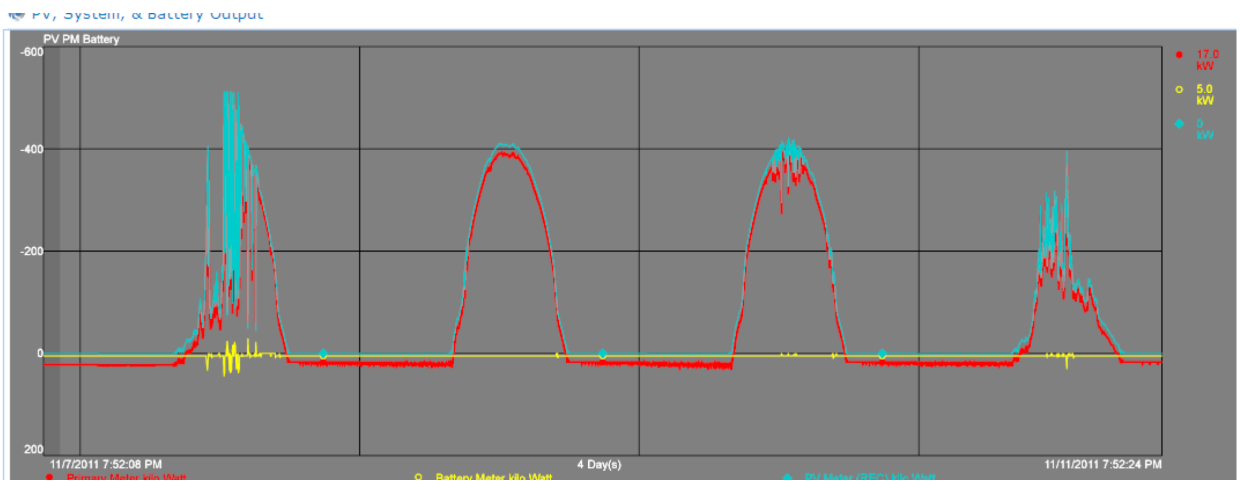


Figure 50 - System Output 1BPV0.1 – 10% of PV Meter

When the System was run at 100% of the PV Meter as an input signal, Figure 11, much more smoothing is apparent. The performance of the smoothing is even more evident in a magnified view of the first day of the data set, 1/15/12, shown in Figure 12. Some spiking occurred because of late response of the smoothing battery, as shown in a magnified view in Figure 13 the magnified view of second day of the data set. This was caused by latency issues from a variety of sources and was resolved, see discussion below.

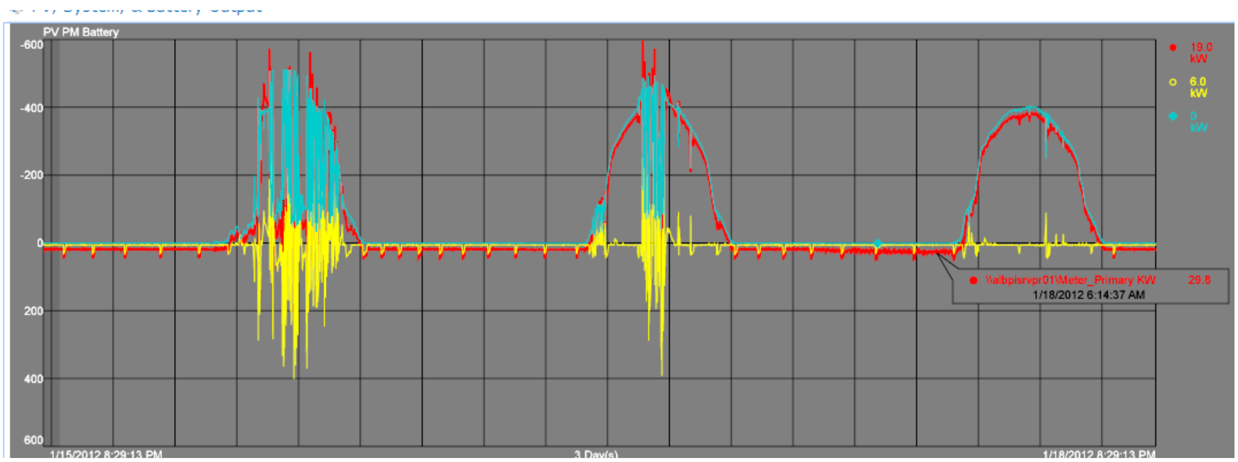


Figure 51 - 1BPV1 100% of PV Meter

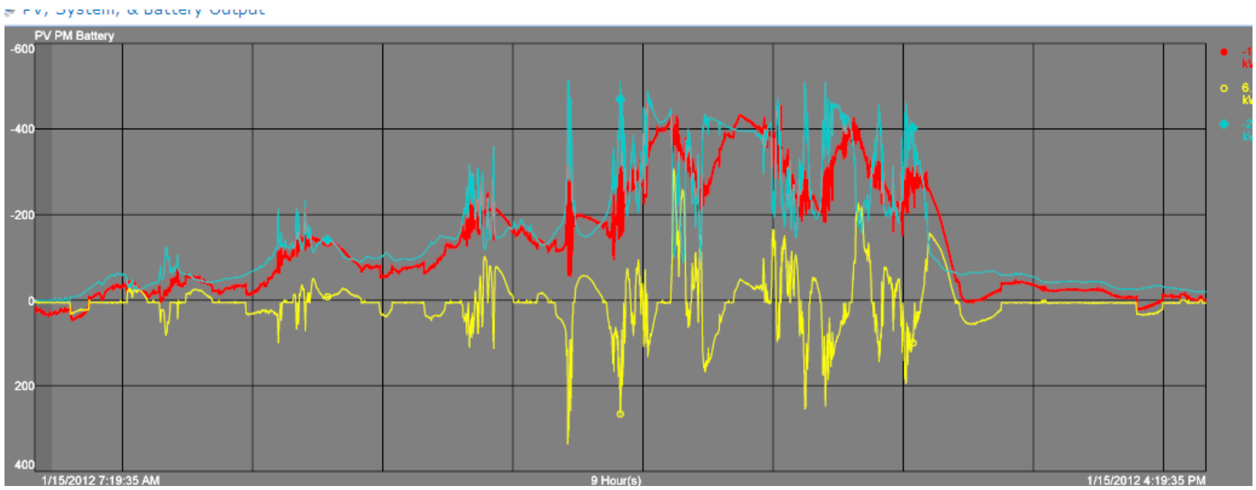


Figure 52 – 1BPV1 - Magnified view of 1/15/12 Smoothing

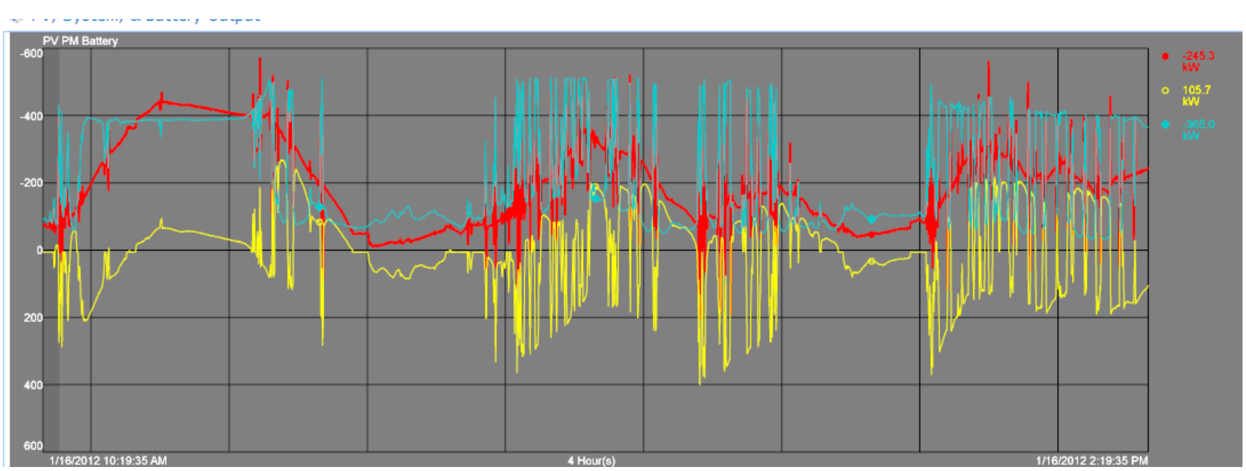


Figure 53 - 1BPV1 - Magnified View of 1/16/12 Smoothing

A subsequent subset of Test Plan 1 utilized the average of the five irradiance sensors as inputs. Figures 28-32 below show a variety of results utilizing various gains of the irradiance sensor average. Of significance is Figure 58 which shows significant spikes from the battery 6/8/2012. The cause of this unwanted effect and subsequent solution is discussed below.

