SANDIA REPORT

SAND2016-3636
Unlimited Release
Printed April 2016

Determination of Duty Cycle for Energy Storage Systems in a Renewables (Solar) Firming Application

David Schoenwald and James Ellison
Sandia National Laboratories

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@adonis.osti.gov
Online ordering:	http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.fedworld.gov
Online order:	http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2016-3636
Unlimited Release
Printed April 2016

Determination of Duty Cycle for Energy Storage Systems in a Renewables (Solar) Firming Application

David Schoenwald and James Ellison
Electric Power Systems Research Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1140

Abstract

This report supplements the document, "Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems," issued in a revised version in April 2016 (see [4]), which will include the renewables (solar) firming application for an energy storage system (ESS). This report provides the background and documentation associated with the determination of a duty cycle for an ESS operated in a renewables (solar) firming application for the purpose of measuring and expressing ESS performance in accordance with the ESS performance protocol.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Dr. Imre Gyuk, program manager for the DOE Energy Storage Systems Program. The authors would also like to express their appreciation to all the stakeholders who participated as members of the Renewables (Solar) Firming Subgroup. Without their thoughtful input and recommendations, the definitions, metrics, and duty cycle provided in this report would not have been possible. A complete listing of members of the Renewables (Solar) Firming Subgroup appears in the first chapter of this report. Special recognition should go to the staffs at Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL) in collaborating on this effort. In particular, Mr. David Conover and Dr. Vish Viswanathan of PNNL and Dr. Summer Ferreira of SNL were especially helpful in their suggestions for the determination of a duty cycle for the Renewables (Solar) Firming application.

Contents

Nomenclature 6
1. Background 7
2. Definition of Renewables (Solar) Firming 10
3. Metrics for Renewables (Solar) Firming 11
4. Source of PV Data 12
5. Philosophy of Duty Cycle Development Process 13
6. Process for Constructing Duty Cycle 14
7. Characteristics of Duty Cycle 15
8. Conclusions 16
9. References 17
Distribution 18

Figures

Figure 1: Schematic of the PNM Prosperity Project 12
Figure 2: Duty Cycle Signal for Renewables (Solar) Firming Application 15

Tables

Table 1. Participants in Renewables (Solar) Firming Subgroup 8

NOMENCLATURE

AC	Alternating Current
ARRA	American Reinvestment and Recovery Act of 2009
AUX	Auxiliary input
BAT	Battery
BESS	Battery Energy Storage System
CABs	Container of Advanced carbon Battery cells
CSV	Comma Separated Values
CDF	Cumulative Density Function
CI	Daily Clearness Index
DC	Direct Current
DOE	Department of Energy
EPRI	Electric Power Research Institute
ESS	Energy Storage Systems
IEEE	Institute of Electrical and Electronics Engineers
kW	kilo-Watts
kWh	kilo-Watt hours
MA	Moving Average
MW	Mega-Watts
MWh	Mega-Watt hours
NNMC	Northern New Mexico College
PJM	PJM Interconnection
PMF	Probability Mass Function
PNM	Public Service Company of New Mexico
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
SNL	Sandia National Laboratories
SoC	State of Charge
UNM	University of New Mexico
V	Volts
VAC	Volts Alternating Current
VDC	Volts Direct Current
VI	Daily Variability Index
VRLA	Valve Regulated Lead Acid

1. BACKGROUND

When the initial effort was undertaken to develop a protocol for measuring and expressing the performance of energy storage systems (“ESS”) in early 2012, it was recognized that, due to the range of ESS applications, not all ESS applications could be addressed at the same time. As a result, it was determined to focus on those applications considered to have the highest priority (i.e., peak shaving and frequency regulation), and after completion of an initial protocol the application of the protocol to additional ESS applications would be pursued. After publication of the initial protocol (see [1] and updated version [2]), the protocol working group was polled to determine which applications they felt should be addressed by the next edition of the protocol. The application of ESS for islanded microgrids and photovoltaic (“PV”) smoothing received the highest level of support. The working group was polled to identify members who were interested in participating in subgroups to develop criteria for each of these new applications. Following the completion of these two applications, additional applications were identified as being very important to the working group. These applications included Volt/Var support, renewables (solar) firming, power quality, and frequency control. The names and affiliations of those who participated in the Renewables (Solar) Firming Subgroup appear in Table 1. The document describing the duty cycle determination for the PV smoothing application is in [3].

