1.0 Introduction

This Technology Performance Report for the Pacific Northwest Smart Grid Demonstration (PNWSGD) project is a project deliverable to the U.S. Department of Energy (DOE). It is a major component of the project's final reporting. The purpose of this document is to present the results of all analysis conducted by the project. As a technology performance report, this document addresses the technologies that were installed and tested during the PNWSGD. The plan for this analysis was reported previously in the project's Metrics and Benefits Reporting Plan (PNWSGD 2013a).

Details regarding the design of the project's transactive control technology and other related project elements are provided in separate project deliverables, including the following:

- PNWSGD Project – Conceptual Design (PNWSGD 2014)
- PNWSGD Project – Interoperability and Cyber Security Plan (PNWSGD 2011).
- PNWSGD Project – Transactive Coordination Signals (PNWSGD 2013b).

Except where necessary to support the representation of analysis results, in this report we refer readers to the related documents to avoid duplicating the material.

This introduction provides a summary of the key points of the project and describes the organization and contents of the report.

1.1 The PNWSGD Project

The PNWSGD was one of 16 regional smart grid demonstration projects that were co-funded by the DOE under the American Recovery and Reinvestment Act of 2009 (DOE 2013). The DOE funding required a minimum of 50% cost-share by the project team.

Battelle Memorial Institute's Pacific Northwest Division; operator of the Pacific Northwest National Laboratory) was the prime recipient of the DOE funds and led the PNWSGD. Another five sub-recipients were infrastructure participants, including IBM (International Business Machines Corp., Thomas J. Watson Research Center), system architect of the transactive coordination system; QualityLogic, interoperability testing; 3TIER (now Vaisala), wind energy forecasting; Alstom Grid, transmission and generation system modeling; and Netezza (acquired by IBM during the project), large-scale data management. Bonneville Power Administration (BPA), a federal regional power marketing agency and transmission system operator, provided funds to support Battelle's activities, data representing the regional system, and actively participated in advising the project. Field demonstration sites in a five-state region of the northwestern United States were hosted by another 11 funding sub-recipient participants, including rural electric cooperatives, a public utility district (PUD), municipalities, investor-owned utilities, and a university campus.

This project implemented one of the world's first transactive coordination systems—a system in which both supply and demand communicate and negotiate the cost and quantity of electrical energy that will be supplied and consumed. Twenty-five of the project's 55 asset systems were made responsive to the transactive coordination system. Other asset systems were installed to improve grid reliability (11 asset systems) or to conserve energy (25 asset systems).

The PNWSGD was planned as a five-year project. The project exceeded that time; it started in December 2009 and concluded in June 2015.

1.1.1 Objectives

The primary objectives stated at the beginning of the PNWSGD project were to accomplish the following:

- Create the foundation for a sustainable regional smart grid that continues to grow after the completion of this demonstration project.
- Develop and validate an interoperable communication and control infrastructure using incentive signals to coordinate a broad range of customer and utility assets, including demand response, distributed generation and storage, and distribution automation; engage multiple types of assets across a broad, five-state region; and extend from generation through customer delivery.
- Measure and validate smart grid costs and benefits for customers, utilities, regulators, and the nation, thereby laying the foundation of business cases for future smart grid investments.
- Contribute to the development of standards and transactive control methodologies for a secure, scalable, interoperable smart grid for regulated and non-regulated utility environments across the nation.
- Apply smart grid capabilities to support the integration of a rapidly expanding portfolio of renewable resources in the region.

1.1.2 Regional Geographical Map

Figure 1.1 shows a regional geographical representation of the project. This map identifies the geographical locations of project sites in relation to political boundaries, energy balancing authority boundaries, major transmission, major regional hydro generation resources, major regional renewable energy resources, major regional load centers, and major conventional electrical generation. Of note is the geographic scope of the effort. The scope covers two time zones and five states. This project is, to the best of our knowledge, the first to deploy technology intended to coordinate the response of multiple utilities across a region to provide a benefit to the region. Note that Inland Power, shown in the figure, was an original member of the project team but withdrew from the project shortly after it started.

