California Energy Commission

STAFF REPORT

Benefits and Costs of PIER Research Enabling Synchrophasor Applications

California Energy Commission

Edmund G. Brown Jr., Governor

MAY 2016 | CEC-500-2016-036

California Energy Commission

Adrienne Kandel
Primary Author(s)

Adrienne Kandel
Project Manager

Fernando Piña
Office Manager
ENERGY SYSTEMS RESEARCH OFFICE

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

ACKNOWLEDGEMENTS

Thanks to the following individuals who provided useful information or review comments.

Al Alvarado, California Energy Commission
Jean Baronas, California Energy Commission
Silas Bauer, California Energy Commission
Bharat Bhargava, Electric Power Group
Merwin Brown, California Institute for Energy and the Environment (CIEE), retired
Lloyd Cibulka, CIEE
Jim Detmers, Power Systems Resources, LLC
David Dieser, California Independent System Operator (California ISO)
Joe Eto, Lawrence Berkeley National Laboratory
Pedro Gomez, California Energy Commission
Mike Gravely, California Energy Commission
David Hawkins, KEMA
Christopher Johnson
Cindy Li
Richard McCann, Aspen Environmental Group
Jim McIntosh, California ISO, Retired
Christopher McLean, California Energy Commission
Linda Monge Guerrero, California ISO
Damir Novosel, Quanta Technology
Jamie Patterson, California Energy Commission
Phil Pettingill, California ISO
Fernando Piña, California Energy Commission
Marc Rothleder, California ISO
Heather Sanders, California ISO
Margaret Sheridan, California Energy Commission
Angela Tanghetti, California Energy Commission
Vickie VanZandt, Western Electricity Coordinating Council
David Vidaver, California Energy Commission
Robert Yinger, Southern California Edison

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Benefits and Costs of PIER Research Enabling Synchrophasor Applications is a staff report on the applications and expectations arising from this avenue of research.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Synchrophasor technologies enable a revolutionary method of determining electric grid stability through measurement of electrical wave phase angles at two or more places on the grid. Synchrophasor applications offer a range of capabilities, including monitoring stresses to the electric power grid, presenting the information in a usable format to grid operators, and ultimately enabling automatic feedback and system correction. Since 1998, the California Energy Commission's Research and Development (R&D) Program has been funding research to develop and demonstrate smart grid applications for synchrophasor technologies. These applications will sharply decrease the risk of a major customer power outage.

By 2020, the effects of R&D synchrophasor research and related applications will save Californians from $210 million to $360 million in avoided customer outages costs because of increased reliability, plus $90 million per year in economic benefits. There is a potential for additional savings, depending on policy decisions and research outcomes. These projected benefits more than offset the $11.4 million in costs that Energy Commission R&D has invested in this research. The savings realized from these synchrophasor applications are substantial because millions of Californians using energy will benefit from the improvements in utility grid reliability. About a quarter of the anticipated benefits are achieved by enabling grid operators to use renewable resources and transmission equipment both reliably and more efficiently. In addition, synchrophasor research will help California reliably meet its renewable and greenhouse gas policy goals.

Keywords: California Energy Commission, Public Interest Research Program, phasor, synchrophasor, smart grid, benefit cost, reliability, transmission capacity, outage, outages, blackout, blackouts, renewable integration

Please use the following citation for this report:

Kandel, Adrienne (California Energy Commission). 2016. *Benefits and Costs of PIER Research Enabling Synchrophasor Applications*. California Energy Commission, Energy Research and Development Division. Publication Number: CEC-500-2016-036.

TABLE OF CONTENTS

Page

Acknowledgements....i

Preface....ii

Abstract....iii

Table of Contents....iv

List of Figures....v

List of Tables....v

Executive Summary....1

Introduction....**Error! Bookmark not defined.**

Findings....**Error! Bookmark not defined.**

Conclusions....**Error! Bookmark not defined.**

CHAPTER 1: Synchrophasors and California....5

What Are Synchrophasors....5

Usefulness of Synchrophasors....6

Avoidance of Customer Outages....6

Improved Power Modeling and Planning....7

Increased Absorption of Renewable Energy....8

Transmission Planning and Potential Cost Savings....8

Other Potential Uses of Synchrophasor Technology....9

Distance Load Balancing....9

Energy Commission Role....10

Benefits of PIER-Funded Work....13

CHAPTER 2: Quantifying Economic Benefits of PIER Synchrophasor-Related Research....15

Large-Scale Customer Outage Avoidance....15

Looking Forward....15

Looking at History....16

Reducing the Cost of Electricity....21

Increased Absorption of Wind Energy....21

Increased Use of Transmission Lines: California-Oregon Intertie....21

Pending Further Research....22

Development and Deployment Costs....22

Research Costs 22
Net Effect of PIER Research on Electricity Rates 22
Benefit Cost Analysis 23
Attribution 24
GLOSSARY 27
REFERENCES 28
APPENDIX A: Assorted Calculations A-1
Annualized California Share of WECC-Wide Savings A-1
Sectoral Weights Used to Estimate Cost of Customer Outages A-1
Probabilistic Combination of Reliability Value Estimates A-1
Alternative Approach: Direct Probabilistic Development of Reliability Value A-2
APPENDIX B: Synchrophasor-Related Work Funded by PIER B-1

LIST OF FIGURES

Page

Figure 1: PIER-Funded Business Case Gave Direction for Synchrophasor-Related Research 12

LIST OF TABLES

Page

Table 1: Estimates of Reliability Value of Synchrophasor Research 20
Table 2: Point Estimates of Benefits Given Different Approaches to Attribution (Year 2010 Dollars) 26
Table 3: PIER Synchrophasor Projects Through 2011 1

EXECUTIVE SUMMARY

Introduction

California must integrate increasing amounts of intermittent or inconsistent renewable energy and self-generation into an electricity grid that was built for simple one-way delivery of electricity from dependable generators to fairly predictable consumer demands. Changes in the power infrastructure, operating tools, and procedures are necessary to take advantage of new possibilities, such as the sale of rooftop solar electricity back to the grid.

The grid has difficulties accepting and changing direct current variable generation, for example from wind and solar energy systems, because electricity travels through the grid as alternating current in wave form. Alternating current waves from different sources need to be properly synchronized for all sources of electricity to properly and efficiently transmit from the source to the end user. In addition, the California electricity grid must be able accommodate high electricity demand from electric vehicles charging at diverse locations and times.

California needs an electric grid intelligent enough and equipped with the right technologies to manage the increasing electrical demand without additional power outages or unwarranted cost increases. Utilities and system operators already have obstacles to overcome to make sure the grid is supplied with enough electricity to satisfy the demand fluctuations, particularly during summer critical peak periods (4 p.m. – 7 p.m.). With the new variables mentioned, such as renewable generation and electric vehicles, more research is critical for these technologies to integrate into California's grid with minimum cost and waste.

To address these concerns, from 1998 through 2011, the California Energy Commission's Research and Development Program provided $11.4 million to fund innovative research on synchrophasor applications and participated in the demonstration of these applications and dissemination of information.

Phasors are measurements of power system quantities, typically voltage and current, that vary at the 60 hertz (Hz) system frequency. Phasor measurement units, called *synchrophasors*, are devices that time-stamp these phasors by means of a highly accurate time reference, such as a GPS clock, so that phasors throughout the system are synchronized. Synchrophasors allow system operators to see in real time the condition of the power system with great detail and accuracy over a wide area. This quality and frequency of information are not possible with conventional monitoring technologies, such as supervisory control and data acquisition (SCADA). The synchrophasor technology offers a wide spectrum of advanced applications in previously unattainable power system monitoring, control, and reliability enhancement.