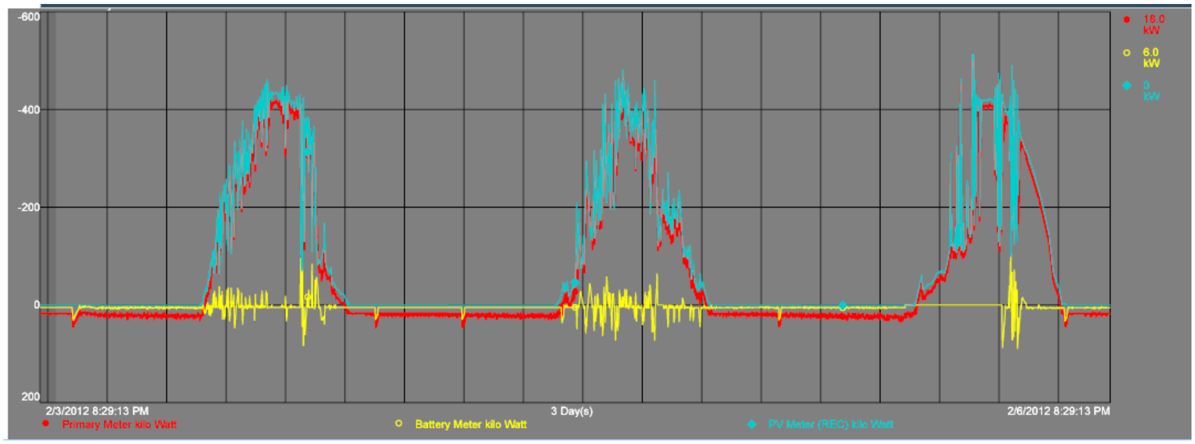


Figure 54 - 1 BIRRA0.4 - 40% of Irradiance Sensor

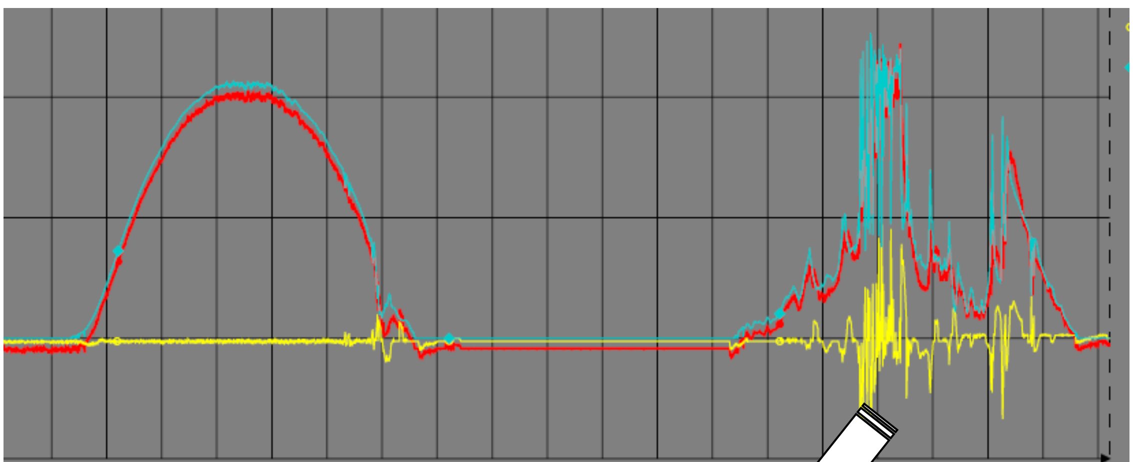


Figure 55 - 1 BIRRA0.7

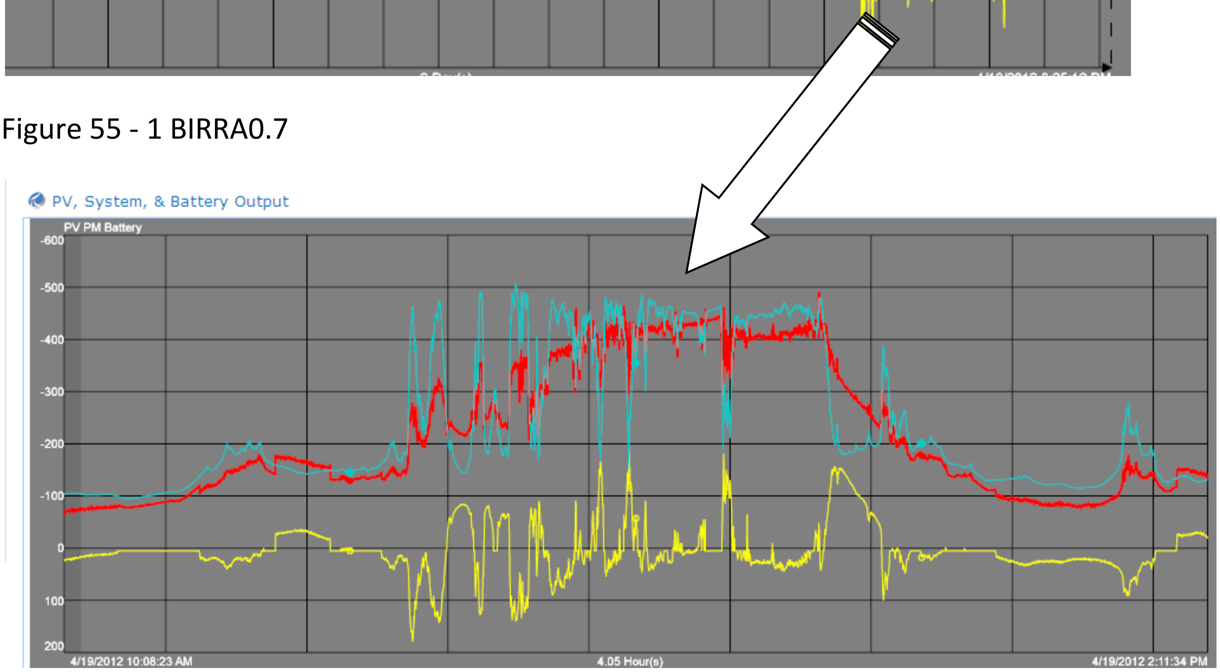


Figure 56 - 1BIRR0.7 magnified

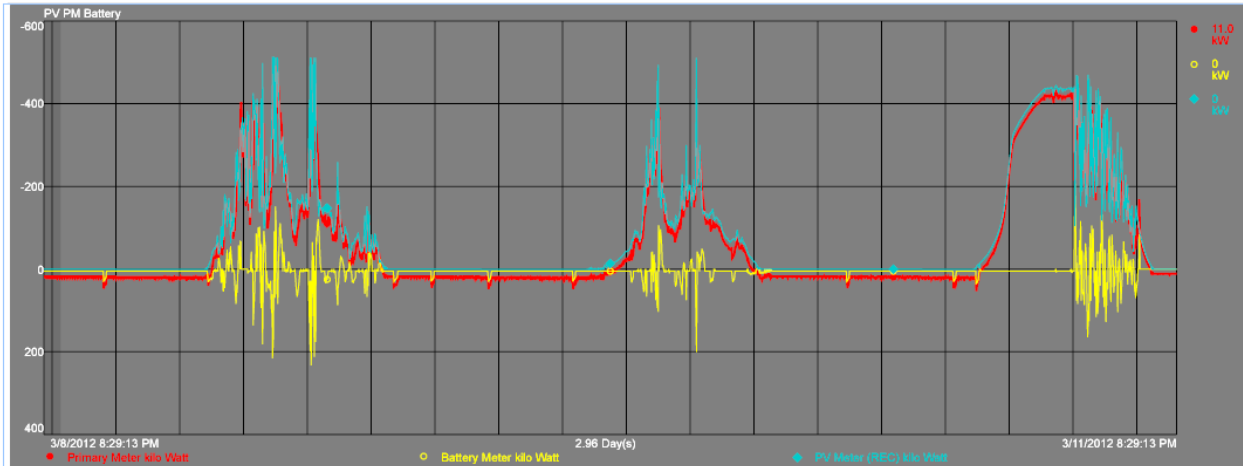


Figure 57 - 2BIRRA1 - 100% of Average of Irradiance Sensors

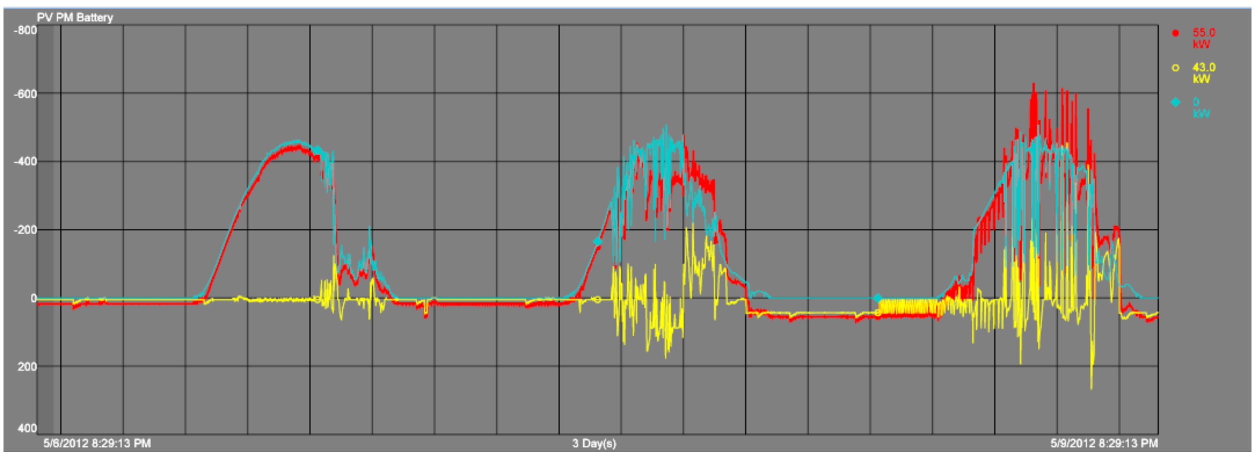


Figure 58 - 3BIRRSW0.7 - 70% of SW Irradiance Sensor

Key Observations – Smoothing

Latency delays in the PCS and BESS software cause the smoothing battery to react too late to severe intermittency. This resulted in upward spikes at the Primary Meter since the battery response happened after the cloud passed and the PV output recovered. The latency was determined by looking at the DAQ gateway. The signal in the DAQ determined control signals are sent a maximum of 37ms, resulting in tuning dead bands in the inverter and battery control system.

Control source Input - Irradiance Sensors
Irradiance values are scanned from Micrologger: **"12:12:57,625"**, "-07:00", Master Protocols/Modicon (MODBUS)/02: CR3000/Scan Rx Data"
Irradiance values are received by the BESS: 6 Irradiance values are being instantaneous except for the nw & ne irradiance, but 1ms later. "12:12:57,625", /Master Protocols/Modicon (MODBUS)/01: BESS/Control", DIRECT EXECUTE on point "BESS_IRR_met" by "BESS Control", value: 775.862." "12:12:57,625", /Master Protocols/Modicon (MODBUS)/01: BESS/Control", DIRECT EXECUTE on point "BESS_IRR_sw" by "Automation Functions Server/02: BESS Control", value: 1077.053." "12:12:57,625", /Master Protocols/Modicon (MODBUS)/01: BESS/Control", DIRECT EXECUTE on point "BESS_IRR_se" by "Automation Functions Server/02: BESS Control", value: 1085.475." "12:12:57,625", /Master Protocols/Modicon (MODBUS)/01: BESS/Control", DIRECT EXECUTE on point "BESS_IRR_cent" by "Automation Functions Server/02: BESS Control", value: 1073.413." "12:12:57,626", /Master Protocols/Modicon (MODBUS)/01: BESS/Control", DIRECT EXECUTE on point "BESS_IRR_nw" by "Automation Functions Server/02: BESS Control", value: 1075.924." "12:12:57,626", /Master Protocols/Modicon (MODBUS)/01: BESS/Control", DIRECT EXECUTE on point "BESS_IRR_ne" by "Automation Functions Server/02: BESS Control", value: 1087.447."
Irradiance values are stored in PI: Irradiance are being recorded in PI 894ms later. "12:12:58,520", /Slave Protocols/DNP3/01: PI/Objects Reported", " Analog Input Point 00009 = 1073 " "12:12:58,520", /Slave Protocols/DNP3/01: PI/Objects Reported", " Analog Input Point 00011 = 776 " "12:12:58,520", /Slave Protocols/DNP3/01: PI/Objects Reported", " Analog Input Point 00012 = 1087" "12:12:58,520", /Slave Protocols/DNP3/01: PI/Objects Reported", " Analog Input Point 00014 = 1076" "12:12:58,520", /Slave Protocols/DNP3/01: PI/Objects Reported", " Analog Input Point 00017 = 1085" "12:12:58,520", /Slave Protocols/DNP3/01: PI/Objects Reported", " Analog Input Point 00019 = 1077 "
Control source Input - Irradiance PV Meter
PV Value from Meter: signal stayed constant at 65kw (for two seconds) **"16:27:15,279",** Master Protocols/DNP3/02: 480V xfmr PV meter/Objects Reported", "Analog Input Point 00015 = -66 "
PV value from Meter received by BESS: BESS received the value 37ms later "16:27:15,316", /Master Protocols/Modicon (MODBUS)/01: BESS/Control", "DIRECT EXECUTE (Simulated confirmation) on point "BESS_PV_inverter_power" by "Automation Functions Server/02: BESS Control", value: -66.000."
PV Signal from Meter: PI received the same point 279ms from when the PV detected the change "16:27:15,557", /Slave Protocols/DNP3/01: PI/Objects Reported", "Analog Input Point 00134 = -66"

- PV Meter trace speed of signal at 37mS from PV meter to BESS (279mS from meter to PI database)
- Irradiance Sensor trace speed is at 0-2mS (faster because of no protocol translation in Gateway)