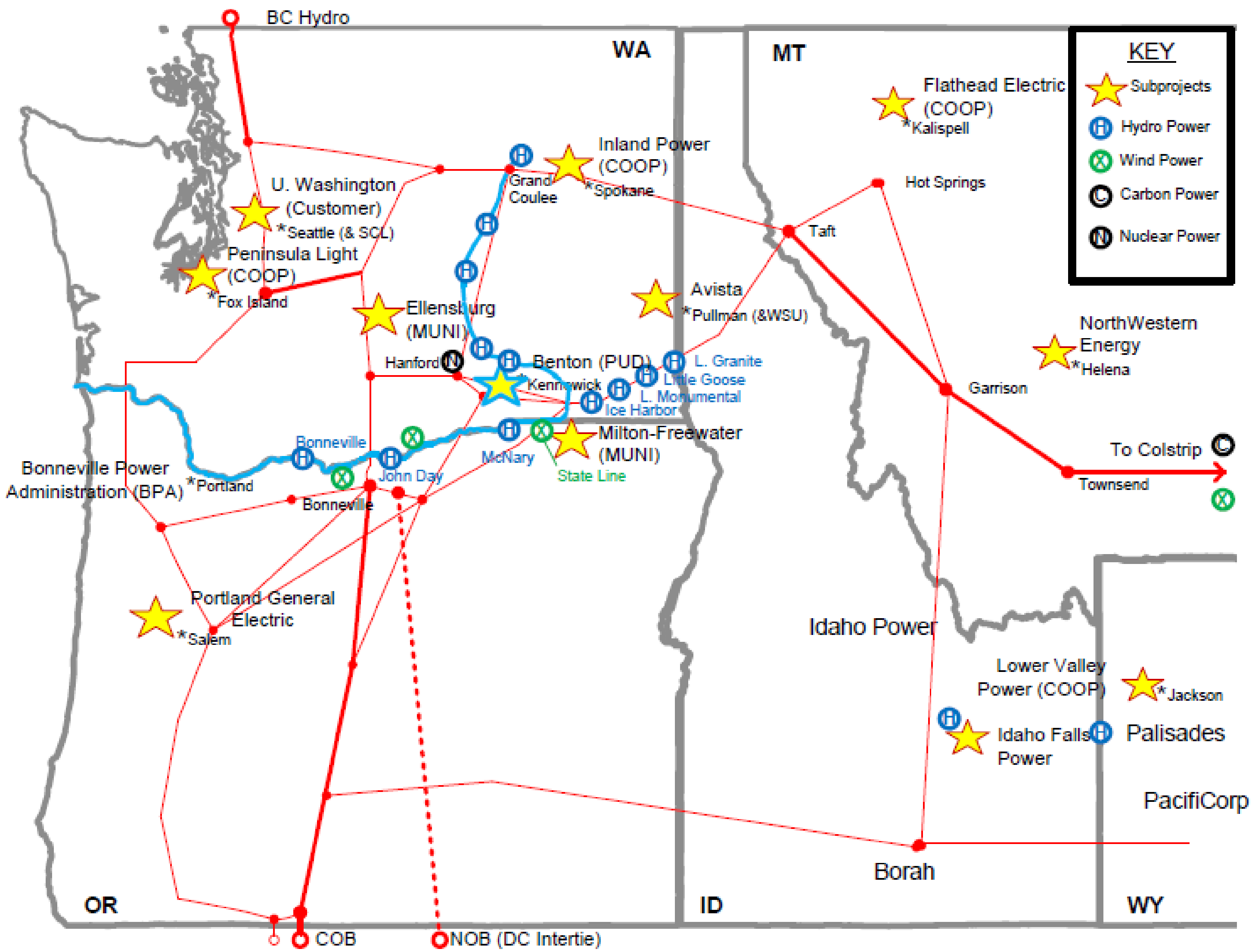

Figure 1.1. PNWSGD Geographical Region, Including Participants' Locations and Major Generation and Transmission Corridors

Pacific Northwest SMART GRID DEMONSTRATION PROJECT

1.2 Technical Approach

The project organized its technical approach around the asset systems deployed by the participating utilities. The PNWSGD defines an *asset system* as “all the components that are needed to provide desired smart grid functionality.” DOE provided guidance making a further distinction between the components based on whether they had been paid for with project funding (*project*) or not (*system*). This distinction was used during the reporting of quarterly build metrics to DOE, but these distinctions are not critical to the assessment of asset-system costs and benefits in the PNWSGD analysis approach. The project’s quarterly build metrics are available at (DOE-OE 2015).