Findings

The Energy Commission funded the business case for synchrophasor research, identifying dozens of possible applications and creating a research and development (R&D) roadmap to plan synchrophasor deployment. The Energy Commission also funded developing applications for a synchrophasor-based platform to make grid status measurements faster and more precise. That platform is used by the California Independent System Operator to let operators visualize system operation information in real time. Through projects, modeling, and automation research, the Energy Commission succeeded in attracting U.S. Department of Energy (DOE) funding and in focusing synchrophasor research on California rather than elsewhere.

The Energy Commission R&D Program collaborated with Southern California Edison (SCE) and other agencies to use synchrophasor data to develop new load models that help warn the grid operator when voltage problems might arise and allow for evaluation of solutions that may help reduce the length of voltage sags, or power outages. With synchrophasor-informed models, planners will be able to choose more intelligently the locations and sizes of electricity generation, transmission, and storage facilities. With better data, modelers could anticipate congestion on the grid more accurately and devise local real-time electricity prices that better capture the cost of this congestion. More accurate real-time pricing would provide incentives for customers to use electricity when lines are less congested.

Synchrophasors can also be used to provide operators with a more accurate view of the behavior of renewable generation and distributed generation on the grid. The increased grid visibility helps operators avoid instability when periods of high wind and solar production coincide with periods of low electrical demand. Using synchrophasors to remedy this problem will avoid wasted generation and save money. The increased use of existing wind generation could save ratepayers an estimated $25 million to $150 million per year in lower electricity rates, most likely around $90 million.

Furthermore, synchrophasor application are able to clearly show moment to moment grid conditions across a wide area and could reduce the need for natural gas-fueled firming power plants close to renewable power plants. *Firming power plants* correct for the variability of renewable energy resources while providing voltage support, and the need for them to be near the renewable energy source means there must be more firming capacity built than the system needs in total. Synchrophasors have the potential to allow already existing but distant firming sources to provide reliable firming power. Staff estimates the potential benefit of avoiding construction of new firming plants to be about $10 million to $30 million per year.

Another possible application for synchrophasors is raising the operating transfer capacity of transmission lines closer to the thermal limits without increasing the risk of electrical blackouts. Electrical blackouts have been particularly hard for planning engineers to reproduce in simulations due to the limited data provided by older systems like SCADA. Utilities and grid operators, therefore, found no way to catch and prevent repeats of the problem. To ensure grid reliability, the utilities' response was to derate the transmission interties, lowering the maximum amount of power below what had previously been permitted. This reduction of the transmission interties is expensive because it lessens the use of existing capital assets and access to low-cost energy sources. Several experts suggest that increased transmission along the same lines will be possible once synchrophasor technology provides for better controls. In particular, staff estimates that rerating the crucial California-Oregon Intertie transmission corridor upward by 200 megawatts (MW) will save Californians between $8 million to $19 million per year in reduced electricity rates.

Conclusions

Combining diverse parties' estimates of customer outage probabilities and costs, Energy Commission staff estimated that synchrophasor technologies should save Californians from $210 million to $360 million in customer outage costs per year by 2020. These benefits are in addition to $90 million per year in reduced electricity costs and the potential for saving $18 million to $39 million more per year should the technologies prove fruitful in avoiding firming power costs and allowing transmission line rerating. This benefits estimate more than offsets the Commission's $11.4 million R&D investment.

An alternative, more rigorous approach used by staff to calculate the value of avoided customer outages gathers all the component report estimates mentioned above and combines them probabilistically, with heavy weighting toward those that are most researched and supported. The approach yields considerably higher benefits centered at $410 million per year, with first and third quartiles of $220 million to $540 million. Thus, the treatment of benefits in this study as centering around $286 million is conservative.

This report derives the net present value and annualized values of benefits, looking forward from 2011. It estimates a present value of net benefits at $2.7 billion, with ratepayer benefits outweighing ratepayer research and deployment costs by a ratio of more than 20 to 1. The annualized benefit of PIER-funded synchrophasor research is estimated at $260 million per year, where annualized value is an average of each year's benefits minus costs from now through 2030, discounted to correct for the money that ratepayer dollars could have earned in alternative investments. These calculations are conservative in that benefits are assumed not to grow after 2020. This report contends that without Energy Commission R&D leadership, synchrophasor and associated development would not have progressed to where they are today and would not be tailored to California requirements, and California might face even more serious problems integrating renewables and electric vehicles.

CHAPTER 1: Synchrophasors and California

California must integrate increasing amounts of renewable energy and self-generation into a grid that was built for simple one-way delivery of electricity from dependable generators to fairly predictable consumers. Changes in the power infrastructure, operating tools, and procedures are required to take advantage of new possibilities, such as the sale of rooftop solar electricity back to the grid.

The grid has difficulties in accepting and changing direct current variable generation, for example, from wind and solar energy systems, because electricity travels through the grid as alternating current in wave form. Those alternating current waves need to be in-phase for all sources of electricity to add together properly and efficiently.[1] In addition, the California electricity grid must be able accommodate high electricity demand from electric vehicles charging at diverse locations and times.

California requires an electric grid intelligent enough and equipped with the right technology to manage the increasing electrical demand without additional power outages or unwarranted cost increases. Utilities and system operators already have obstacles to overcome in making sure the grid is supplied with enough electricity to satisfy the demand fluctuations, especially during critical peak periods. With the new variables mentioned above, such as renewable generation and electric vehicles, more research is necessary for new technologies to integrate into California's grid with minimum cost and waste.

To address these concerns, the California Energy Commission's (Energy Commission) Research and Development Program (R&D) through the Public Interest Energy Research Program (PIER) funded innovative research on synchrophasor applications and participated in the demonstration and dissemination of information.

What Are Synchrophasors

Phasors are measurements of power system quantities, typically voltage and current, that varies at the 60 Hz system frequency. Phasor measurement units are devices that time-stamp these phasors by means of a highly accurate time reference, such as a GPS clock, so that phasors throughout the system are synchronized, hence the term *synchrophasors*. This allows system

1 The electric grids in North America transport electric power as alternating current, that is, in waves, at a frequency of 60 cycles/second. For several reasons, such as reliability, this frequency must be closely maintained at 60 cycles/second. Customers turning equipment, appliances, lights, and so forth, on and off cause disturbances in the electric grid that tend to change this frequency. Traditional power plants, especially those with large rotating turbines and generators, are operated in a manner to offset these disturbances to maintain the 60 cycle/second standard. Many renewable power plants, especially those powered by the sun and wind, because of the variability of the weather and the fact that these types of power plants do not use massive, stable rotating generators, tend to cause disturbances similar to those caused by customers. As the number of renewable power plants grow, it becomes more difficult to keep the frequency stable.

operators to see the condition of the power system with great detail and accuracy over a wide area, in real time. This is not possible with conventional monitoring technologies such as Supervisory Control and Data Acquisition (SCADA). The synchrophasor technology offers a wide spectrum of advanced applications in previously unattainable power system monitoring, control, and reliability enhancement.

Phasors are synchronized throughout the system by means of a highly accurate time reference such as a GPS clock.