Figure 59 - Gateway Screen Shot of Signal Speed Check

- Corresponding software revisions were mapped to the test plan to allow for configuration alignment to the data set
- The 10% setting produced no discernible effect, however the 40%, 70% and 100% settings had noticeable effects on smoothing
- The effects have be to analyzed from a strict statistical analysis to screen out variance from clouds, seasonality, ambient temperature and configuration settings – see discussion below on statistical methodology results
- The data must be optimized against PNM status quo solutions to smoothing and high penetration PV intermittency in order to understand and establish an adequate level of smoothing (how much smoothing is enough?)
- OpenDSS and GridLAB models will need to be relied upon to model high penetration PV feeder effects – the Studio feeder in reality doesn't have enough penetration to present a problem
- The irradiance sensors should not be used as an input especially when PV production is close to inverter capacity (shoulder months – especially May). The irradiance may drive upward but the PV output is limited by inverter capacity. The smoothing battery with

irradiance as a control signal input ,may, in this case, over respond and cause an upward spike at the Primary Meter

- Ripple effects were introduced to the Primary meter during hotter weather due to battery and PCS air conditioning units cycling. The ripple presents a challenge in analyzing PV vs smoothed output at the Primary Meter

Shifting Field Results

The Shifting Algorithm was initially tested in UNM's PI OSI ACE environment, with beta testing complete in January 2012. The first field tests of the algorithm assumed the following

- Clear Day Prediction was used assuming no clouds. The algorithm uses the date to calculate a PV production curve based on a clear day.
- The Hour Ending (HE) delivery is scheduled as follows to align with PNM WSM Peaking requirements:

  Nov: HE5-8 & HE18-21

  Dec-Feb: HE6-9 & HE18-21

  Mar: HE5-8 & HE18-21

  April-October HE13-20

The output of the model appears as follows, in Figure 60

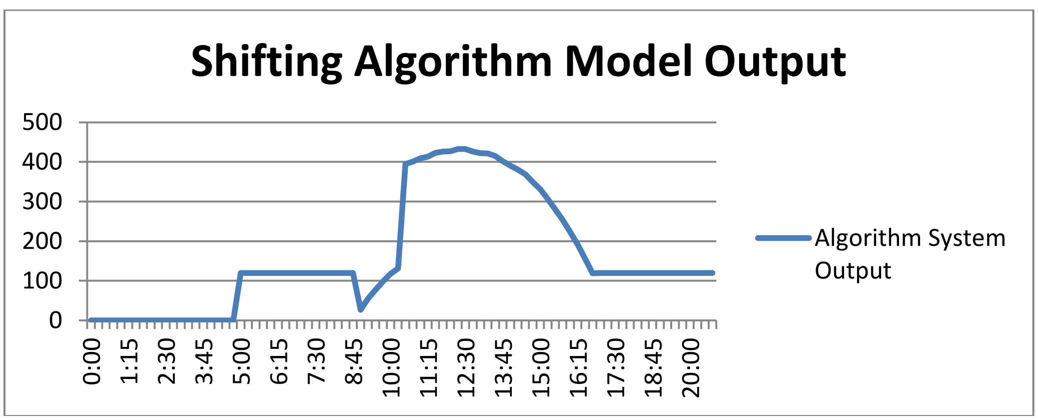


Figure 60 - Shifting Model Output

The numerical outputs were then manually entered every 30 minutes into PNM OSI ACE to produce the following field results:

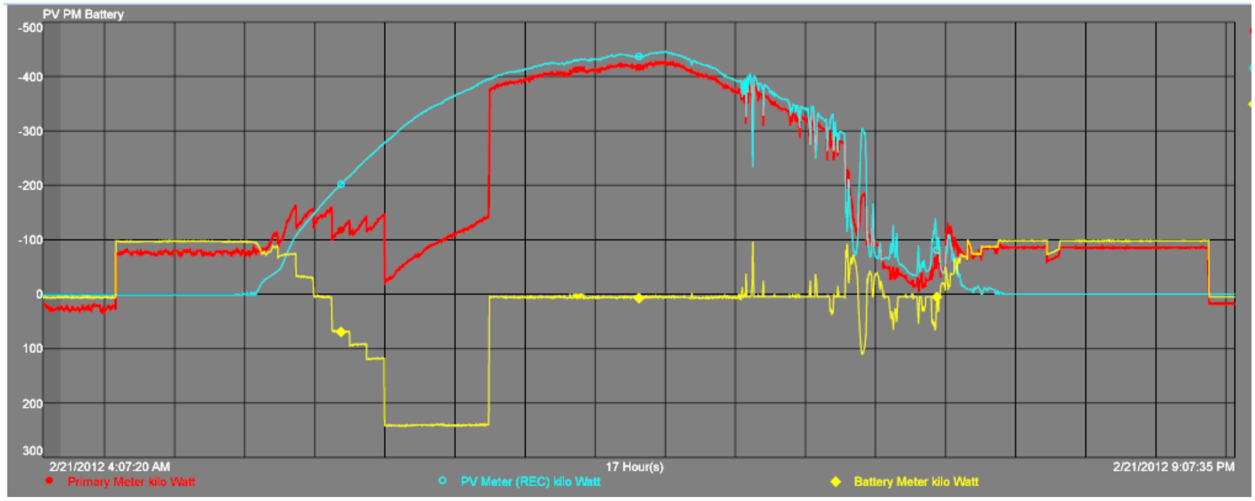


Figure 61 - First Iteration - Manual Shifting – Winter Schedule

The firming production from the battery began at 5am and it can be seen graphically in Figure 30. When the PV production started later in the morning the algorithm didn't correctly adjust for the PV increase, resulting in an increase in the Primary Meter output rather than a desired flat production. Additionally the time steps associated with manual inputs were too granular.

The algorithm was refined to accommodate 1 minute instruction to the BESS from the OSI ACE and modified to better account for the PV production curve. With validation of the algorithm attempts were then made to transfer the operating code from UNM's OSI ACE to PNM's ACE_1. Issues arose in the transfer that turned out to be related to version issues (UNM developed the algorithm in a higher version than PNM was operating). Once these software issues were resolved the automated version was placed on PNM's OSI ACE. Figure 31 shows a much better flat top production at the Primary Meter.

This is significant in that it demonstrated the ability of the storage system to produce a rectangular shaped energy output, from external utility based commands, by storing sinusoidal shaped PV and producing output on top of the PV output.

Note the ragged nature of the Primary Meter readings in the summer months is due to the cycling of the battery container air conditioner units. The ripple presents an issue for statistical analysis of ramp rate mitigation and mitigation plans will be developed to address this (see Future Plans Section). Figure 63 shows automated shifting over successive days.

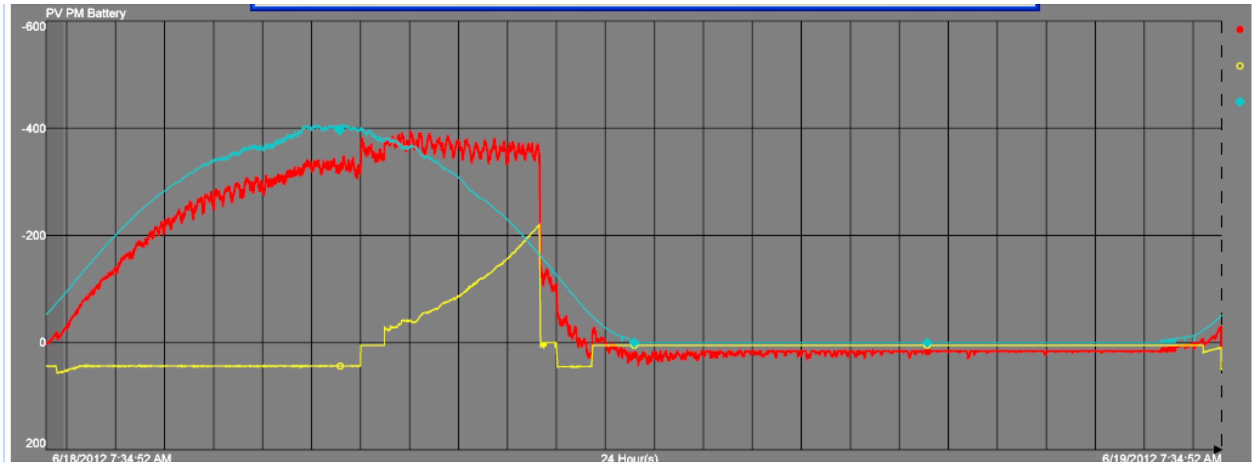


Figure 62 - V1.8 - Automated Shifting – Summer Schedule

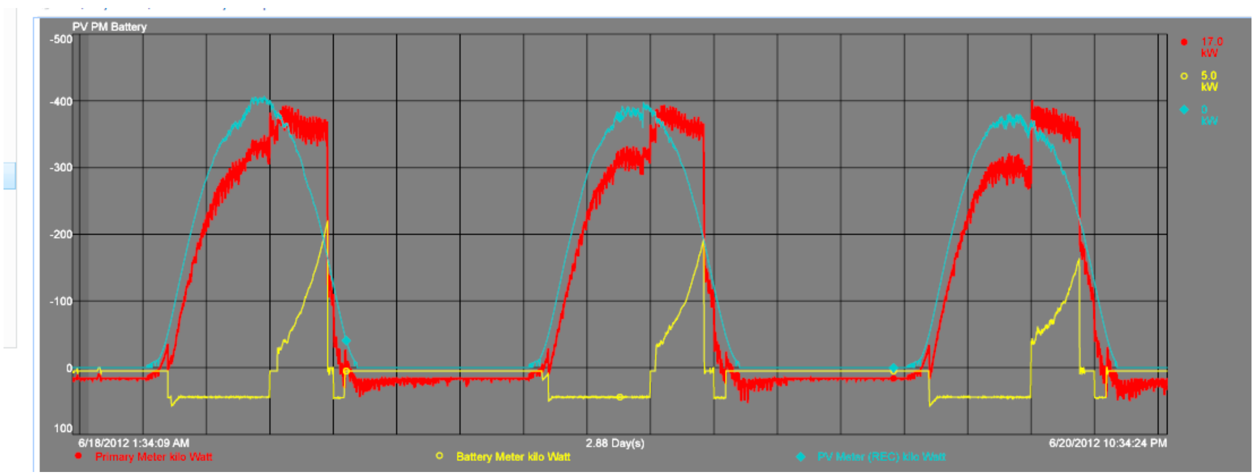


Figure 63 - Automated Shifting Summer Schedule - Multiple Days

The following, Figure 64 and Figure 65, demonstrate the ability of the system to sustain shifting with high intermittency cloud cover. Note the rapid and sustained drop in PV output due to a strong thunderstorm passing through. The shifting battery was able to respond and sustain a firm output.