Regional utilities competed for the opportunity to participate in the PNWSGD by responding to a solicitation from BPA during the fall of 2009. Respondents were asked to identify which assets or systems they were willing to allow to respond to the planned time-varying incentive signal and to identify smart grid technologies they had already installed, planned to install, or proposed to install as a part of the project. From the responses, 12 utilities were selected for the proposal and subsequent project. As noted earlier, one utility, Inland Valley, withdrew from the project shortly after funding was awarded.

The project’s tests were organized into three categories of smart grid functionality:

- Conservation and efficiency − asset systems that were installed to conserve energy or to improve efficiency. Targeted efficiencies may include either operational efficiencies or energy efficiencies.
- Demand-responsive (Transactive) − asset systems that have been installed responsive to demand-response signals from the project’s transactive system
- Reliability − asset systems that have been installed to provide more reliable service to distribution customers.

An asset may have been used in more than one of the test categories.

1.3 The Demonstration Test Sites and Asset Systems

In this document, we summarize the performance of smart grid technologies that were installed and implemented at the project’s 13 field sites. The owners of these field sites selected commercial smart grid technologies that they were interested in and selected vendors to install the technologies. The field site owners paid at least half of the technologies’ costs, and the DOE paid the other half. Table 1.1 lists the field sites, field site owners, and technologies that were installed by the PNWSGD project.

Table 1.1. Site Owners, Sites, and Asset Systems of the PNWSGD

Site Owners	Field Sites	Asset Systems	Cat.[a]
Avista Utilities (Avista Corporation 2013)	Pullman, WA, including parts of the WSU campus	Voltage Optimization	1 & 3
		Configuration Control for Optimization	3
		Smart Transformers	3
		Residential Loads and Web Portals	1 & 3
		AMI and In-Home Displays	3
		Biotechnology Generator for Outage Prevention	2
		Configuration Control for Optimization (FDIR)	2
		WSU Controllable HVAC Load	1
		Controllable WSU Chiller Load	1
		Diesel Generator	1
		WSU Generator 1	1
		WSU Generator 2	1
Benton PUD (Benton PUD 2011)	Reata Substation, Kennewick, WA	DataCatcher™ and AMI	2
		Demand Shifter™ and DataCatcher	1
City of Ellensburg (Ellensburg 2013)	City of Ellensburg Renewables Park, Ellensburg, WA	Recloser Switch	2
		Polycrystalline Flat Panel 58 kW PV System	3
		Thin-Film Solar Panel 54 kW Array	3
		Honeywell WindTronics 1.5 kW Model WT6500	3
		Windspire® 1.2 kW Wind Turbine	3
		Home Energy Int. 2.25 kW Energy Ball® V200	3
		Southwest Windpower 2.4 kW Skystream 3.7®	3
		Bergey WindPower 10 kW Excel 10	3
		Tangarie Alternative Power 10 kW Gale® Wind Turbine	3
		Urban Green Energy 4 kW Wind Turbine	3
		Ventera Wind 10 kW Turbine	3
		Wing Power 1.4 kW Wind Turbine	3
Flathead Electric (Flathead Electric 2013)	Libby, MT	AMI for Outage Recovery − Libby	2
		In-Home Displays − Libby	1
		Demand-Response Units − Libby	1
		Smart Appliances − Libby	1
	Haskill Substation, MT	AMI for Outage Recovery − Haskill	2
		In-Home Displays − Haskill	1
		Demand-Response Units − Haskill	1
		Smart Appliances − Haskill	1

Table 1.1. (cont.)