Usefulness of Synchrophasors

Avoidance of Customer Outages

Attempting to foresee and prevent customer outages using the current SCADA systems has been compared to driving a car at 65 miles per hour in the fog and being able to open your eyes only once every 4 seconds – important information can be missed. New synchrophasor-based measurement systems in contrast make the fog vanish and allow you to open your eyes 30 times per second. These tools give operators better warning information on potential outage risks. The costly August 1996 blackouts in the western United States and 2003 in the Northeast might have been detected in time for corrective measures to be taken had synchrophasors and associated applications been in place. These applications can help grid operators monitor system stability and to see frequency oscillations which SCADA cannot detect. Synchrophasor applications can also identify power conditions leading up to a customer outage that current SCADA equipment does not detect.

In January 2008, grid trouble, customer outages, or both may have been avoided when the California Independent System Operator (California ISO) reliability coordinator noted oscillations on the synchrophasor monitoring system that were not perceived on SCADA and shut down the Pacific DC Intertie link. The California ISO uses real-time synchrophasor data for basic monitoring and evaluates after-the-fact synchrophasor data to understand the cause and impact of system disturbances.

By increasing system visibility, synchrophasors can offer essential tools system to handle intermittent renewable generation issues as well as the electricity demand changes caused by the advent of large numbers of electric vehicles and plug-in hybrids charging from the grid. One example of the need for synchrophasor-provided data monitoring comes with the replacement of thermal power plants with certain alternative electricity sources. Many alternative electricity sources provide less help than the thermal power plants they may replace in keeping the power grid stable. With increasing risk to grid stability, there is an increased need for the detailed and action-ready monitoring capability that synchrophasors can provide.

Grid instability is a growing concern as solar photovoltaic (PV) generation becomes more cost-effective than the higher inertia solar thermal plants, creating market pressures to use PV in lieu of thermal solar generation. Synchrophasor data availability and specialized computer programs may address this problem by converting moment to moment synchrophasor data into signals to generators and electricity storage and discharge providers when needed to restore grid stability, according to a recent California ISO smart grid roadmap and architecture report. [2]

Customer outages can cause companies to lose sales or productivity, companies to pay workers to stand idle, and may even cause damage to equipment, materials, or products. Even short power outages can cause longer downtime for computers and key processes that do not restart smoothly or instantly. The work presented in Chapter 2 estimates the potential benefit resulting from Energy Commission-supported synchrophasor R&D to avoid future customer outages near $210 million to $360 million per year.

Improved Power Modeling and Planning

In addition to avoiding costly customer outages and maintaining stable electric service, the high-resolution data of synchrophasors can be used to improve power system models needed to better predict the behavior of the system under differing operating conditions. A few years ago, grid operators experienced unusually long voltage sags due to air conditioner stalling. Southern California Edison (SCE) engineers identified the problem but could not model it with enough precision to evaluate potential solutions properly until they migrated from infrequent SCADA data to more frequent synchrophasor data. One SCE engineer noted that the existing SCADA data provided only one data point per 4 seconds, which for an event that lasts 10 to 30 seconds was not sufficient to evaluate the model. SCE then turned to the synchrophasor data, which provided a data point every 2 cycles and obtained a much better picture of what was happening during an air conditioning stall.[3] The Energy Commission R&D Program has collaborated with SCE and other agencies to use synchrophasor data to develop new load models that help warn the grid operator when such voltage problems might arise and allow for evaluation of solutions that may help reduce the length of voltage sags.[4]

Better modeling supports better planning. According to the California ISO smart grid roadmap report, synchrophasor data are "useful in calibrating the models of generation resources, energy storage resources, and system loads for use in transmission planning programs and operations analysis, such as dynamic stability and voltage stability assessment."[5]

Synchrophasor measurement can also reduce modeling costs. The Western Electricity Coordinating Council (WECC) has recently reported that it can use synchrophasor measurements to validate generator models while the plant is being used, as newly required by

2 California Independent System Operator. (December 2010). *Smart Grid Roadmap and Architecture.* Retrieved from http://www.caiso.com/2860/2860b3d3db00.pdf.

3 Personal communication from Robert Yinger, P.E., Consulting Engineer, Advanced Technology, Southern California Edison. 4/29/2011.

4 Bravo, Richard, Robert Yinger, Dave Chassin, Henry Huang, Ning Lu, Ian Hiskens, Giri Venkataramanan. (2010). *Final Report: Load Modeling Research.* Lawrence Berkeley National Laboratory. Retrieved from http://uc-ciee.org/downloads/LM_Final_Report.pdf.

5 California Independent System Operator. (December 2010). op. cit.

the North American Electric Reliability Corporation. The traditional approach to validating generator modes requires that the plant be taken off-line, a much more expensive procedure.

Increased Absorption of Renewable Energy

The intermittency and variability of many renewable energy sources pose daunting challenges for system operators, who must coordinate such sources with existing generation and customer demand to maintain system reliability and power quality. Sometimes the quantity of renewable energy that is available can be more than the system can accommodate.

As the use of intermittent renewable resources such as wind and solar expands, there is growing concern that transmission systems will be unable to absorb all the available generation. Wind and other variable resources might be increasingly cut off from the grid at times when it is unclear to operators that the variability can safely be absorbed without risks to reliability. The wind energy would then be "spilled," not used. [6] The result would be to make it more difficult and costly to fulfill renewable and greenhouse gas policies. Estimates presented in Chapter 2 suggest that the increased use of existing wind generation will save ratepayers from $25 million to $150 million per year in lower electricity rates.

Transmission Planning and Potential Cost Savings

Operating Transfer Capacity

Another benefit of synchrophasor data and applications may be the ability to safely raise the operating transfer capacity of transmission lines back up (or at least closer) to the thermal limits.[7] After the summer 1996 Western blackouts, planning engineers were unable to reproduce the customer outages in simulations using presynchrophasor data. Thus, utilities and grid operators found no way to catch and prevent repeats of the problem. Therefore, to ensure reliability, the interties connecting utility grids were derated, and they were not allowed to carry as much power as had been previously permitted. Derating is expensive because it results in lower usage of existing capital assets and reduces access to low-cost energy sources such as northwest hydroelectric power. As a result of derating, growth in systemwide energy use could ultimately require the building of new and costly transmission line that might otherwise be avoided.

After an initially larger derating, the California-Oregon Intertie (COI) and Pacific high-voltage, direct current (DC) interties were ultimately rerated at 6,300 MW collectively, 1,600 MW below the preblackout limit of 7,900 MW. "To this day, transmission facilities are not used to their full capacity in the WECC because grid operators lack sufficiently granular, time-synchronized measurements of the flows of electricity throughout the transmission system," according to a

---

6 Energy and Environmental Economics. (July 29, 2009). *Benefits of Synchro-Phasor Program.*

7 California Independent System Operator. (2010). *Smart Grid Roadmap: IP-1 ISO Uses Synchrophasor Data for Grid Operations, Control, Analysis and Modeling, Version 2.1 (Draft).* Retrieved from http://www.caiso.com/285f/285fb7e24f2c0.pdf.

synchrophasor program benefits report Energy and Environmental Economics, Inc. (E3) prepared for the Western Interconnection Synchrophasor Project (WISP). [8]

Several experts suggest that increased transmission along the same lines will be possible once synchrophasor technology provides for better controls. Jim Detmers, former vice president of operations at California ISO, noted that synchrophasors "will provide the capability, someday soon, to arrest oscillations, thereby providing for a safer and more capable operation of the system (increased ratings at given interfaces such as COI). This will provide better utilization of the existing system and in some cases avoid building of new major transmission. Increased capacity and ratings of the existing Bulk Power System is very necessary to access renewables across the WECC region."[9] According to Vickie VanZandt, former senior vice president for transmission at Bonneville Power Administration, and Synchrophasor Program manager of the WECC and of WISP, "due to some automatic controls that will be deployed by BPA (Bonneville Power Authority) for reactive control" the California-Oregon Intertie could be rerated some 200 MW above current ratings.[10]

The California-Oregon Intertie is the one example that has been studied, but it may not represent the only transmission savings that can be achieved through synchrophasor use. The need for transmission will continue to grow as California grows and as more remote renewables need to be integrated into the grid. Synchrophasor deployment may allow these transmission lines to be planned and used more efficiently.