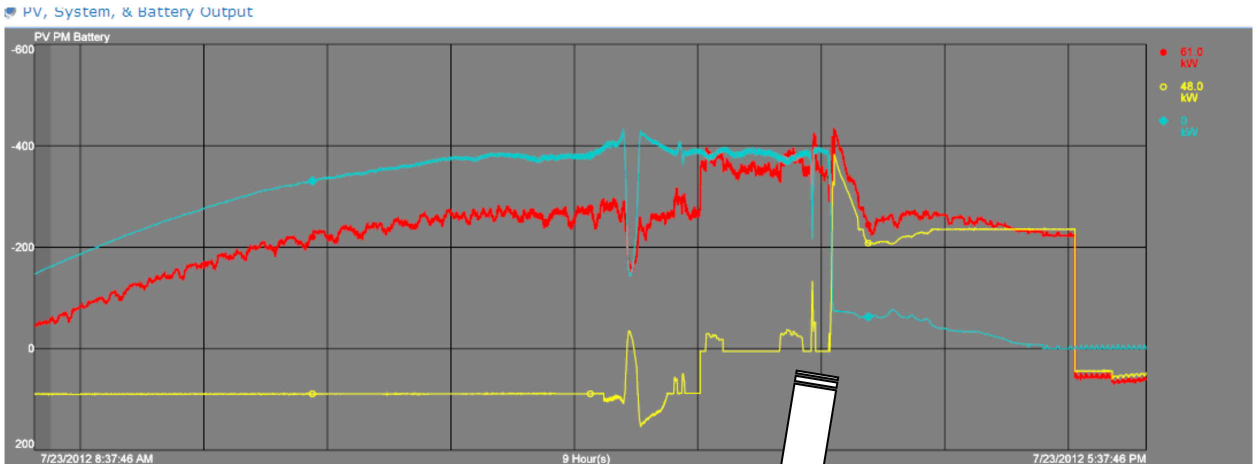


Figure 64 - Shifting with Cloud Intermittency

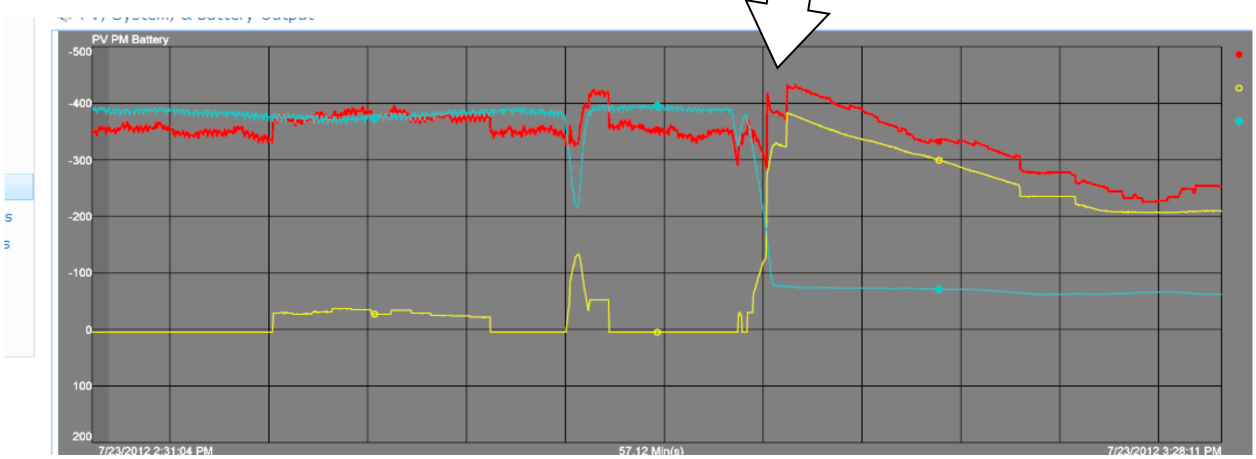


Figure 65 - Magnified View of Shifting with Cloud Intermittency

Key Observations Shifting

- The shifting algorithm works very well and is quite accurate on clear days. There is lowered confidence in the output on cloudy days.
- SoC limits and rate of charge both limit the amount of morning PV that can be stored, especially in the summer schedule.
- The automation was hindered by software versioning issues.
- Other shapes for firmed output need to be investigated. WSM doesn't care too much for the sharp drop off in the evening (summer schedule)

Simultaneous Smoothing and Shifting Field Results

The ability to create a firmed product through shifting during cloudy days remains a challenge but the output is roughly approximating a firmed shape. As Figure 66 shows, PV intermittency does have an effect on the firmed shape output, in this case the effect appears minimal as the cloud induce intermittency was not large.   Note also that the periodic spikes in battery charging (downward pulses) were due to an unforeseen drift in SoC on the shifting batteries. Incorporating a dead band in the algorithm removed these charge pulses.

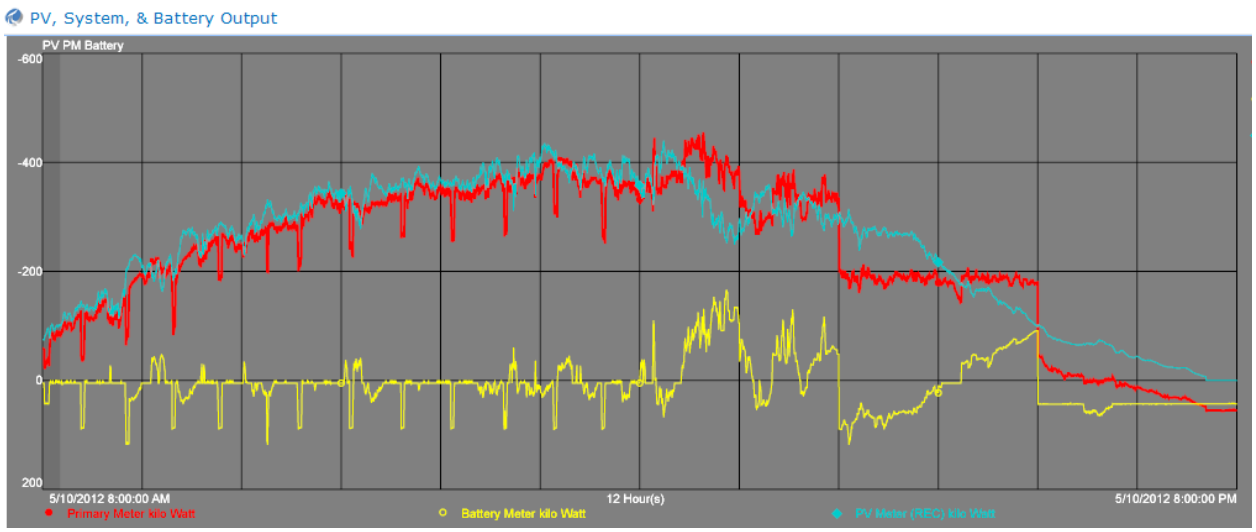


Figure 66 - Simultaneous Smoothing and Shifting - Low % Cloud Cover

In Figure 67 - Same Day Smoothing and Shifting the smoothing takes place in the morning, the clouds clear in the afternoon and shifting takes place. Note the smoothing battery operating simultaneously with the shifting performing a morning charge of the PV.

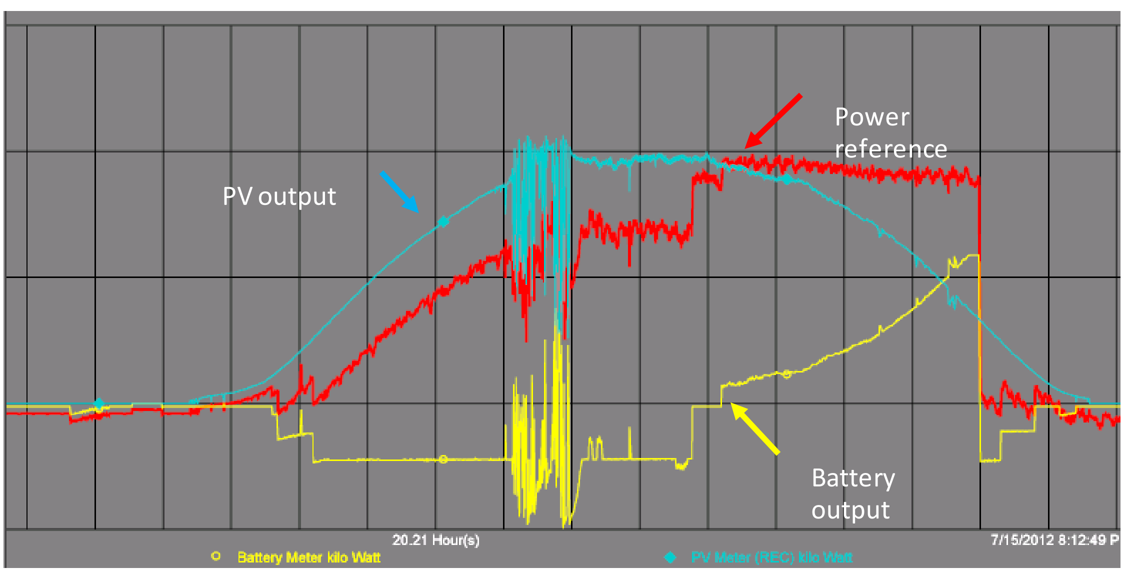


Figure 67 - Same Day Smoothing and Shifting

Simultaneous smoothing and shifting discharge takes place in Figure 68. During days with heavy intermittence the system was able to charge the shifting, simultaneously store shifting power and in the afternoon produce a firmed PV product, albeit with a lowered confidence in the kW delivered on a firm basis.

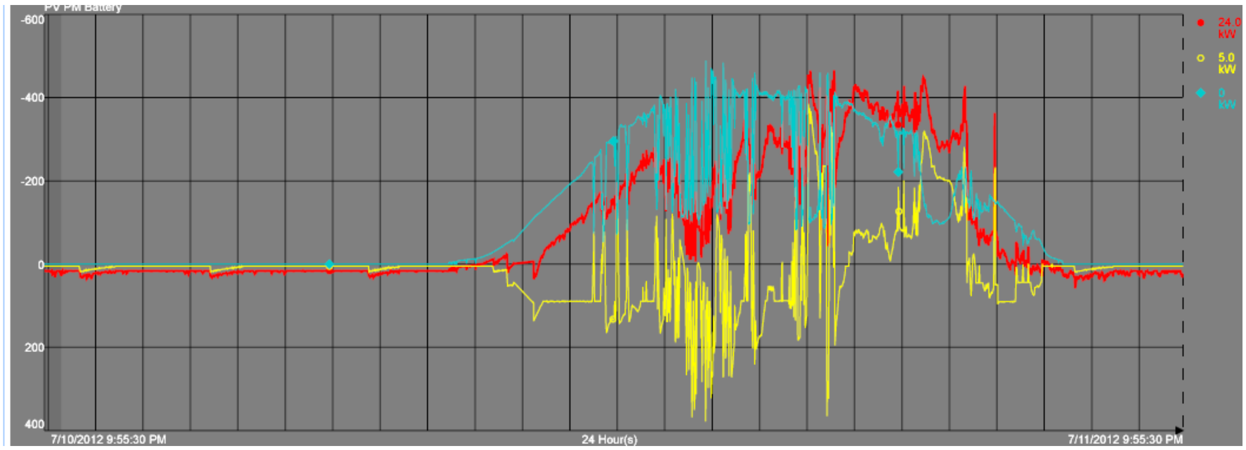


Figure 68 - Simultaneous Smoothing and Shifting - High % Cloud

Key Observations - Simultaneous Smoothing and Shifting

- Simultaneous Shifting and Smoothing with lots of intermittent PV is achievable but the shifting power reference may need to be lowered during cloudy periods to ensure the firmed output remains flat without spikes especially during instances where the smoothing battery performs a quick and deep charge.

Ramp Rate Methodology Comparison Results

As the graphs in Figure 69 and Figure 70 indicate there is significant smoothing being implemented. The plot of the empirical probability distribution for the Primary Meter lies well above the PV Meter's ECDF. We note that the Primary Meter signal was contaminated by an extra signal from an HVAC load in summer months when the air conditioners are operating. To compensate for this we introduced an additional level of smoothing when calculating the ramp rates for the Primary Meter. This will be corrected in succeeding test plans.