From the formation of the renewables (solar) firming subgroup (April 9, 2015) until the completion of their work (July 7, 2015) there were 4 webinar meetings, many e-mail exchanges among subgroup members, and several drafts leading up to the proposed enhancements to the Protocol to cover the renewables (solar) firming application. These enhancements focused on needed terms and definitions, metrics applicable to ESS performance, the applicable duty cycle for the ESS, and the manner in which operational data is to be captured; from this data, performance of the ESS would be reported.

There were several factors discussed within the subgroup that needed to be decided upon as either within or outside the scope of the protocol. Modeling, while considered important, was not considered a use case, and hence was considered to be outside the scope of the protocol. It was also agreed that the effort would not include determining failure mechanisms for the ESS because those were not considered to be within the scope of the protocol. Periodic capacity tests were considered to be a good proxy for the state of health of the ESS. In addition, safety related issues were not considered, as they are also outside the scope of the protocol.

The renewables (firming) subgroup spent considerable time discussing and developing an appropriate duty cycle for assessing the performance of an ESS in a renewables (solar) firming application. Data used in developing the renewables (solar) firming duty cycle was obtained from the PNM Prosperity Project, with permission from PNM (see Section 4). The renewables (solar) firming subgroup discussed which metrics are applicable to measuring and expressing the performance of an ESS in a renewables (solar) firming application. It was determined that all of the metrics applicable to PV smoothing, included in the April 2016 revision of the Protocol [4], were relevant. After finalizing the duty cycle, the renewables (solar) firming subgroup discussed the characteristics of the duty cycle that should be reported in this document (see Section 7). Most of these characteristics relate to the variability of the ESS tracking signal as well as some of the duty cycle statistical properties. The revised version of the Protocol, which incorporates the renewables (solar) firming application was published in April 2016 and appears in [4].

Table 1. Participants in Renewables (Solar) Firming Subgroup

Name	Affiliation
Schoenwald, David	**Sandia National Laboratories**
Balliet, Ryan	Bosch Energy Storage Solutions LLC
Becker, Dagmar	Bosch Energy Storage Solutions LLC
Borneo, Dan	Sandia National Laboratories
Bossart, Steven	National Energy Technology Laboratory
Bray, Kathy	Pacific Northwest National Laboratory
Byrne, Ray	Sandia National Laboratories
Chatwin, Troy	GE Energy Storage
DeLucia, Tom	NEC Energy Solutions, Inc.
Conover, David	Pacific Northwest National Laboratory
Favela, Roberto	El Paso Electric Company
Ferreira, Summer	Sandia National Laboratories
Fife, Mike	Demand Energy Networks
Franks, Ryan	National Electric Manufacturers Association
Fribush, David	Pacific Gas & Electric
Gully, Ben	DNV-GL
Hernandez, Jaci	Sandia National Laboratories
Hone, Matt	Los Angeles Department of Water and Power
Jezierski, Kelly	Next Energy Center Electric Applications Incorporated
Karner, Don	Next Energy Center Electric Applications Incorporated
Kaucic, Robert	GE Power & Water
Kaun, Ben	EPRI
Maguire, Greg	JuiceBox Energy, Inc.
McLellan, Nick	Johnson Controls Inc.
Mulder, Greg	Coffman Electrical Equipment
Murphy, Kelly	Steffes Corporation
Nichols, David	DKN Consulting

Patterson, Glenn	Rosendin Electric, Inc.
Rosewater, David	Sandia National Laboratories
Steiber, Joe	Southwest Research Institute
Sun, Chauncey	UniEnergy Technologies
Vechy, Stephen	EnerSys
Wang, Shawn	Brookhaven National Laboratory
Williams, Ben	ZBB Energy
Wills, Robert	forENGics
Viswanathan, Vish	Pacific Northwest National Laboratory

2. DEFINITION OF RENEWABLES (SOLAR) FIRMING

From an energy storage systems performance standpoint, the following sentence shall serve as our operating definition of renewables (solar) firming.