Estimates presented in Chapter 2 suggest that if the decision is made to rerate the California-Oregon Intertie upward by 200 MW, Californians will save from $8 million to $19 million per year in reduced electricity rates.

Other Potential Uses of Synchrophasor Technology

Distance Load Balancing

Intermittent renewable generation sources such as wind and solar PV need complementary power or storage sources to compensate for the fluctuating output of intermittent sources. Those sources need to be near the renewable power plant, typically as firming power provided by a natural gas peaker plant. Firming power plants correct for the variability of renewable energy resources while providing voltage support, and the need for them to be near the renewable source means there must be more firming power built than the system needs in total.

---

8 Energy & Environmental Economics. (July 29, 2009). *Benefits of Synchro-Phasor Program.*

9 Email communication from Jim Detmers, Founder of Power System Resources,;Former Vice President of Operations at the California ISO, (2011).

10 Email communication from Vickie VanZandt, VanZandt, Electric Transmission Consulting, Former Senior Vice President for Transmission at Bonneville Power Administration, and Synchrophasor Program Manager of the WECC and for WISP (2011)

One topic of promising research is the use of increased wide-area system visibility offered by synchrophasor technology to let distant sources, such as natural gas power plants that are already built and operating, provide firming power and related services.

A preliminary estimate presented in Chapter 2 places this potential benefit in the neighborhood of $10 million to $30 million per year if synchrophasors are able to make distance load balancing feasible.

Congestion

Synchrophasor data should provide a clearer picture of costly transmission line congestion, a condition that is defined as too many generators seeking to send their power over the same transmission path at the same time. With better data, modelers could devise local real-time electricity prices that better capture the cost of congestion. Using smart equipment such as programmable price-responsive thermostats and energy management systems with automated demand response functionality, electricity customers could purchase electricity when the real-time prices are lowest and the lines are least congested. Congestion pricing is a cost-effective way to reduce congestion, and better modeling improves the efficiency.

Distributed Generation

As E3 notes in its analysis for the WISP, better information on grid conditions could help planners find the best locations for distributed generation to minimize congestion and substation overloading.

Energy Commission Role

Since the early 2000s, the Energy Commission R&D Program through the Public Energy Interest Research Program (PIER) has ensured that synchrophasor research occurred in California and that it remains relevant to California utility needs throughout several research stages. PIER funded the business case for synchrophasor research, identifying dozens of possible applications and creating an R&D roadmap used by many entities to plan synchrophasor deployment.[11] PIER funded developing a platform now used by the California ISO to let operators visualize information in real time from synchrophasors about system operations.[12] PIER also funded the development of applications for that platform, making grid status measurements faster and more precise. These applications have provided operators with better

11 Novosel, Damir. (2007). *Phasor Measurement Application Study (Final Project Report).* KEMA. Retrieved from http://uc-ciee.org/downloads/PMTA_Final_Report.pdf.

12 Eto, Joe, Manu Parashar, Bernard Lesieutre, and Nancy Jo Lewis (Lawrence Berkeley National Laboratory). (2008). *Real-Time Grid Reliability Management* (No. CEC-500-2008-049). California Energy Commission Public Interest Energy Research Program. Retrieved from http://www.energy.ca.gov/2008publications/CEC-500-2008-049/CEC-500-2008-049.PDF.

information over larger areas and have helped them reduce congestion and lower the risk of widespread blackouts from such things as wide-area power oscillations.[13]

Although synchrophasors can keep system operators better informed of what is happening over a wider area than previous data systems, operators cannot always respond quickly enough to prevent the system from becoming unstable. To address this challenge, PIER is funding the development of automated applications that will use synchrophasor measurements to protect the grid, for example, modifying protective relay settings in real time.

Through these projects, funded modeling, and automation research, the Energy Commission R&D Program has succeeded in attracting U.S. Department of Energy (DOE) funding and in focusing synchrophasor research on California rather than elsewhere. One system operator noted that experts and funding come together where interesting research is happening. A research director described a PIER-DOE collaboration as a "leapfrog" where DOE would fund the early project development and then PIER would develop the next phase, but "tailored to California's needs." DOE would then build upon PIER's research. At times, DOE and PIER split the work, and at times, they co-funded work.[14]

Tailoring synchrophasor-related work to California is a critical PIER role. Figure 1 illustrates how PIER's synchrophasor research roadmap dealt with the complex interplays among California industry needs, the value of furthering research, and the deployment challenges associated with each of the 16 potential synchrophasor-related research tasks.[15] PIER has also addressed California's needs by partnering with the California ISO, to test PIER-funded synchrophasor applications and implement the results of PIER-funded research. California ISO Director of Grid Operations Jim McIntosh reported, "PIER's research program has resulted in the [California] ISO installing the most advanced synchrophasor application in the country relative to phase angle detection and oscillation detection. This [research] is the most significant improvement in control room technology in my career."

The Energy Commission through PIER is partnering with other Western Electricity Coordinating Council (WECC) members to create the Western Interconnection Synchrophasor Program (WISP) for deploying synchrophasors and associated smart grid functions on a large scale throughout the West. The WISP effort incorporates the results of PIER research, including recent PIER projects on oscillation detection and mode analysis for grid operation. WISP

---

13 Brown, Merwin, Larry Miller, Alexandra von Meier, Lloyd Cibulka, Lorraine Hwang. (2012). *Modernizing the Transmission Grid: Research to Improve Infrastructure, Operations, and Planning.* California Institute for Energy and Environment. Retrieved from http://uc-ciee.org/downloads/Transmission_Research.pdf.

14 Personal communication from Merwin Brown, former director of the Electric Grid Research Program at the California Institute for Energy and Environment (2011).

15 Novosel, D., B. Snyder, and K. Vu (2006). *A Business Case Study on Applying Phasor Measurement Technology and Applications in the WECC.* California Energy Commission Public Interest Energy Research Program.