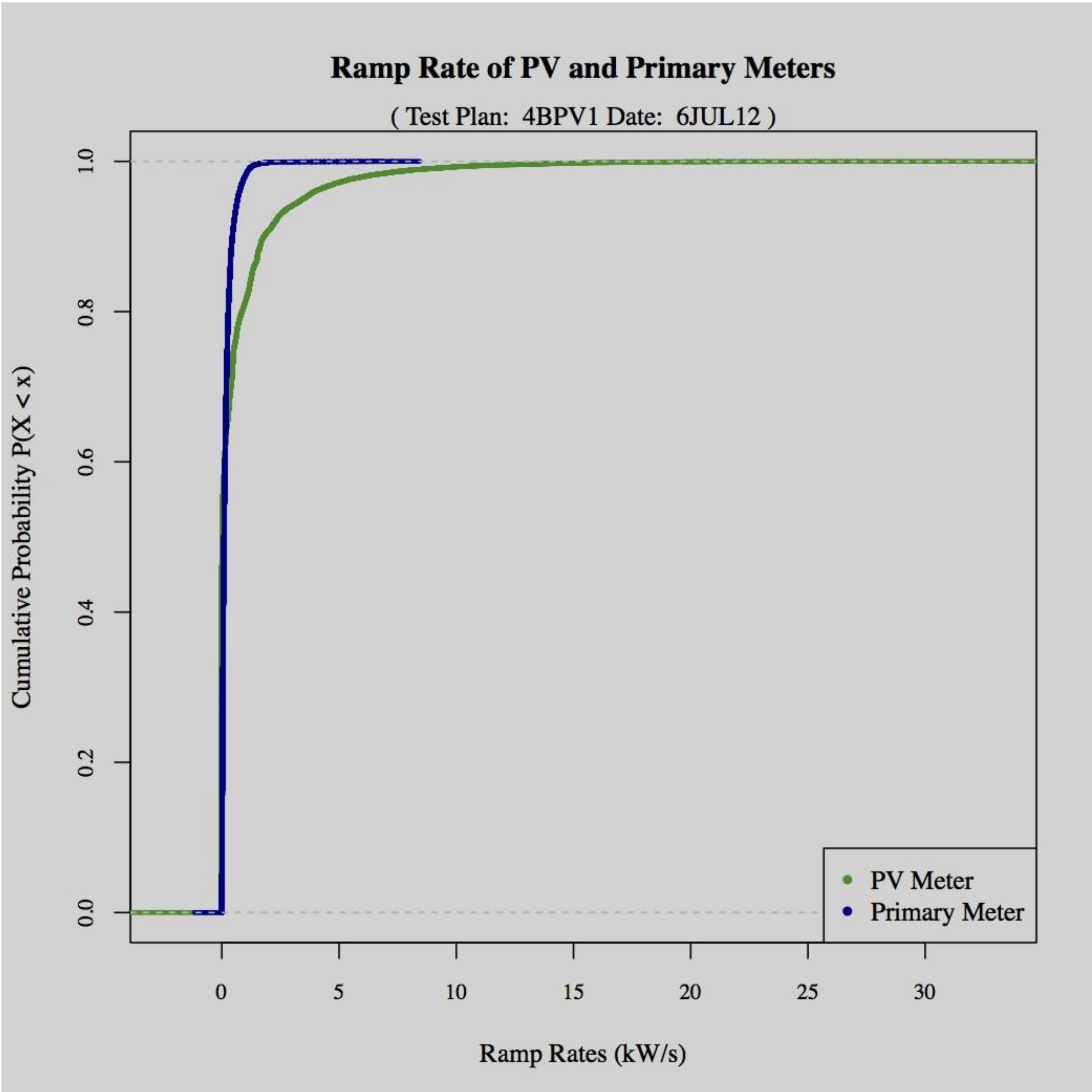


Figure 69 – Primary Meter and PV Meter ECDF – July 6, 2012

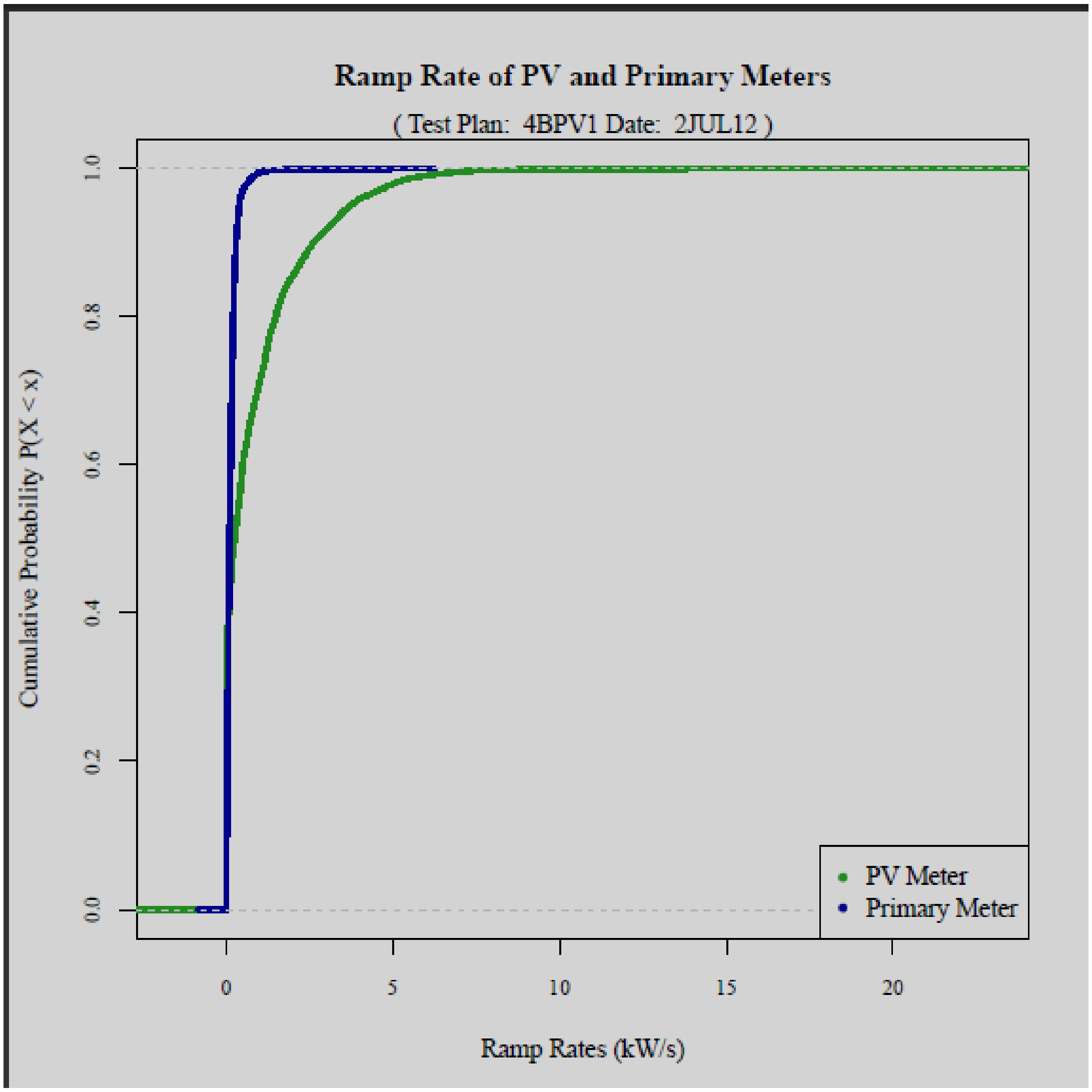


Figure 70 - Primary Meter and PV Meter ECDF – July 2, 2012

Technical Aspects

The measurement for the degree of smoothing is

$$A = \frac{\int_0^\infty (1 - ECDF_{PM})dr}{\int_0^\infty (1 - ECDF_{PV})dr}, \quad \text{Equation 6}$$

where the empirical cumulative distribution functions are $ECDF_{PV}$ for the ramp rates observed with the PV meter measurements and $ECDF_{PM}$ for the ramp rates observed with the Primary Meter measurements. With *A* as the dependent variable the following are the independent variables considered:

- Smoothing control source (a categorical independent variable)

- Cloud cover (an ordinal or a ratio independent variable)
- Increment of battery capacity (an ordinal or a ratio independent variable)
- Potentially season (an categorical variable)

Smoothing splines are among the best options for calculating derivatives, typically giving performance well above any finite-differencing method. For doing off-line analysis there is little reason to utilize any other method. For online processing of data splines may not be ideal. They are a global method, so any point of evaluation relies, at least indirectly, on a whole day's measurements. Online processing would be ideally handled using Savitzky-Golay filters. These are a finite-length, fixed-coefficient filter provided there is even sampling times. The Savitzky-Golay filters act simultaneously as a low-pass filter and a differentiator. Difficulties arise when sampling times are not evenly spaced. Now the coefficients are no longer fixed and must be calculated 'on the fly'. It's unlikely that this would prevent their use numerically, since the actual calculations could be performed relatively quickly. But, this is still an unsolved problem, so an actual algorithm will need to be designed prior to any implementation.

It needs to be emphasized that this project is the first to use smoothing splines and Savitzky-Golay filters for ramp rate calculations. These methods are mathematically among the best for calculating derivatives. This methodology is on theoretically solid ground by employing these techniques, not relying on any prior ad-hoc methods. [12]

---

[12] Ahnert , Karsten , Abel , Markus, Numerical differentiation of experimental data: local versus global methods, Computer Physics Communications, V177, N10,p 764-774, 2007

Hanke , Martin, Scherzer , Otmar, Inverse Problems Light: Numerical Differentiation, The American Mathematical Monthly, V108, N6, 2001

Jianwen Luo, Kui Ying, Ping He, Jing Bai, Properties of {S}avitzky–{G}olay digital differentiators, Digital Signal Processing Journal, V15, P122-136, 2005

Reinsch, C., Smoothing by spline functions, Numerische Mathematik , V10, N3, p177-183, 1967

Reinsch, C., Smoothing by spline functions, Numerische Mathematik , V16, N4, p451-454, 1970

Ronald W. Schafer , What Is a {S}avitzky-{G}olay Filter?, IEEE Signal Processing Magazine, V2, N4, p111-117, 2011,

Ramp Rate Analysis Results

Historical Irradiance Data

Irradiance data which was recorded at a sample rate of 0.2 seconds was selected, intentionally seeking cloudy days which exhibited significant variability. Below, Figure 71 shows the irradiance data for April 10th, 2012 through April 12th, 2012.

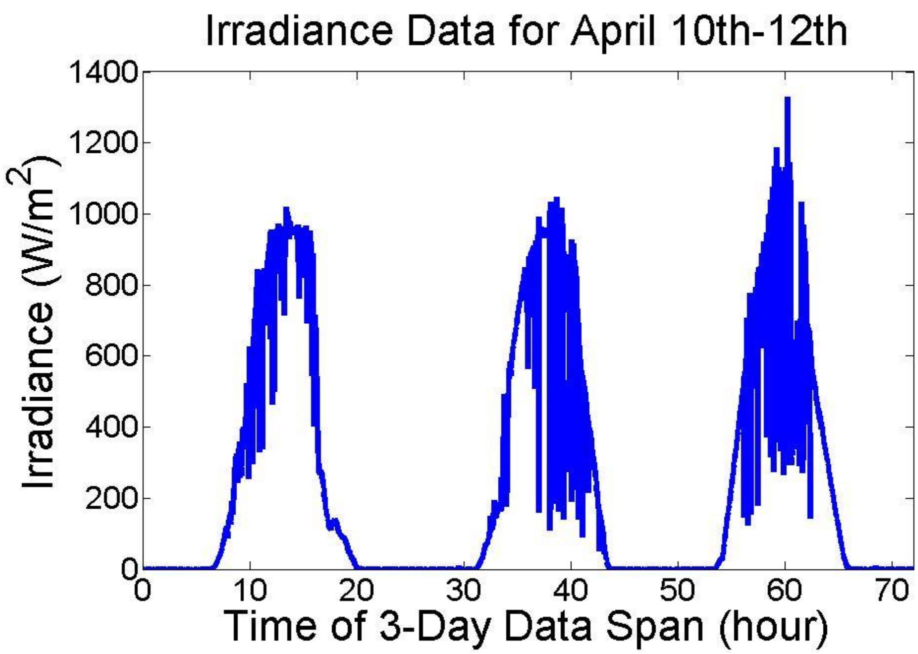


Figure 71 - Irradiance Data for April 10th through 12th, 2012

Because of the greater accuracy of the fourth-order central difference method, it was used for obtaining the final results using actual irradiance data keeping in mind that smaller time step ramp rate calculation may produce inaccurately high ramp rates. This regular time step of 0.2 seconds was used in preliminary testing of the code. However, the time stamp for the irradiance data ranged from about 0.2 to 0.7 seconds (at a precision of +/- 0.001 seconds) during a day's data collection. Accuracy was increased greatly by incorporating the difference in time stamps belonging to data points used to calculate ramp rates. Figure 72 shows the ramp rates calculated throughout the day along the same timeline as the irradiance data shown above in Figure 71.