The application of an energy storage system (ESS) to provide energy to supplement renewable (solar) generation such that their combination produces steady power output over a desired time window.

Thus, the purpose of renewables (solar) firming is to provide energy (conversely, to absorb energy) when renewable generation falls below some threshold (conversely, exceeds this threshold); performed to provide steady power output over a desired time window, usually a period of multiple hours. Typically, the threshold is derived from the forecasted nominal renewable power generation over the desired time window. Thus, the ESS is compensating for the forecast uncertainty in actual renewable generation during that time window.

The method by which the ESS achieves renewables (solar) firming is to discharge power during periods for which renewable generation falls short of the threshold and absorb power when renewable generation exceeds this threshold.

The key factor that differentiates PV firming from PV smoothing is the time duration over which the ESS is attempting to smooth or firm. PV smoothing is attempting to limit the ramp rate of the power output, which results in applying ESS power over one second to one minute time periods. PV firming is concerned with smoothing (or firming) longer time windows, such as 15 minute to multiple hour time periods. PV smoothing is attempting to limit potentially negative consequences to the grid from highly variable PV power output. PV firming is attempting to “fill in” the gaps in PV power output such that the resultant composite power more closely resembles a “block” of energy with upward slopes, magnitude, downward slopes, and total time duration desired by the grid operator. Specific examples of PV firming can be found in Akhil et al. (2013) [5] and Lemaire et al. (2012) [7].

3. METRICS FOR RENEWABLES (SOLAR) FIRMING

The following metrics shall be applied for the purposes of performance testing. To be useful, test procedures must include definitions to narrow the margin for interpretation and increase the repeatability of tests. Terms not defined here shall have their normal dictionary meaning and be applied as such. For a complete list of definitions on ESS performance metrics, see the SNL/PNNL ESS Performance Protocol (2016) [4].

1. System Rating – at ambient conditions
2. Roundtrip Energy Efficiency – for the entire ESS
3. Duty-Cycle Roundtrip Efficiency – for the entire ESS
4. Response Time of ESS in responding to a command signal – does not include communication delay times
5. Ramp Rate
6. Energy Capacity
7. Energy Capacity Stability
8. Reference Signal Tracking – how well does ESS track the reference signal; metric definition is: [reference signal power – ESS power]^2
9. State-of-Charge Excursions
10. Operating Temperature Range

Duty Cycle. A charge/discharge profile that represents the demands associated with a specific application that is placed on an energy storage system (ESS).

Ramp Rate. The rate of change of power delivered to or absorbed by an ESS expressed as a percentage change in rated power over time (percent per second).

Roundtrip Energy Efficiency. The useful energy output from an ESS divided by the energy input into the system over one duty cycle, and expressed as a percentage, and including all system losses as well as any electrochemical, electromechanical, or electrical inefficiency involved in the storage of the energy under normal operating conditions.

Response Time. The time in seconds it takes an ESS to reach 100 percent of rated power during charge or to reach 100 percent of rated power during discharge from an initial power measurement taken when the ESS is at rest.

Stored Energy Capacity. The amount of electric or thermal energy capable of being stored by an ESS expressed as the product of the ESS rated power and the discharge time at rated power.

4. SOURCE OF PV DATA

The data used for this study is from the Public Service Company of New Mexico's Prosperity Electricity Storage Project ("PNM Prosperity").

PNM Prosperity consists of a 500 kW/350 kWh advanced lead-acid battery with integrated supercapacitor (for power smoothing) and a 250 kW/990 kWh advanced lead acid battery (for energy shifting), and is co-located with a 500 kW solar photovoltaic ("PV") resource. The project received American Reinvestment and Recovery Act ("ARRA") funding, and has been operational since 2011. More details and analysis of the project can be found in Roberson, et al (2014) [8] and Willard (2014) [10].

We have received permission from PNM to use both PV and battery power output from PNM Prosperity for this study. This data has a time resolution of one second, and has been archived from 2011 onward. A schematic of the project is depicted in Figure 1.