Figure 1: PIER-Funded Business Case Gave Direction for Synchrophasor-Related Research

	Synchronized Measurement Values		
Industry Needs	**Requires more Investigation**	**Offers additional Benefits**	**Necessary**
Critical **Criteria that industry feels are of critical importance.** **These criteria range from easy to implement to hard to implement.**	**None**	**Voltage Stability Monitoring** **Thermal Overload Monitoring** **State Estimation (Improvement)** **State Estimation (Boundary Conditions)** **Congestion Management** **Power System Restoration** **DG/IPP Applications**	**Angle/Frequency Monitoring** **Real-Time Control** **State Measurement (Linear)** **Post-Mortem Analysis (including Compliance Monitoring)** **Estimation (Dynamic)** **Planned Power-System Separation**
Moderate **Criteria that industry feels are of moderate importance.** **These criteria range from easy to implement to medium-level difficulties to implement.**	**WA Stabilization (WA-PSS)**	**Adaptive Protection** **Estimation (Steady-State) Model Benchmarking, Parameter**	**None**

Industry Needs vs. Synchronized Measurement Values: Sixteen Criteria Reviewed with Key Implementers

Level of Implementation Difficulties:

Easy to Implement = Green Highlight
Medium-level Difficulties = Yellow Highlight
Hard to Implement = Red Highlight

Source: *California Energy Commission*

program manager and former senior vice president of Bonneville Power Administration, Vickie VanZandt notes, "We can stand on the shoulders of utility, government, and academic visionaries involved in the PIER (P)rogram whose research and development will guide us in the implementation of a better, more flexible, and more resilient grid. The industry is benefitting today from PIER's imagination of a better future."[16]

The Energy Commission is viewed as an essential partner in the development and deployment of synchrophasor applications in California. As a result of this image and the public goods nature of knowledge, the benefits of PIER-funded synchrophasor related research and applications to California ratepayers can be attributed to PIER funding. These benefits are summarized in the next section.

Benefits of PIER-Funded Work

By 2020, PIER synchrophasor research and applications will be saving Californians from $210 million to $360 million in reliability benefits each year, plus on the order of $90 million per year in reduced cost of electricity. These benefits more than offset the $11.4 million investment that PIER has made. There is potential for more savings if additional fields of synchrophasor research prove fruitful. Chapter 2 shows how these numbers were estimated.

Benefits will be growing over the coming years to reach this 2020 value. Chapter 2 also derives the net present value and annualized values of benefits from an analysis prepared in 2011. The present value of net benefits is $2.7 billion, with ratepayer benefits outweighing ratepayer research and deployment costs by a ratio of more than 20 to 1. The annualized benefit of PIER-funded synchrophasor research is $260 million per year, where the annualized value is an average of each year's benefits minus costs from now through 2030, discounted to correct for the money that ratepayer dollars could have earned in alternative investments. These calculations are conservative in that benefits are assumed not to grow after 2020, not even due to population growth.

Benefits are in the hundreds of millions of dollars primarily because there are millions of Californians who are using the energy and who will benefit from the quantum change in reliability that synchrophasor applications afford. About a quarter of these benefits come from synchrophasor technology enabling grid operators to capture more of the capabilities of both renewable sources and also the transmission system. Further benefits could be realized in other promising lines of research; for example, long-distance load balancing could save an additional $20 million per year.

14 Vickie VanZandt, personal communication, 2011.

CHAPTER 2:
Quantifying Economic Benefits of PIER Synchrophasor-Related Research

This chapter will present the basis for estimating the savings Californians will realize by 2020. Savings estimated will be from $210 million to $360 million per year in avoided customer outage costs and $90 million per year in reduced electricity costs, due to PIER-funded research, and a potential for more if other research outcomes and policy choices are favorable. These savings will come at a time when the grid will be challenged by both a 33 percent Renewables Portfolio Standard and by a requirement for greenhouse gas emissions to be at or below 1990 levels.

Large-Scale Customer Outage Avoidance

This section estimates the value of avoiding large-scale customer outages based on various experts' estimates of the likelihood and costs incurred due to customer outages with and without synchrophasor research, per year, by 2020. This value will be estimated several ways, introducing conservative assumptions throughout. The final estimate will be the average of these independent estimates. A separate probabilistic analysis presented in Appendix A shows that the result is conservative.

Looking Forward

Smart grid researcher Massoud Amin argues that the grid will face many new challenges to reliability over the next decades, but these issues can be alleviated if Americans would bring electric sector RD&D in line with other sectors, expand and strengthen transmission, create highly efficient microgrids with combined heat and power as well as storage, and build a self-healing smart grid.[17] Specifically, Amin estimates a $49 billion per year savings, representing a 31 percent to 41 percent reduction in reliability failure costs from the $119 billion to $168 billion that the consulting firm Primen estimated outages cost customers annually. Primen arrived at this estimate by surveying 985 businesses for the Electric Power Research Institute (EPRI).[18]

While keeping the 31 percent to 41 percent reduction rate, Energy Commission staff uses the lower reliability failure costs found in a more recent comprehensive study by Lawrence Berkeley

17 Amin, S. Massoud. (January 2011). *U.S. Electrical Grid Gets Less Reliable* *IEEE Spectrum* Retrieved July 6, 2012, from http://spectrum.ieee.org/energy/policy/us-electrical-grid-gets-less-reliable.

18 Lineweber, David and Shawn McNully. (2001). *The Cost of Power Disturbances to Industrial & Digital Economy Companies* (No. EPRI TR-1006274). Madison, WI: Primen.

National Laboratory (LBNL). [19] LBNL puts the annual cost to consumers of power interruptions at a lower $79 billion, based on a meta-analysis of 24 electricity customer surveys conducted over 13 years.[20] While Primen estimated the cost of power interruptions and power quality events to California electricity consumers at $13.2 billion to $20.4 billion per year, the LBNL study puts California customer interruption costs at a lesser estimate of $8.1 billion per year. The Energy Commission staff uses this $8.1 billion per year figure as a conservative baseline, although failure costs may be higher by 2020 with more customers on the grid and with customer outages becoming more likely to happen during peak hours.[21] This approach is also conservative because, by 2020 with increasing renewables, the grid will be more challenged, and customer outages will probably become more frequent.

Energy Commission staff then applies Amin's forward-looking assessment that the actions he calls for reduce reliability failures by 31 percent to 41 percent. The suggested actions include public interest energy research and a self-healing smart grid, which will use synchrophasor output to either guide operators or directly guide the system to avoid customer outages. About 10 percent of reliability problems occur in transmission rather than distribution lines;[22] therefore, the potential customer outage avoidance rate drops from a range of 31 percent to 41 percent to a range of 3.1 percent to 4.1 percent.

In its synchrophasor business case study, KEMA interviewed utility grid operators and estimated that half of the transmission outages that lead to power interruptions could be prevented with synchrophasors.[23] Conservatively, Energy Commission staff applies the 50 percent prevention rate to the customer outages deemed preventable by smart grid research and applications, rather than to all customer outages. If 3.1 percent to 4.1 percent of outages are deemed preventable, then 1.55 percent to 2.05 percent are deemed preventable using synchrophasors.

With this approach, one can expect synchrophasor development and research to save on the order of $125 million to $166 million per year in increased reliability ($8.1 billion times 1.55 percent to 2.05 percent). This constitutes the forward-looking estimate.

Looking at History

---

19 Hamachi-LaCommare, Kristina and Joseph H. Eto. (2004). *Understanding the Cost of Power Interruptions to U.S. Electricity Consumers* (No. LBNL-55718). Lawrence Berkeley National Laboratory. Retrieved from http://certs.lbl.gov/pdf/55718.pdf.

20 Lawton, L., M. Sullivan, K. Van Liere, and A. Katz. (2003). *Characteristics and Trends in a National Study of Consumer Outage Costs.* San Francisco: Population Research Systems, LLC.

21 Hines, Paul, Jay Apt, and Sarosh Talukdar. (2009). "Large Blackouts in North America: Historical Trends and Policy Implications.: *Energy Policy,* 37.