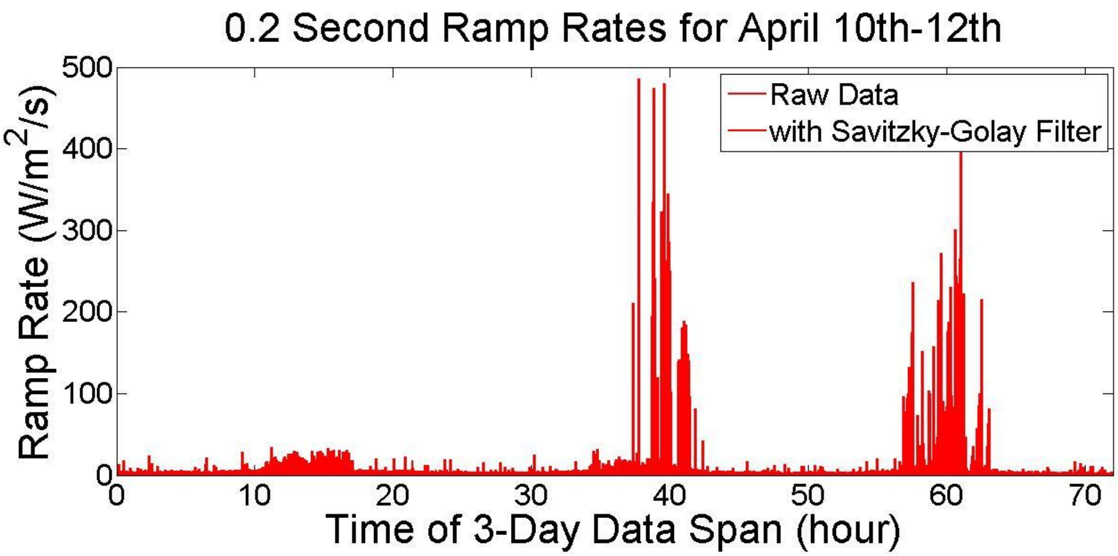


Figure 72 - Ramp Rates Using Time Stamp Difference (0.2 second Sample Rate)

A primary concern of ramp rates is the maximum ramp rate the battery bank providing output power for smoothing may experience. Below, Figure 73 shows the variation of maximum ramp rate depending on sampling rate for each of the three days.

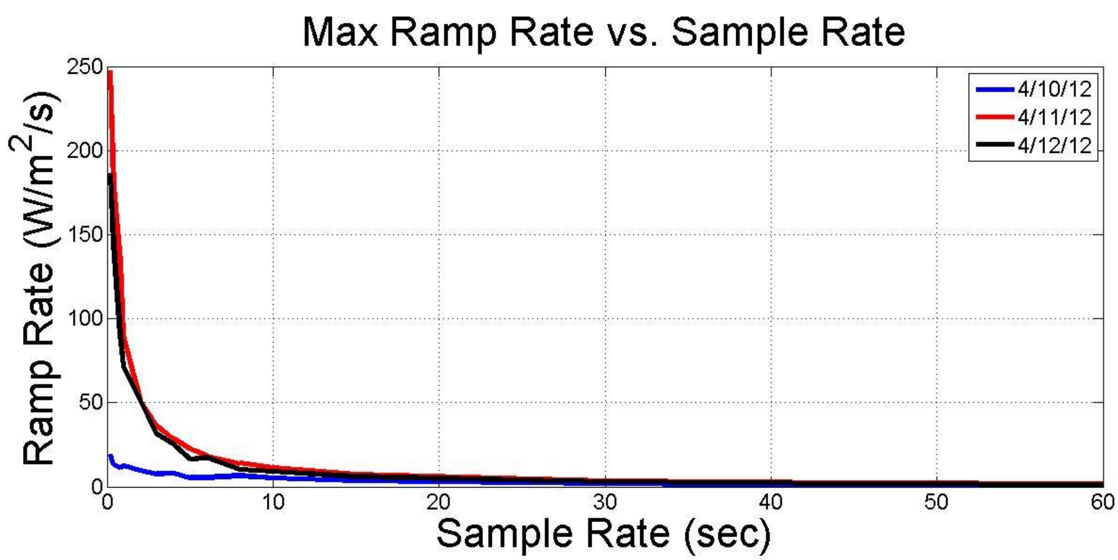


Figure 73 - Max Ramp Rate versus Sample Rate

The same data shown on a logarithmic scale for both the x and y axes is shown below in Figure 74. Both of these graphs show a clear increase in maximum ramp rate as sampling frequency increases.

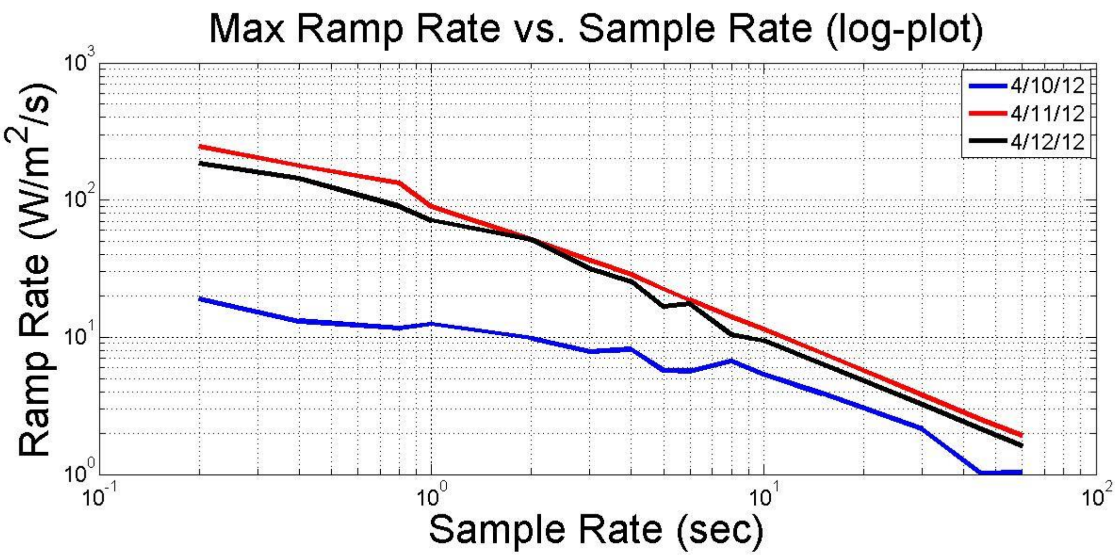


Figure 74 - Max Ramp Rate versus Sample Rate Log-Plot

Additionally, the average ramp rate for each day was calculated to see its trend using Equation 7 (Average Ramp Rate) for ramp rates calculated using the forward difference method.

$$Avg.Ramp\ Rate = \left|\frac{\sum_{i=0}^{X-1} f(x_i) - \sum_{i=0}^{X-1} f(x_i + h)}{Xh}\right| \qquad \text{Equation 7}$$

In Figure 75 below, the sliding average ramp rate distribution progression using Equation 7 for April 10th is shown versus the sample rate used for equation 3 with sample rates of 10 seconds, 5 seconds, 2 seconds, 1 second, and 0.2 seconds. Again, it is shown that the calculated ramp rate distribution spreads out with decreasing time interval, but unlike other distribution series, the progression is much smoother.

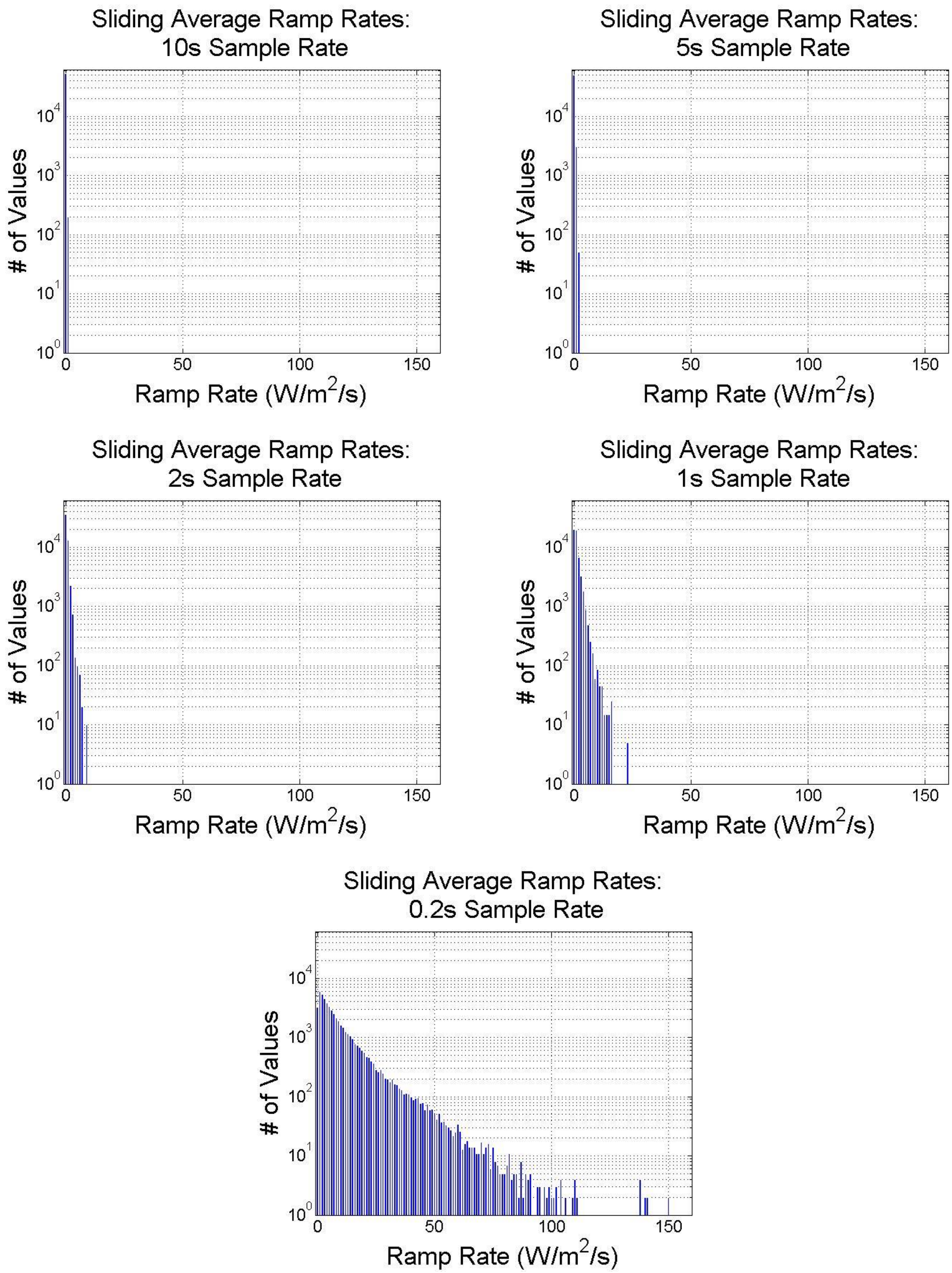


Figure 75 - Sliding Average Ramp Rate Distribution

Additionally, the maximum ramp rate for sliding average data above is significantly higher as compared to the distribution progression shown below in **Error! Reference source not found.**. This may not be a desired outcome because artificially high ramp rates may be generated.