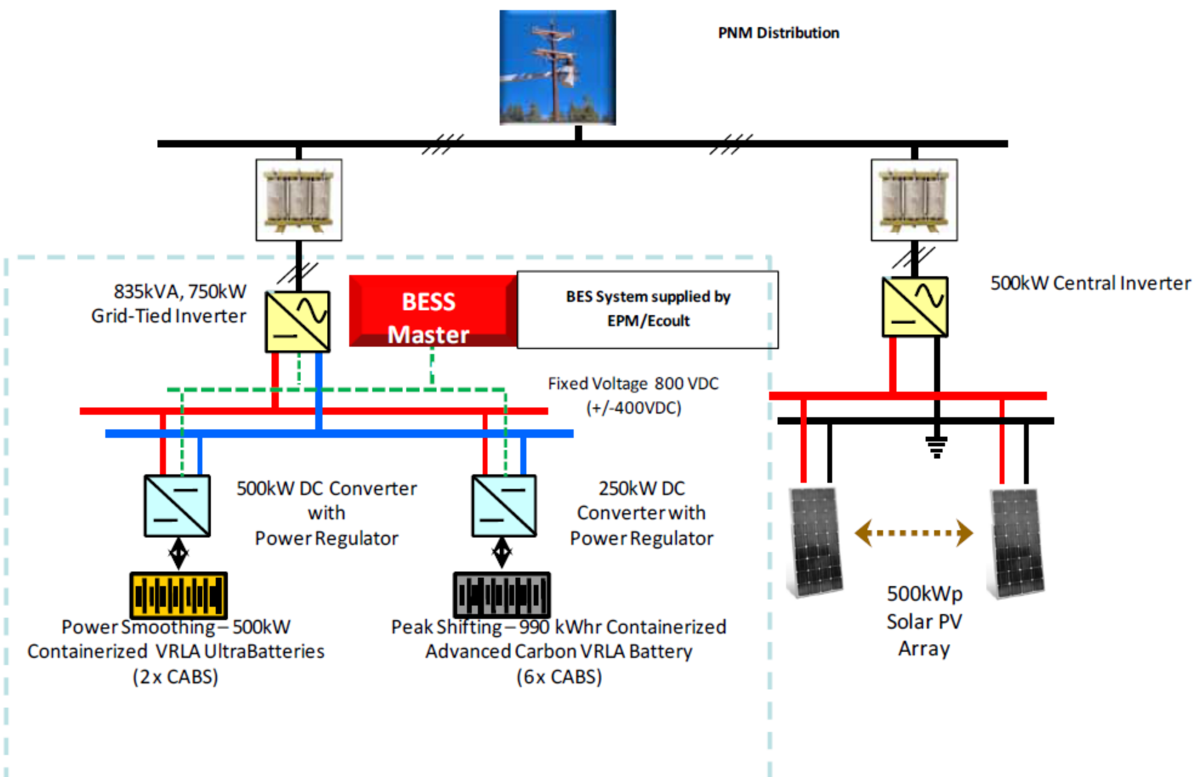

Figure 1: Schematic of the PNM Prosperity Project.

5. PHILOSOPHY OF DUTY CYCLE DEVELOPMENT PROCESS

A duty cycle is a charge/discharge profile that represents the demands placed on an energy storage system ("ESS") by a specific application. A renewables (solar) firming duty cycle should take into account what an ESS would need to do on a daily basis to firm PV power output.

From the start we faced a choice: create many different duty cycle profiles to reflect PV generation variability differences due to differences in regions, weather, and time of year, or create one duty cycle profile that represents a challenging, yet realistic, signal. We chose the latter approach because we believe that it is more straightforward, and that designing an ESS for a challenging yet realistic scenario is most appropriate for this application.

A duty cycle that is not stringent enough would encourage the development of systems that are not robust enough to firm PV power output on challenging days. A duty cycle that is too stringent could specify systems that are more capable (and therefore potentially more expensive) than necessary. Since we are concerned with PV output variability when a significant amount of power can be produced, a 10-hour duty cycle (representing the typical daylight hours of significant PV generation) should be sufficient.