22 Hammachi-LaCommare, Kristina, and Joseph H. Eto, *op. cit.*

23 Novosel, Damir. (2007). *op. cit.*

Another approach is to look at historical customer outage frequencies and costs. A PIER-funded benefit cost study by the consulting firm KEMA noted that the observed historical frequency of major customer outages is 1.6 per year, an indicator of outage likelihood. [24] Using California data and published research on the relative probability of various outage sizes,[25] KEMA derived an expected major power outage size for California (3,839 megawatt hours [MWh]) and applied estimates for the likelihood of that outage and assumptions about the related costs. In this section, that approach will be repeated using three sources of cost estimates, beginning with the KEMA analysis.

Since the KEMA benefit/cost study was estimating the benefits of the earliest synchrophasor applications without, for example, PIER's power grid self-correction research, KEMA assumed that synchrophasors would reduce outages by 30 percent. Following KEMA's business case study, the present analysis covers the entirety of PIER synchrophasor-related research and uses a power outage reduction rate of 50 percent. Major power outages begin on transmission lines, so there is no need to apply only 10 percent of this reduction value as one would for an estimate of all power outages, both major and minor.

Likelihood of Outage

Choosing the most conservative estimates whenever there was a choice among several sources or methods for developing key input assumptions, KEMA's benefit/cost study turned the observed historical frequency of 1.6 major power outages per year into the upper bound of the sensitivity range of 0.2 to 1.6 naturally occurring outages per year, rather than the midpoint. Thus, KEMA is assuming a drop in naturally occurring outage rates, when in fact increased pressure from renewables and potentially more severe or variable weather will strain the power grid. While KEMA's interval is retained for reporting its cost estimate, the other estimates created in this report will use the historical outage frequency as the future outage frequency in the absence of synchrophasor research. Even historical outage frequency is arguably conservative.

KEMA Cost Estimates and Results

KEMA's estimates assume the cost per unserved kilowatt-hour (kWh) of outage to be $13, a number that is low compared to other current estimates. KEMA derives the estimate by supposing the 2003 Northeast Power Outage cost the United States $7 billion because that is the midpoint of the $4 billion to $10 billion range of U.S. costs used in a joint Canadian-U.S.

---

24 KEMA. (2010). *Benefits Assessment of Seven PIER-Sponsored Projects* (Final Draft No. CEC 500-2014-023).

25 Carrerras, B. A., D. E. Newman, I. Dobson, and A. B. Poole. (2000). "Initial Evidence for Self-Organized Criticality in Electric Power System Blackouts." Presented at the International Conference on Systems Sciences, Hawaii: IEEE. Retrieved from http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&arnumber=926768&contentType=Conference+Publications.

23 Talukdar,N., J. Apt, M. Ilic, L. B. Lave, and M. G. Morgan. (2003). "Cascading Failures: Survival Versus Prevention." *The Electricity Journal,* 16(9), 25–31.

report on blackout prevention strategies.[26] KEMA notes that its estimate lies within a range suggested by an earlier literature review that finds costs ranging from $2 to $5 per unserved kWh for surveyed Finnish consumers in 1977 to $25 per unserved kWh for surveyed British consumers in 1993.[27] KEMA also cites a 2004 Sandia Labs Storage Benefits report that suggests using $20 per kWh as a placeholder, [28] based on a 1992 paper by Woo and Pupp that reviewed older studies yielding customer outage cost estimates ranging from $1 to $83 per unserved kWh (converted here to 2011 dollars).[29] These studies all occurred before the Internet was commonly used, at a time when electricity customer outages did not cause companies to lose Internet customers and outages did not prevent as many financial transactions. Personal and small business computing was less common and did not even exist for the earliest studies, so there was less vulnerability to the costly computer crashes that power interruptions can cause. Other technologies that are impacted by power outages differed as well.

Applying KEMA's costs to the range of likelihood of outages without synchrophasors, and the 50 percent outage reduction attributable to synchrophasors, one obtains reliability benefits of $7 million to $43 million per year[30], with $43 million representing savings based on historical outage rates, while $7 million assumes that an eightfold drop in outages would occur without the introduction of synchrophasors.

Applying E3-HMG Cost Estimates

In 2008, E3 and the Heschong Mahone Group (HMG) estimated the costs of California summer customer outages at $42 per unserved kWh,[31] using results from a 1999 Southern California Edison study,[32] a year 2000 Pacific Gas and Electric (PG&E) study,[33] and the Woo and Pupp study. This customer outage cost suggests synchrophasor research saves $133 million per year so long as naturally occurring major power outages are taken as the historical rate of 1.56 per year. (At $13.4 per unserved kWh, savings were $42.3 million a year; at $42.0 per unserved kWh, they are 42/13.4 times 42.3 million = $133 million.)

---

26 U.S.-Canada Power System Outage Task Force. (2006). Final Report on the Implementation of the Task Force Recommendations. Natural Resources Canada, U.S. Department of Energy.

27 Cramton, P. and J. Lien. (2000). Value of Lost Load. University of Maryland.

28 Eyer, J. M., J. J. Iannucci and G. P, Corey. (2004). Energy Storage Benefits and Market Analysis Handbook: A Study for the DOE Energy Storage Systems Program (No. SAND2004-6177). Sandia National Laboratories.

29Woo, Chi-Keung and Roger Pupp. (1992). "Costs of Service Interruptions to Electricity Consumers." Energy, 17(2), 109–126.

30 KEMA. (2010), op. cit., Figure 7.

31 Energy & Environmental Economics, Heschong Mahone Group. (2008). Time Dependent Valuation of Energy for Developing Building Efficiency Standards: 2008 Time Dependent Valuation (TDV): Data Sources and Inputs.

32 Southern California Edison. (1999). Customer Value of Service Reliability Study. Rosemead.

33 Pacific Gas and Electric. (2000). "Value of Service (VOS) Studies." Presented at the ISO Grid Planning Standards Subcommittee, San Francisco.

Applying LBNL Cost Estimates

A more recent LBNL study combining 28 surveys estimated much higher customer outage costs[34], particularly for small businesses that are less likely to invest in backup generation and other customer outage mitigation strategies. Among medium and large businesses, mining firms and manufacturers were most likely to suffer losses from customer outages, and when suffered, the outage costs were highest in the construction and manufacturing sectors, followed by data-intensive business sectors such as finance. Costs per unserved kWh were higher for shorter duration outages.

The LBNL study finds costs of $300 to $1,600 per unserved kWh for small businesses, $11 to $97 per unserved kW for medium and large businesses, and $1 to $17 per unserved kWh for residential customers whose inconveniences are not typically characterized in monetary cost estimates. These findings put the weighted average cost per unserved kWh at $100 to $550, using the weights derived in Appendix A. With costs that high, avoiding half of the historical major power outage rate would be worth between $318 million and $1.75 billion per year or around $10 to $50 per Californian.

California Share of WECC-Wide Benefits

A final estimate comes from taking the California share of a study commissioned by WISP to assess benefits of WECC-wide synchrophasor deployment. E3 estimated synchrophasor technology deployment and use over the next 40 years would save WECC from $1.5 billion to $3.5 billion in present value.[35] California's one-third share of this annualizes to $47 million to $137 million per year. The calculations for this estimate are presented in Appendix A. E3 conservatively assumed a 10 percent customer outage avoidance rate due to synchrophasors and counts only power outages involving at least a million customers. Its calculations are based on historical power system outage frequencies and assumed costs per customer class.