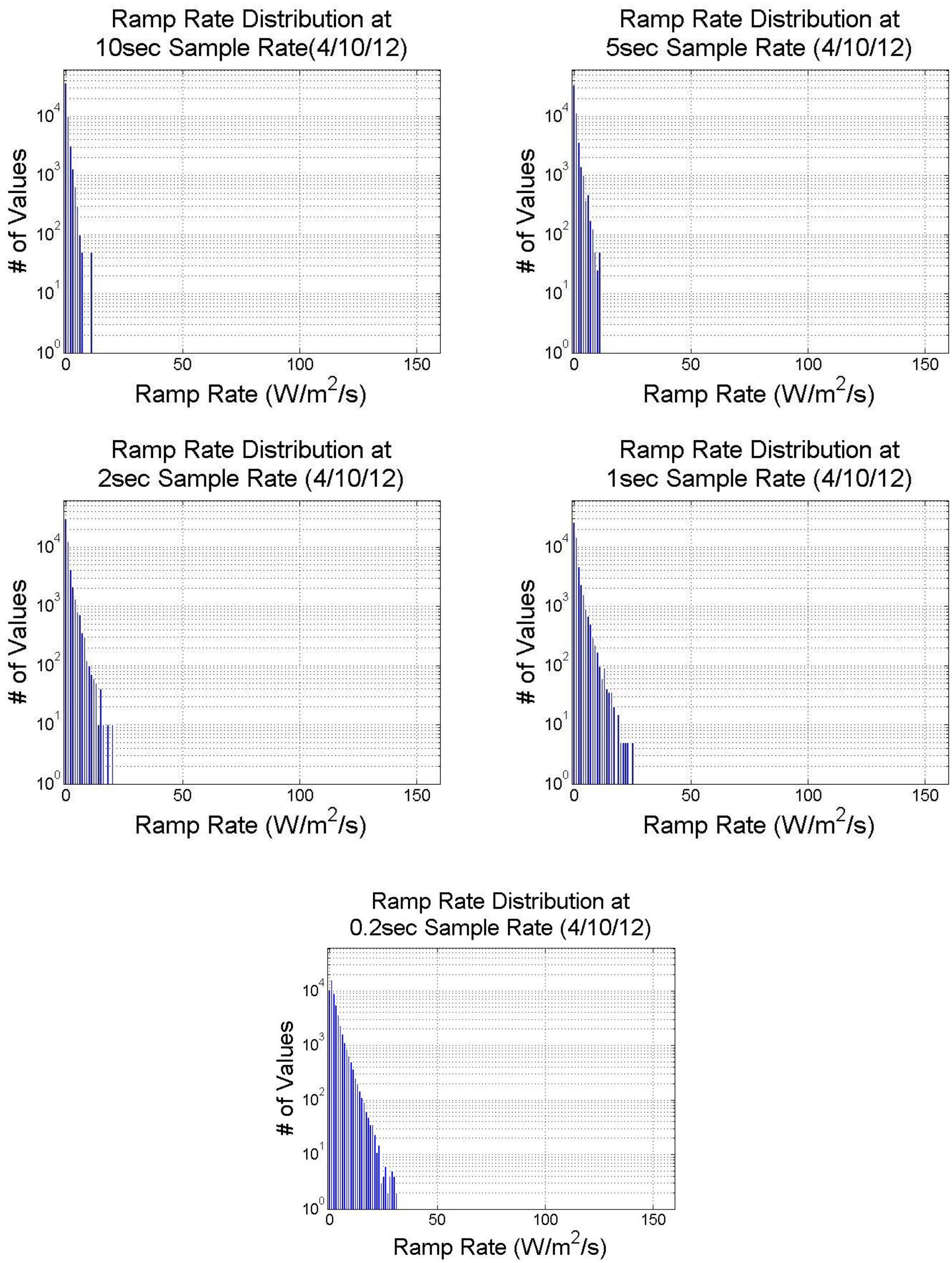


Figure 68 - Ramp Rate Distribution for April 10th, 2012

Irradiance vs. Percent Cloud Cover Results

The predicted clear day irradiance data for a given day and sample rate were obtained using well-known geometric equations coupled with air mass attenuation models [1]. The calculations also provided the angle of incidence necessary for finding the normal component of irradiance impinging on fixed plate collectors. For the solar array's latitude, longitude, altitude and orientation, the theoretical terrestrial clear-day direct-beam irradiance plotted over the year is represented in Figure 76 for a South-facing surface tilted at 25˚.

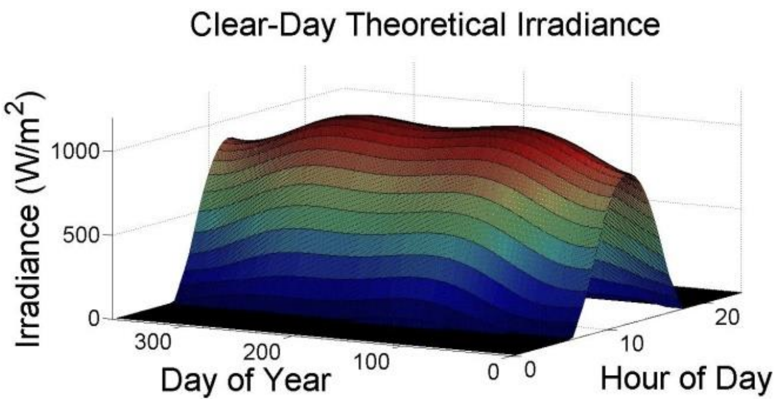


Figure 76 - Clear-Day Theoretical Irradiance; for array's location and orientation

The contributions of secondary effects, such as diffuse irradiance, air mass attenuation and local to solar time adjustments based on location with respect to the local time zone's standard meridian were also considered. More specific to this site, adjustments were made to account for a hill just east of the array which caused a delay in apparent sunrise every morning. As an example of prediction accuracy for a clear day, consider a single day's irradiance data (September 23, 2011) shown in Figure 73. It is difficult to see the difference between nearly overlapping lines. To show consistency, a separate day (October 20th, 2011) is shown directly below in Figure 78.

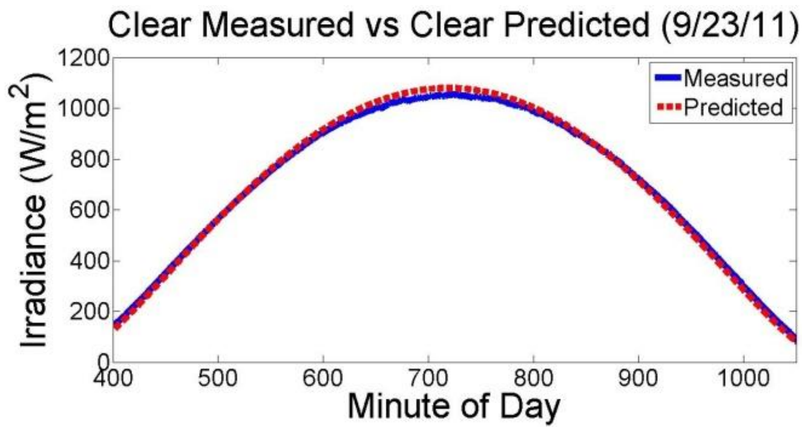


Figure 77 - Clear Day’s Irradiance (9/23/2011) vs. Clear Day Prediction

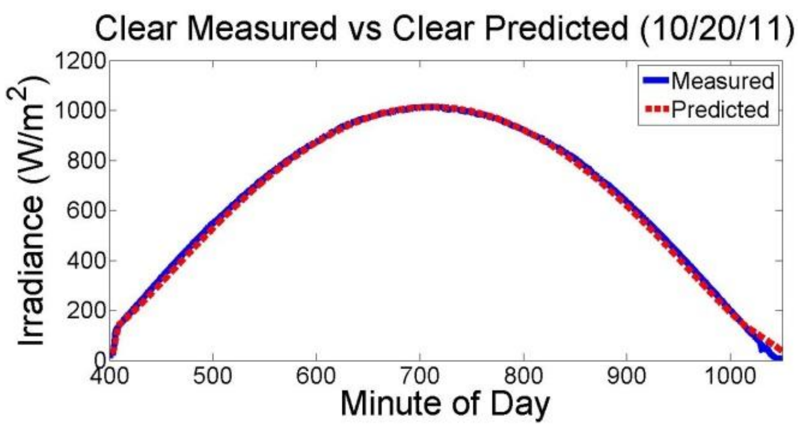


Figure 78 - Clear Day’s Irradiance (10/20/2011) vs. Clear Day Prediction

Historical day-ahead predictions of percent cloud cover were made available by the NWS. For these predictions, the NWS makes a prediction of 0, 20, 50, 80 or 100 percent cloud cover at times 9:00am, 12:00pm, 3:00pm and 6:00pm. These values were interpolated over the entire day’s samples using a cubic spline interpolating function. Checks were also put in place to ensure no percentages exceeded 100% or became negative.

After modifying the clear-day curve in Figure 73 according to equation 2, the year’s irradiance predictions show sharp drops where percent cloud cover predictions are available.

$I_{Prediction} = I_{ClearDay}\left(1 - k\left(\frac{\%\,Cloud\ Cover}{100}\right)\right)$ (Equation 2)

Shown below in Figure 79 is the resulting prediction plot with cloud cover. Continuously smooth, unaltered curves are present where NWS data were either unavailable or 0% cloud cover and steps down indicate cloud cover.

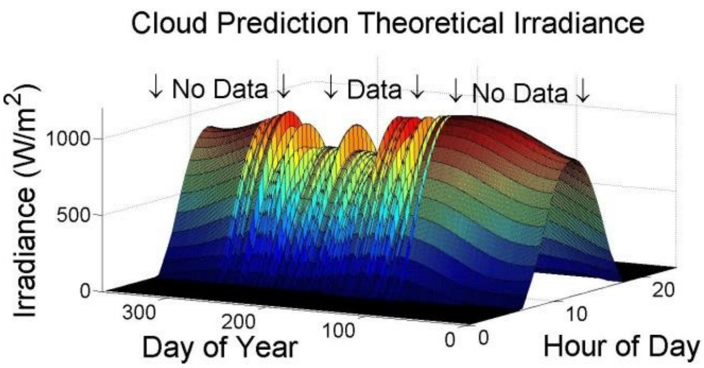


Figure 79 - including cloud cover; original curve unchanged where data unavailable

For a closer look, September's predicted irradiance curve appears as Figure 76 below. Comparing to a previous figure in this section (Figure 20), high percent cloud cover was predicted early in the month, corresponding to measured irradiance. Later in the month, when there were clear skies, the NWS predicted light cloud cover, suggesting conservative forecasting.