We sought to create such a duty cycle profile by splicing together one-hour segments of actual PV generation obtained from different days. These segments were chosen to capture different PV generation scenarios, which we grouped into mostly sunny, partly cloudy, and mostly cloudy days. In order to make the profile challenging, we sought segments that were moderate to high in the level of PV power generation variability.

Given that cloud cover can rapidly change PV output, we determined that having a 1-second PV output time series was best, though more coarse time resolutions up to 15 seconds can suffice for this application. The data collected at the PNM Prosperity site is of one-second time resolution.

To create a challenging duty cycle, it is necessary to have a quantifiable means of determining the variability of PV power output. For this application, we used the Variability Index ("VI"), described in Stein, et al (2012) [9] (additional measures, not used here, can be found in Hoff and Perez (2010) [6]). In the next section, we outline the procedure employed to construct the PV firming duty cycle.

6. PROCESS FOR CONSTRUCTING DUTY CYCLE

We used the following process to construct the renewables (solar) firming duty cycle.

- Step 1: Locate and download files containing time series data for PV power generation daily profiles. Ideally, the data should have a temporal resolution of one second, though resolutions of up to 15 seconds are acceptable. There should be daily generation profiles for different seasons of the year.
- Step 2: Using Excel, Matlab, or other graphical tools, plot the data from these files to observe the range of variability in PV power among the different days and form a "composite" day.
- Step 3: From the composite day, compute the moving average. Time windows in the 5 to 60 minute range are acceptable, with a 15-minute window considered the nominal value.
- Step 4: Construct the PV power residue = Threshold power value – PV moving average, where the threshold power value represents the value of the desired "firmed" power.
- Step 5: Duty Cycle will be the normalized values of this residue, w.r.t. ESS rated power, +/- 500 kW in this case.
- Step 6: Assess several characteristics of this signal to be sure that it meets assumptions and desired variability.

We used a number of assumptions in constructing the renewables (solar) firming duty cycle. Our sign convention was that a positive duty cycle value means that the ESS is discharging power, and a negative value means that the ESS is in charging mode. We used a 15-minute window length to compute the moving average of the constructed PV power profile. All ramp rates were computed using 1-minute intervals.

7. CHARACTERISTICS OF DUTY CYCLE

Following the process outlined in Section 6, a 10-hour time series for the renewables (solar) firming duty cycle was derived. This time series is graphically depicted in Figure 2.

An Excel spreadsheet containing the full 10-hour time series data for the renewables (solar) firming duty cycle can be downloaded from the link given in Schoenwald (2016) [11].