Overview

These numbers and the studies they come from highlight the uncertainty in customer outage probabilities, as well as in avoided costs estimates. The lower estimates apply low customer outage costs (KEMA) or low customer outage avoidance rates (E3). The higher estimates consider more recent and sweeping customer cost estimations (LBNL), or expert judgment on how the future challenges of renewable integration and electrified vehicles will put the grid at higher risk (Amin). These estimates are summarized in Table 1.

---

34 Sullivan, Michael J., Matthew G. Mercurio, Josh A. Schellenberg, and Joseph H. Eto. (2010). "How to Estimate the Value of Service Reliability Improvements." Power and Energy Society General Meeting, IEEE. Retrieved from http://escholarship.org/uc/item/8gz990pz.pdf.

35 Energy and Environmental Economics. (July 29, 2009). *op. cit.*

Table 1: Estimates of Reliability Value of Synchrophasor Research

Approach	Avoided Customer Outage Cost ($million/year)
Looking forward. LBNL estimate of grid reliability failure costs ($8.1 billion) x Amin's implied percentage of disturbances that are avoidable (31 percent to 41 percent) x LBNL estimate that 10 percent of reliability problems occur in transmission x KEMA estimate that half of transmission outages are preventable by synchrophasors.	125 to 166
Looking at history – KEMA. Assume the natural customer outage rate lies between one-eighth of and 100 percent of the historical average customer outage rate. Assume half of transmission outages leading to customer outages are preventable by synchrophasors. Let customer outage cost be $13 per unserved kWh, congruent with pre-Internet European and general North American studies.	7 to 42
Looking at history 2. Let customer outage cost be the E3/Heschong-Mahone (2008) California summer customer outage cost, natural customer outage rate be the historical average, and otherwise apply KEMA calculations	133
Looking at history 3. Let customer outage cost be based on the 2008 LBNL study, let the natural customer outage rate be the historical average, and otherwise apply KEMA calculations	318 to 1,750
California share of WECC-wide benefit. California share of E3's estimate of synchrophasor reliability value for all WECC	47 to 137

Source: *California Energy Commission staff calculations*

These estimates average to $286 million per year. To provide an uncertainty range, the estimates are turned into probability distributions and combined as detailed in Appendix A. The result is that the value of avoided customer outages is expected to fall in the neighborhood of $210 million to $360 million per year, and the expected value remains $286 million. This value represents an estimate of savings when synchrophasor deployment is complete, for example, starting in 2020.

An alternative approach gathers all the component estimates and combines them probabilistically, with heavy weighting toward those that are most researched and supported, and a large range of options for the most judgment-based parameter – the rate at which synchrophasors prevent outages. Detailed in Appendix A, this more rigorous approach yields considerably higher benefits centered at $410 million per year, with first and third quartiles of

$220 million to $540 million. Thus, the treatment of benefits of this study as centering around $286 million is conservative.

Reducing the Cost of Electricity

In addition to reducing customer outage costs, synchrophasor deployment will help reduce the overall cost of electricity.

Increased Absorption of Wind Energy

As discussed in Chapter 1, synchrophasor deployment should allow grid operators to better observe fluctuating wind power signatures and better understand when accepting wind power from a particular turbine would pose a risk to power quality and reliability. The operators will more frequently receive better grid information and will therefore spill less wind power. This increases wind capacity factors, a measure of the proportion of time and intensity at which wind turbines furnish electricity to the grid.

E3 estimated two scenarios for deployment throughout the West: in one scenario, the capacity factor for wind generation increases 1 percent, in the other 5 percent. E3 used its WEIL model to estimate costs of wind energy sales under these two scenarios and found wind energy costing 0.3 cents or 1.6 cents less per kWh, respectively. Costs per kWh drop because delivered kWh rise while costs remain constant. Wind turbines require the same investments for construction and maintenance whether they spill electricity and the fuel (wind) is free.

The Energy Commission estimates 9.2 million GWh of wind energy will be supplied to California in 2020. Applying the savings of 0.3 cents to 1.6 cents per kWh, analysts obtain $26 million to $150 million per year (in real 2010 dollars) saved to ratepayers, centering around $88 million per year.

Increased Use of Transmission Lines: California-Oregon Intertie

Many experts suggest that with synchrophasor-enabled monitoring and operation, the California-Oregon Intertie (COI) can be rerated to carry more electricity, avoiding new transmission investment. The WISP program manager suggests a 200 MW rerating can be expected. This section estimates the benefits that would result from the rerating of just that intertie.

In a study for WISP, E3 multiplied electricity price differences across the COI by number of MW of rerating for the various high load hours of the year. Adjusting for an intertie charge, E3 estimated the present value of long-term savings at 35 million to 75 million year-2008 dollars per 100 MW of rerate. This equates to 8.4 million to 18.5 million year-2010 dollars per year for a 200 MW upgrade, changing present value to annual value based on E3’s 40-year lifetime and 11.8 percent discount rate. The 2008 dollar number is multiplied by 1.02 to become a 2010 dollar number. The lower estimate is estimated over June to September, while the higher supposes the extra transmission capacity has value from April to October. The expected value (the average estimate) is $13 million per year.

Pending Further Research

Distance Load Balancing

In a study for WISP, E3 provided preliminary estimates that over 10 years the reduced capacity firming costs due to intermittent generation for all of WECC could be around $310 million to $630 million in avoided construction of gas peaker plants. E3's avoided cost estimates used a 40-year lifetime and an 11.8 percent discount rate; reversing that translates these estimates to annualized payments of around $40 million to $80 million, expressed in year 2010 dollars. California is expected to account for 36 percent of the WECC's peak demand in 2020, so the range is multiplied by 36 percent. The result is a California benefit in reduced peaker plant construction of around $10 million to $30 million per year.

Congestion Relief

With better visibility of grid conditions, operators might better price and manage congestion. As one example, they might improve their state estimation models and better manage real-time power transfer. Estimating these effects is beyond the scope of this report.

Development and Deployment Costs

To deploy synchrophasor technologies throughout the West, WISP is spending $107.8 million; half of this is funded by a DOE grant. California utilities and the Energy Commission are contributing $10.9 million of ratepayer monies to intrautility network infrastructure.[36] In addition, PG&E is contributing $22 million to complete deployment within its territory, matched equally by DOE stimulus funding for a total deployment expenditure of $44 million. Since PG&E provides 32 percent of the electricity delivered to California consumers (in 2010), deployment throughout California might cost around $44 million/32 percent = $137.5 million. Since DOE is funding $22 million of this, the cost to Californians might be around $117.5 million. This is a high estimate, making net savings estimates conservative, because PG&E has a more dispersed grid with more transmission interconnections than SCE and San Diego Gas & Electric Co.

Financed over 30 years at the utility-weighted average cost of capital (8.75 percent), the $117.5 million deployment cost annualizes to $11 million per year.

Research Costs

PIER has invested or is investing a total of $11.4 million in synchrophasor-related research. At an 8.75 percent discount rate, this amount annualizes over 30 years to $1 million per year. The projects included in this calculation are listed in Appendix B.