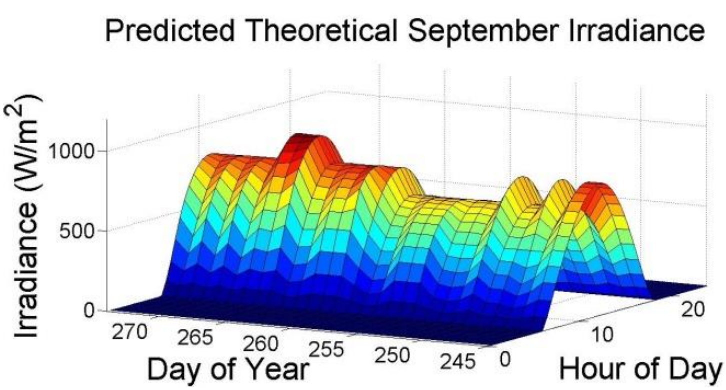


Figure 80 -September's Prediction; compare lower curves to spikes in Figure 20

Smooth behavior on a cloudy day is not realistic and should not be used for real-time control, but may be inevitable for day-ahead planning. Consider, for example, September 10, 2011 which was a cloudy day with NWS predictions to match. The following comparison (zoomed in for detail) shows actual irradiance versus predicted irradiance.

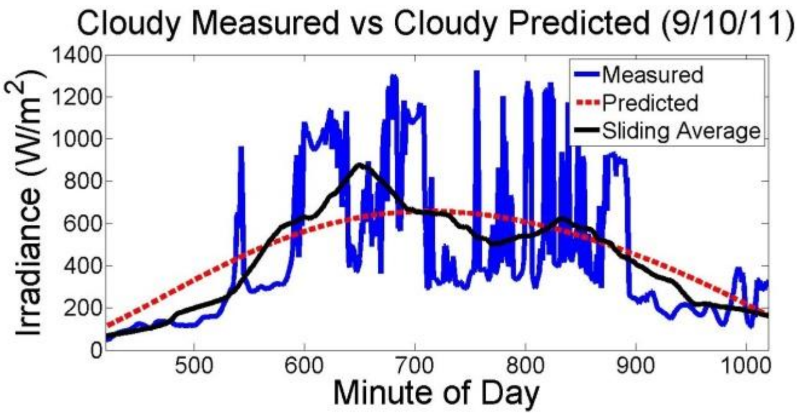


Figure 81 - Cloudy Day's Irradiance (9/10/2011) and Sliding Average vs. Prediction

As an overall comparison of the measured and predicted irradiance values, a one-to-one scatter plot was generated. If compared to a perfect prediction method, all data points would be located on a line at 45 degrees from the origin (i.e. y=x).

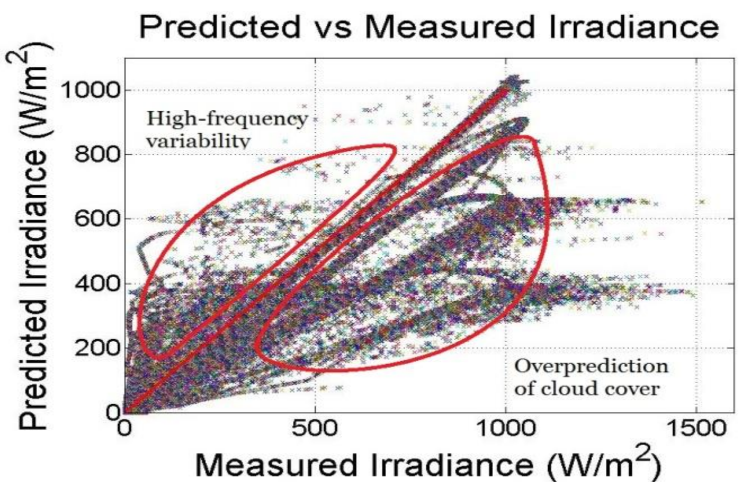


Figure 82 -Cloudy Day's Irradiance (9/10/2011) and Sliding Average vs. Prediction

The scattering around the y=x line is due to cloud cover. The three line patterns, shown flowing low and right of the y=x line, are days where a prediction greater than zero percent cover was made, but the array experienced clear day irradiance. Moving away from y=x, the lines correspond to 20%, 50% and 80% cloud cover predictions.

One of the user determined characteristics in this analysis was the effect of cloud cover resulting from the constant k in equation 2. Considering this, secondary lines were added at 34 and 60 degrees out from the origin to help center the data cloud equidistantly from x-coordinate of the y=x line. This means for a predicted irradiance (e.g. 600 W/m^2) we have an equal range of irradiance above and below the predicted value. The resulting centering generated the plot in Figure 83 below.

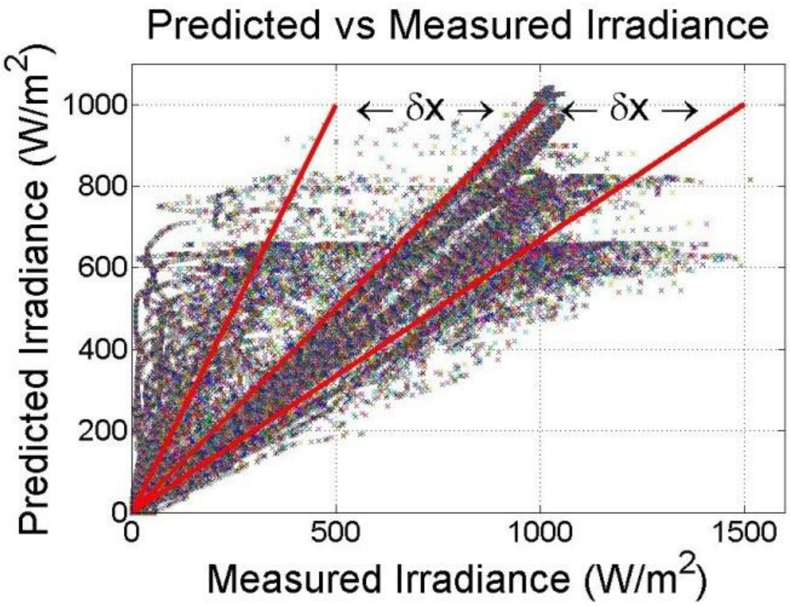


Figure 83 - Centered Predicted vs. Measured Irradiance; average distribution of scatter

The sliding average of the measured data in Figure 80 below provides further clean-up by removing many of the large spikes seen in measured data. This also yields clear path lines for specific days' sliding average irradiance curves.

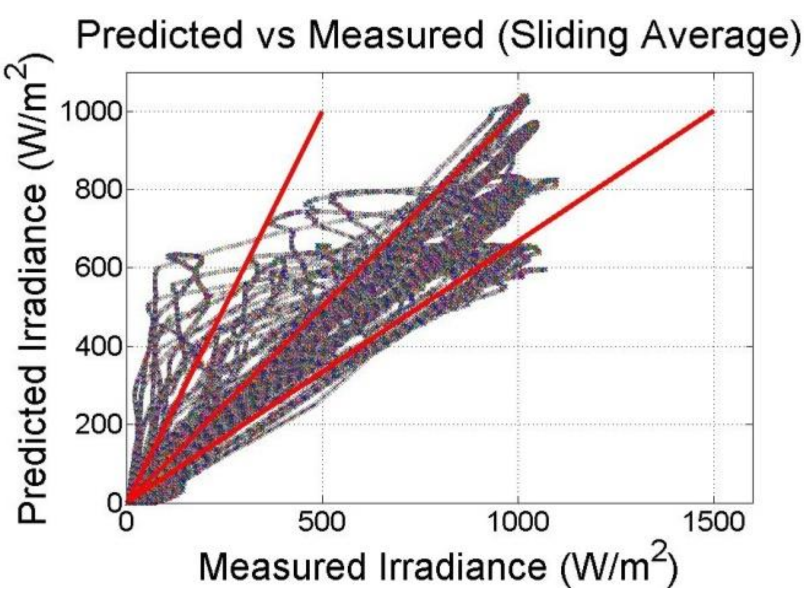


Figure 84 - Predicted vs. Sliding Average of Measured Irradiance

For a closer look, Figure 85 compares two days' irradiance. The line nearly coincident with the y=x line is a clear day and the scattering black path and green looped path are a cloudy day's measured and sliding average irradiance, respectively.

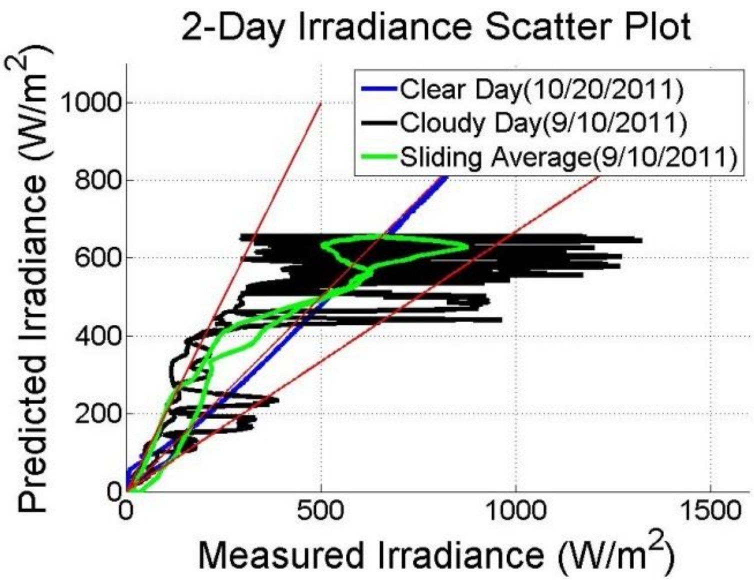


Figure 85- Clear and Cloudy Day Comparison

One test of this algorithm may include adjusting the data cloud or cloud cover weighting based on total energy for the day. A preliminary energy comparison was done by calculating the area under both theoretical and measured irradiance curves, producing Figure 86 below. The scatter low and right of the red line suggests that the prediction is too low. However, this is largely due to over-predicted cloud cover by the NWS.

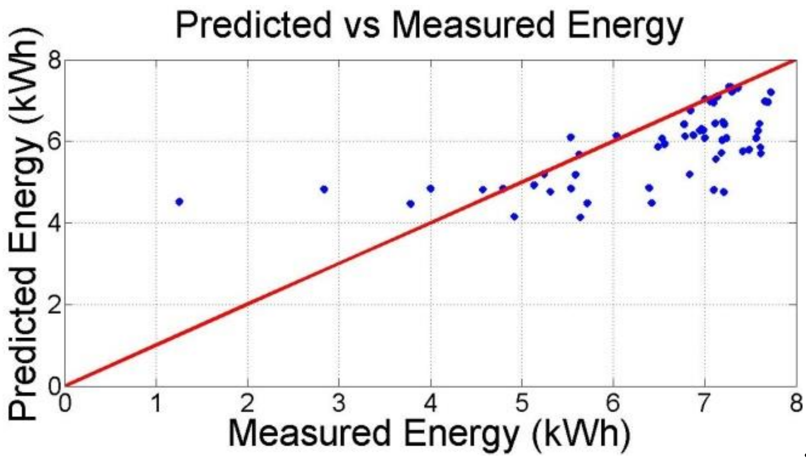


Figure 86 -Predicted vs. Measured Energy per day; over-predicted cloud cover evident

Testing is ongoing for this irradiance prediction method. Once this prediction method is perfected to within an acceptable reliability, predictions can be checked against the solar array's different irradiance sensors located at different corners of the array. This would ideally provide an immediate prediction of impending irradiance based on cloud-level, wind direction and cloud cover.