Site Owners	Field Sites	Asset Systems	Cat.[(a)]
Idaho Falls Power (Idaho Falls Power 2013)	Idaho Falls, ID	Automated Voltage Reduction	1 & 3
		Automated Power Factor Control	2
		Distribution Automation	2
		Water Heater Control	1 & 3
		PHEV, Solar, and Battery Storage	1
		Thermostat Control	1 & 3
		In-Home Displays	3
Lower Valley Energy (Lower Valley Energy 2013)	Teton-Palisades Territory, WY	Existing AMI and In-Home Energy Displays	3
		Demand-Response Units	1
		Demand-Response Units/AMI	2
		Adaptive Voltage Regulation	3
		SVC for Power Factor Improvement	3
		Battery Storage System	1
		20 kW Solar Photovoltaic System	3
		Four 2.5 kW WindTronics Wind Turbines	3
City of Milton-Freewater (City of Milton-Freewater 2013)	Milton-Freewater, OR	Load Control with Demand-Response Units	1
		Conservation-Voltage-Regulation Peak Shaving	2
		Voltage-Responsive Grid-Friendly DRUs	1
		Conservation from CVR on Feeders 1-4	3
NorthWestern Energy (NorthWestern Energy 2013)	Helena, MT	Automated Volt/VAr Control − Helena	3
		Fault Detection, Isolation, and Recovery	2
		Demand-Response Units	1
	Philipsburg, MT	Automated Volt/VAr Control – Philipsburg/Georgetown	3
Peninsula Light Company (Peninsula Light Company 2013)	Fox Island, WA	Load Reduction with Load-Control Modules	1
		CVR with End-of-Line Monitoring	1 & 3
		Padmount & Overhead Automated Switching	2
Portland General Electric (Portland General Electric 2013)	Salem, OR	Residential Demand Response	1
		Commercial Demand Response	1
		Commercial Distributed Standby Generation	1
		Battery Storage in High-Reliability Zone	1
		Distribution Switching and Residential/Commercial Microgrid	2

Table 1.1. (cont.)

Site Owners	Field Sites	Asset Systems	Cat.[a]
University of Washington Facilities Services (University of Washington Facilities Services 2011)	University of Washington Campus, Seattle, WA	Steam Turbine	1
		Diesel Generators	1
		Solar Renewable Generation	3
		Direct Digital Controls	1 & 3
		FEMS Data for Campus Building Managers	3
		Impact of Energy Reports to Building Managers	3

Key to test-case categories: 1-transactive coordination, 2-reliability, and 3-conservation and efficiency.

AMI = advanced metering infrastructure
CVR = conservation voltage reduction
FDIR = fault detection, isolation and restoration
FEMS = Facility Energy Management System
HVAC = heating, ventilating, and air conditioning
PHEV = plug-in hybrid electric vehicle
PV = photovoltaic
SVC = static VAr compensator
VAr = volt-amperes reactive
WSU = Washington State University

Each individual utility chapter (Chapters 7 – 17) describes the mapping for the site owner's asset systems within its distribution system. The PNWSGD referred to these diagrams as *layout diagrams*. They proved very useful for referencing the relationships between distribution system data and the asset systems. They also point out the potential for confounding results at places where the asset systems overlap and may influence the results of each other.

1.4 Demonstration Data and Data Processes

Over the course of the project about 16 TB of data were collected. The project followed its cyber security risk management process in the design, implementation, and operation of the transactive control system and in the approach used to collect the technical and engineering data for the project. Please refer to the project's Interoperability and Cyber Security Plan for details (PNWSGD 2011).

The data collected by the project is of two major types: data having a prediction horizon and data having no prediction horizon. The transactive system consumes and creates predictions. Each transactive incentive signal, for example, includes predictions for a series of 56 future time intervals. The PNWSGD often referred to this predictive data simply as *transactive data*. Other project data does not include predicted intervals. These other data—meter readings, for example—were often collected in real time as series of time intervals.

Data statistics for the data collected by the project are summarized in Table 1.2. The project collected and organized an expansive data archive documenting the performance of the systems and various technologies involved. Battelle and DOE are working on the protocol for making the data available to researchers and students after the project has concluded.

Table 1.2. Data Statistics

Volume	Velocity	Data Type	Multiplicity
~16 TB of data stored on an IBM PureData System (Netezza)	Near real time	Configuration files and location information	For each transactive node and test case
	Daily – historical utility data uploads	Transactive signal data	Incentive signal, resource, and load predictions
		Measurement data	Feeder (substation and end-of-line), PV, Wind, AMI, etc.
	Manual – monthly, yearly or one-time submissions of data	Weather data	Actual data from MesoWest and typical meteorological year data
		Test and device events	Status reporting
		System management events	System logs

The project experienced significant problems with consistent reporting of data and data quality. As a result, we are concerned that many utilities are not prepared to manage the large volumes of data that can be generated by smart grid technology, in particular detecting and correcting equipment problems and faulty data. New tools are needed to enable utility operators to detect intelligent end-device or sensor problems and prevent bad data from entering smart grid systems.