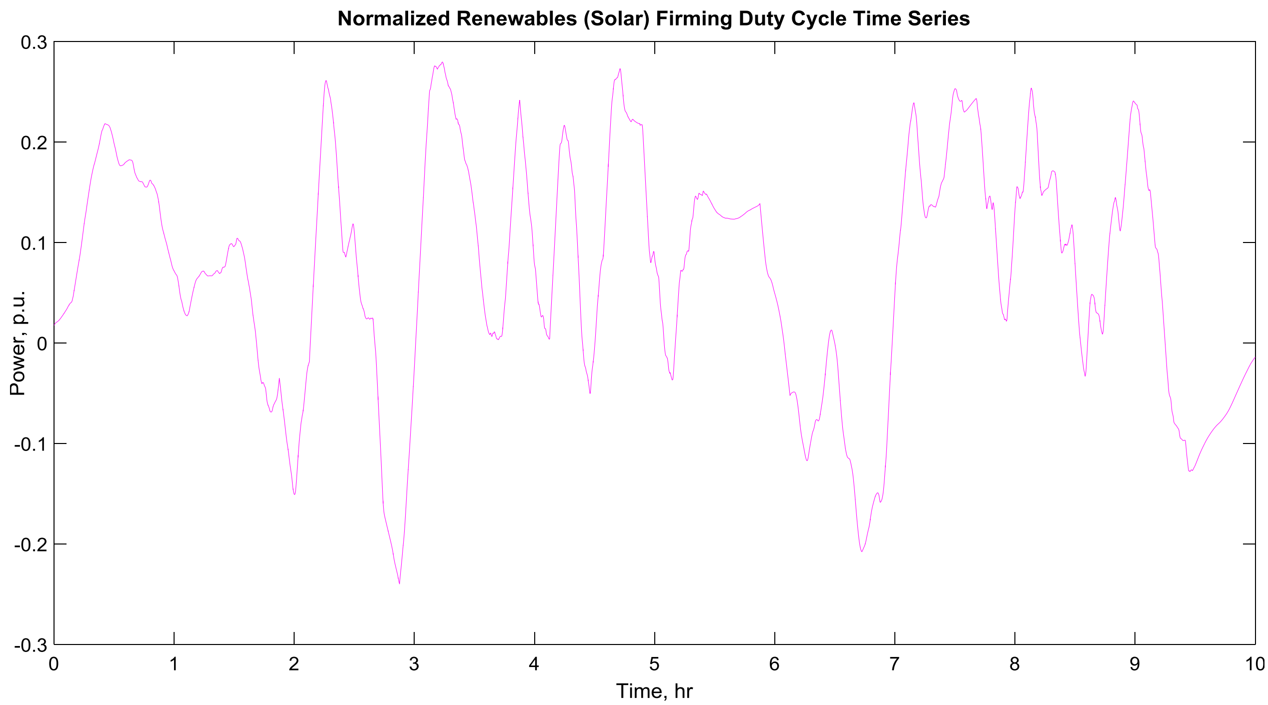

Figure 2: Duty Cycle Signal for Renewables (Solar) Firming Application.

8. CONCLUSIONS

A duty cycle is a charge/discharge profile that represents the demands placed on an energy storage system ("ESS") by a specific application. A renewables (solar) firming duty cycle should take into account what an ESS would need to do on a daily basis to firm PV.

In creating a duty cycle for the renewables (solar) firming application, our overall goal was to have a signal that was challenging yet realistic. Through understanding what an energy storage system tasked with firming PV would need to be able to do, we can get a better sense of the required capacity and characteristics of such a system.

We believe that one can draw the following conclusions:

1) Renewables (solar) firming is an energy smoothing application – it requires a relatively large energy storage capacity and a moderate to low power rating; and
2) The ESS should be designed to perform many charge/discharge cycles per day with little to no degradation in performance.

This methodology of constructing a challenging yet realistic duty cycle can be performed for the particular location and PV system being considered in the renewables (solar) firming application to get precise specifications for the ESS needed. An Excel spreadsheet containing the full 10-hour time series data of the renewables (solar) firming duty cycle can be found from the link given in Schoenwald (2016) [11].

9. REFERENCES

1. Ferreira, Summer, David Rosewater, David Schoenwald, Kathy Bray, David Conover, Michael Kintner-Meyer, and Vilayanur Viswanathan, “Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems,” Sandia National Laboratories technical report, SAND2013-7084, August 2013.

2. Conover, David, Alasdair Crawford, Vilayanur Viswanathan, Summer Ferreira, and David Schoenwald, “Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems,” PNNL-22010 Rev. 1, Pacific Northwest National Laboratory, Richland, Washington, June 2014.

3. Schoenwald, David and James Ellison, “Determination of Duty Cycle for Energy Storage Systems in a PV Smoothing Application,” SAND2016-3474, Sandia National Laboratories, Albuquerque, New Mexico, April 2016.

4. Conover, David, Alasdair Crawford, Jason Fuller, Sri Nikhil Gourisetti, Vilayanur Viswanathan, Summer Ferreira, David Schoenwald, and David Rosewater, “Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems,” PNNL-22010 Rev. 2/SAND2016-3078 R, Pacific Northwest National Laboratory, Richland, Washington, Sandia National Laboratories, Albuquerque, New Mexico, April 2016.

5. Akhil, Abbas A., Georgianne Huff, Aileen B. Currier, Benjamin C. Kaun, Dan M. Rastler, Stella Bingqing Chen, Andrew L. Cotter, Dale T. Bradshaw, and William D. Gauntlett, “DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA,” SAND2013-5131, Sandia National Laboratories, Albuquerque, New Mexico, July 2013, http://www.sandia.gov/ess/publications/SAND2013-5131.pdf.