1.5 Organization of this Report

This Technology Performance Report has two volumes. This volume contains information about the technologies deployed by the project and their performance. The second volume is the Interoperability and Cyber Security report. Due to the sensitivity of the information contained in that volume it has limited distribution.

This volume consists of summary chapters covering

- the transactive coordination system,
- conservation and efficiency test cases,
- transactive coordination test cases, and
- reliability test cases.

The transactive coordination system chapter (Chapter 2) presents background on the design and implementation of the transactive coordination system, assessment of performance of the system relative to BPA system events, and the results of modeling and simulation of the regional system and utility assets considering a scaled-up implementation.

Chapters 3, 4, and 5 summarize the findings for the 3 categories of tests across the 11 participating field sites. Conclusions are discussed in Chapter 6.

Chapters 7 through 17 address details from the analyses of all of the utilities' asset systems that they demonstrated during the PNWSGD. Each of the site chapters is intended to be self-contained. The following discussion provides background on the methods used in analyzing and reporting the tests for the utility projects. This should help in understanding the material presented in Chapters 7 through 17.

The analysis of data generated by the utility participants was an ambitious undertaking. The participants provided data from a variety of smart grid asset systems across the three categories of test cases: transactive coordination, reliability and conservation, and efficiency.

With the overall amount of time available for analysis there were inherent limits to the amount of time that could be spent on each individual test case. For many of the test cases there were multiple iterations with the corresponding utility to answer questions about the data, fill in missing data, correct time labels, provide metadata, and so on. Only when this data triage process was complete and the data were put into a standard format could the analysis proceed. In some cases it was not possible to complete this step and the test-case analysis could not be completed.

This was a field project and the challenges in working with the data are characteristic of such a project. The participating utilities are operational entities for which meeting the needs of their customers naturally comes first. The utilities were cooperative in working with the Battelle team to address questions about the data, but even so, there were limits to what they could do.

The PNWSGD was a *demonstration*. The Principal Investigator took this to mean that benefits were to be *verified* from the field data that the project collected. This is a higher bar than the creation of a business case for a technology. Early in the PNWSGD, project staff sat face-to-face with the utility staff to help define their asset systems, including the definition of testable objectives, the definition of metrics by which those objectives might be verified, data that would be needed, and the control of potentially confounding influences. The project encouraged the careful definition of baseline control groups, where appropriate, so that meaningful side-by-side comparisons might be possible between the performances of those who were affected by a test system and those who were not. The project next worked with the utilities to collect the data into the project's relational database. This was an iterative process, because the project had to work with a utility if their data were found deficient. A simplified *view* of the database was created for each utility to support the analysis of its assets. A data dictionary was created for each view, and this dictionary defines each named data series that is available to analysts. Finally, most of the analysis was completed and reported by Battelle staff. Some utilities chose to also conduct their own analysis, and where this occurred, the results of the utilities' analyses have been included. We encourage other researchers to work with the data, and where possible, perform more in-depth analysis and confirm or correct the project's analysis results.

The discussions in the following test chapters about the asset systems tested by each utility have these three subsections in common:

1. Introduction − The reader is introduced to the asset system and its components. This subsection includes a compilation of the system's annualized costs.
2. Available data and characteristics of the asset − Events, if relevant, are shown or listed. The relevant data series to be used by the analysis are shown at the level of aggregation available to analysts. Data problems and remedies, if any, are described. Assumptions are stated.
3. Analysis and analysis results − Analysis methods and results, if supported, are stated. The descriptions of methods are terse, so as not to repeat the details of methods that were used similarly for multiple asset systems. The monetary impacts that directly follow from the analysis are compiled.

Annualized costs. The project worked with each utility to capture the costs of its asset systems. The utilities were advised to state the costs that would be incurred for the *next* implementations of their systems, thus giving them permission to omit the research and organizational costs that were, perhaps, unique to the PNWSGD. In this cost model, the starting point is critical. For example, it must be made clear whether the costs of existing advanced metering infrastructure that are needed by an asset system were included or not. The set of components should include all devices and subsystems that must exist if the asset system's functionality is to be achieved. The project elected to annualize the costs. Subsystems having different lifetimes are thereby accommodated by presuming that each subsystem is replaced after its lifetime and maintained in perpetuity. Where a subsystem was used in more than one of a utility's asset systems, its costs were allocated proportionally among them. The present value and annualized equivalent costs were calculated by discounting the future lifecycle costs at a 7% discount rate.

Monetized benefits. The PNWSGD intended to evaluate all of the anticipated benefits and the monetized values of all of the benefits, from which cost-benefit analysis could be completed and reported. The PNWSGD fell short in this effort. The benefits, based on the project's analysis methods and available data, often fell short of those anticipated or were not, in fact, convincingly demonstrated at all. The monetization of energy benefits from the utilities' perspectives followed from the costs of wholesale electricity rates in the Pacific Northwest, which remain relatively low. The calculated values of deferred energy purchases and avoided demand charges were, therefore, often less than compelling. Softer outcomes, like changes in truck rolls and changes in operations costs, were not consistently available or captured across the multiple organizations. And even fewer of these indirect benefits are verifiable to the degree that they could be claimed as having been *demonstrated*. A parallel effort by BPA generated business cases for the classes of tested asset systems.

The analysis approach by test-case categories is summarized below.

Analysis of reliability asset systems. The goal of these asset systems was to improve distribution system reliability. From the perspective of a *demonstration*, metrics should verify that the circuits are more reliable after the installation of the asset system than before. This is challenging because the region's circuits are already very reliable, and the asset systems strive to further reduce what are infrequent events. Outages are as unpredictable as the weather. Regardless, the project attempted to use existing, accepted reliability indices to observe impacts and trends. A long history of circuits' performance was requested. Monthly assessments are important if useful trends are to be observed. There is a troubling encroachment of self-reported indices for the valuation of reliability asset systems. These are useful for the formulations of business cases, but they are backward-looking and do not seem to truly verify improved system performance going forward.

Conservation and efficiency assets. These asset systems were to conserve energy or achieve operational efficiencies. The project attempted to confirm that the circuits or premises that received the asset system used less energy after the asset system had been engaged than before. Where available, control groups were used to mitigate otherwise uncontrolled influences like load growth, affluence, etc. The treatment and control groups were often found to be dissimilar, which might be attributed to selection or self-selection biases. Knowing the precise date of the installation or precise timings of the applications was critical. Much historical data was needed from before the installation or application of the asset system. The comparison of historical and recent data was exacerbated by the fact that new meters themselves were sometimes components of the systems being tested.

Demand-responsive (transactive) asset systems. These systems were intended to modify (usually curtail) energy consumption during relatively short events. The project requested that these systems automatically respond to advice from the PNWSGD transactive system, but the coincidence between the utilities' reported events and the transactive system's events was found to be poor. The project therefore focuses on quantifying the impacts of the asset systems on power during the events, during the rebound hour immediately following events, and throughout days that events had occurred. This entailed creating baselines that emulated power at the pertinent feeders or premises as if the events had not occurred. Where a useful control group was established, the consumption of the control group could be normalized to be as similar as possible to the test group at times that events were idle. Alternatively, linear regression models of the test groups' power were created to represent their characteristic behaviors. The actual power consumption of the test group was then compared with the *modeled* or *controlled* baselines. If an impact had occurred, it should be evident as a difference between the test and baseline powers during the event periods. It is critical that the list of event periods is accurate so analysts know where to look for these differences. This analysis also relies heavily on the accuracy and precision of fine-interval metering. A 15-minute event may be difficult to detect with 1-hour meter intervals. The calculated impact will become diminished if the meters' intervals misalign with the asset-system events or if the meters' timestamps have not been calibrated to a precision such that their measurements of the short events will be aligned. Finally, the meter points themselves must, in fact, monitor the asset system's impacts and must be close enough to the impacts that the impact might be measureable among the meters' baseload and noise.