6. Hoff, Thomas E. and Richard Perez, "Quantifying PV Power Output Variability," Solar Energy, vol. 84, no. 10, pp. 1782-1793, October 2010.

7. Lemaire, Elisabeth, Nicolas Martin, and Per Norgard, “European White Book on Grid-Connected Storage,” European DER Laboratories Report No. R- 003.0, Feb. 2012.

8. Roberson, Dakota, James Ellison, Dhruv Bhatnagar, and David Schoenwald, “Performance Assessment of the PNM Prosperity Electricity Storage Project: A Study for the DOE Energy Storage Systems Program,” Sandia National Laboratories Technical Report, SAND2014-2883, June 2014.

9. J. S. Stein, C. W. Hansen, and M. J. Reno, "The Variability Index: A New and Novel Metric for Quantifying Irradiance and PV Output Variability," in *World Renewable Energy Forum*, 2012.

10. Willard, Steve, “PV Plus Battery for Simultaneous Voltage Smoothing and Peak Shifting,” Final Technology Performance Report, Smart Grid Demonstration Project, Public Service Company of New Mexico, Project No. DE-OE0000230, April 2014.

11. Schoenwald, David, "PV Firming Duty Cycle," Sandia National Laboratories technical report, SAND2016-2544R, Sandia National Laboratories, Albuquerque, NM, March 2016, http://www.sandia.gov/ess/publications/SAND2016-2544R.xlsx.

DISTRIBUTION

External distribution (*distributed electronically unless otherwise noted*):

1 Dr. Imre Gyuk
U. S. Department of Energy
1000 Independence Ave SW
Washington, D.C. 20585-0001
Imre.Gyuk@hq.doe.gov

1 David Conover
Pacific Northwest National Laboratory
David.Conover@pnnl.gov

1 Vilayanur Viswanathan
Pacific Northwest National Laboratory
Vilayanur.Viswanathan@pnnl.gov

Internal distribution (*distributed electronically unless otherwise noted*):

1	MS0576	Raymond H. Byrne	05521
1	MS0613	Summer R. Ferreira	02546
1	MS0613	Christopher Orendorff	02546
1	MS0613	Thomas F. Wunsch	02540
1	MS0734	Anthony Martino	06124
1	MS1033	Robert J. Broderick	06112
1	MS1033	Abraham Ellis	06112
1	MS1033	Sigifredo Gonzalez	06112
1	MS1033	Clifford Hansen	06112
1	MS1033	Jay Johnson	06112
1	MS1033	Matthew S. Lave	06112
1	MS1033	Olga Lavrova	06112
1	MS1033	Joshua Stein	06112
1	MS1104	Charles J. Hanley	06110
1	MS1104	Juan J. Torres	06120
1	MS1108	Stanley Atcitty	06111
1	MS1108	Ana-Marie Beare	06111
1	MS1108	Daniel R. Borneo	06111
1	MS1108	Babu Chalamala	06111
1	MS1108	Jacquelynne Hernandez	06111
1	MS1108	David M. Rosewater	06111
1	MS1140	Laurie Burnham	06113
1	MS1140	Ricky J. Concepcion	06113
1	MS1140	Mohamed Elkhatib	06113
1	MS1140	Ryan T. Elliott	06113
1	MS1140	James Ellison	06113

1	MS1140	Ross Guttromson	06113
1	MS1140	Brian J. Pierre	06113
1	MS1140	Matthew J. Reno	06113
1	MS1140	Dakota Roberson	06113
1	MS1140	Sharon A. Ruiz	06113
1	MS1140	David A. Schoenwald	06113
1	MS1140	Cesar A. Silva Monroy	06113
1	MS1140	Felipe Wilches-Bernal	06113
1	MS1152	Steven F. Glover	01353
1	MS1152	Jason C. Neely	01353
1	MS1498	Erik J. Faye	095461
1	MS0899	RIM-Reports Management	09532
1	MS0899	Technical Library	09536

Sandia National Laboratories