Net Effect of PIER Research on Electricity Rates

As a result of synchrophasor-related research and applications, electricity ratepayers should be saving around $88 million per year ($26 million to $150 million) from increased absorption of

---

36 Western Electricity Coordinating Council. (n.d.). *WISP Project FAQs*. Retrieved from http://www.wecc.biz/awareness/Documents/WISP project FAQs 05-05-10.pdf.

wind energy by 2020. If policy makers take advantage of increased transmission reliability to rerate major transmission lines, they will save another $13 million per year ($8 million to $18 million). Ratepayers could save another $21 million ($13 million to $28 million) per year if improved system visibility allowed for long-distance load balancing. The net effect of these benefits and the $1 million per year research cost will be an electricity cost reduction on the order of $90 million per year (potentially $110 million with long-distance load balancing), thus compensating for the $70 million annual cost of the entire PIER program. These calculations consider only reductions in the cost of electricity, not savings from avoided customer outages, estimated around $286 million per year ($210 million to $360 million).

Benefit Cost Analysis

A benefit cost analysis prepared by staff in 2011 shows that considering the investments made by PIER in research, along with expected California utility investments in deployment, PIER-motivated synchrophasor applications, and related deployment have a net projected present value benefit of around $2.7 billion, comparable to receiving annual payments of $260 million over the 30 years from 2011 through 2040. The ratio of benefits to costs including deployment for Californians is 22 to 1. These numbers are large because synchrophasors and associated applications will substantially improve reliability, which is valuable, and will allow grid operators to reliably use the capabilities of wind turbines and transmission lines more effectively. The numbers do not include the potential for long-distance load balancing; this could raise the net benefit to $2.8 billion and the annualized cost savings to more than $270 million per year.

This calculation assumes:

- The discount rate is 8.75 percent, the utility-weighted average cost of capital.
- The cost of deployment to ratepayers is $117.5 million, recognized half in 2011 and half in 2012.
- PIER research costs are $11.4 million, incurred variously from 2002 through 2013.
- Reliability benefits reach $286 million per year by 2020, along a straight line trajectory from zero benefits in 2011, and stay at $286 million per year through 2040.
- Benefits from wind integration reach $88 million per year by 2020 along a straight line path, and stay there through 2040.
- The California Oregon Intertie is slowly rerated by 200 MW for an annual savings of $6.55 million, along a straight line path through 2020 starting at no rerating, and stays rerated through 2040.
- If long-distance load balancing is included its benefits are zero in 2015 and then grow along a straight line trajectory to reach $21 million per year by 2020.
- If synchrophasor technology and applications and value are assumed to last only 10 rather than 20 years beyond 2020, perhaps then replaced by a now-unknown technology, net benefits fall 20 percent to $2.2 billion.

Attribution

Without PIER leadership, synchrophasor and associated development would not have progressed to where it is today and would not be tailored to California needs, and California might face more serious problems integrating renewables and electric vehicles. California partnership in WECC-wide and national efforts is essential as well; programs like WISP materialize only if enough entities show the good faith to participate. The California ISO working with the PIER team helped move the industry quickly into adapting this technology and moving it into the control center for an immediate benefit to California both in improved grid reliability and significant costs reduction for congestion management. This section covers how much of the research benefits described above can be attributed to PIER funding and direction. In evaluating to what extent these benefits can be attributed to PIER investments, it is important to understand the public good nature of the knowledge gained from the research.

Economists define a public good as a product that is used by one person does not exclude or limit the use by any other person. Knowledge, clean air, national defense, and street lighting are examples of public goods. While the value of a private good is measured by the price an individual pays for it, the value of a public good is measured by the sum of what everyone is willing to pay for it, because everyone gets to benefit from it. Economists have found that while the private sector may on its own produce the efficient amount of private goods (in a perfect economy with perfect information and perfect competition), the private sector is expected to produce less than the efficient amount of public goods. The efficient amount of a public good would be purchased if every individual contributed toward procurement according to the value of the good to them, but each individual faces a temptation to be a free rider – to benefit from the public good without paying because others contributed. If every individual is a rational *homo economicus*, none will contribute, and no public good will be produced.

The key points to take from this exposition are (1) each user procures the full value of the public good regardless of how much other individuals use, and (2) free ridership can cause too little or none of the good to be produced. Based on the first point, it is not appropriate to attribute benefits of a public good to each contributor according to their share of total cost: doing so would falsely set the total value of the public good at the benefit for a single user. If California and Oregon each contributed to knowledge that reaped for Californians $100 million of benefits, Californians would have those benefits regardless of how much Oregonians contributed and how much Oregonians benefited.

Following this logic, California and the rest of the nation (via DOE) are contributing funds for a public good Hknow ledge and app
keep electricity reliable and affordable. California and the rest of the nation have full benefits and should count them as such in a benefit/cost comparison.

There is some overlap between California and the rest of the nation in that Californians also contribute toward DOE's work. If that expenditure were known, it could be added to Californians' costs or subtracted from their benefits. One approximation is to suppose, per the description of alternating and shared contributions in Chapter 1, that DOE and the Energy Commission each provided funding for half the costs. Because Californians provide 11.7

percent of U.S. tax revenue, they can be assumed to provide 11.7 percent of DOE funding. Add 11.7 percent of research and deployment costs as a California share of a DOE match, and net benefits still round to $2.7 billion (dropping from $2.74 billion to $2.72 billion) and still annualize to around $260 million per year. The benefit cost ratio drops to 21 to 1, while the year 2020 effect on electric bills and customer reliability values are unchanged.

A second approach rewards free ridership, arguing that an agency achieves benefit only from contributing funding for a public good insofar as that public good would not be created without that agency's contribution.

In evaluating the Real-Time Dynamics Monitoring System (RTDMS) developed for California ISO, the essential system that collects synchrophasor data and displays and interprets them meaningfully for grid operators, the KEMA surveyed involved professionals. The key finding of the survey was that all respondents believed PIER support was essential to developing RTDMS.[37] Respondents said that, in the absence of PIER, RTDMS would have received considerably less funding and been delayed by at least seven years. As a result, KEMA attributed 70 percent of its 10-year savings estimate to PIER. Respondents thought that without PIER, DOE might have chosen a different development partner than California ISO. Applying synchrophasors to dampen grid oscillations to prevent western blackouts might not have been a priority if an eastern partner had been chosen as the short length of eastern transmission lines inhibits oscillations. California ISO might not have obtained the RTDMS due to other pressing duties and might instead have tried to derive a tool from the Eastern Interconnection Phasor project. It is likely that that tool would have been experimental and used only for post-event analysis rather than real-time problem avoidance.

These interviews further suggested that at a minimum PIER participation accelerated California synchrophasor-related applications by seven years. At most, PIER participation may have been essential to procuring the synchrophasor applications essential to Californians. Consider the lowest benefit case, where PIER accelerated development by seven years but otherwise did not affect the value of the resulting projects.

If all investment and work are delayed seven years but otherwise follow the schedule assumed in the benefit/cost calculations above, present value year 2010 benefits drop from $2.73 billion to $1.35 billion. The net benefit of PIER's accelerating this work by 7 years then becomes $1.38 billion, comparable to receiving $131 million per year over the next 30 years.

Delaying the research seven years, however, would not have guaranteed full deployment by 2020, in time to help California reliably meet stringent renewable and greenhouse gas policy goals. With a seven-year delay under the straight-line deployment assumption, by 2020 Californians are receiving only $86 million per year of reliability and electricity price benefits, rather than the $388 million they are estimated to receive without the seven-year delay. Thus, the effect of PIER's seven-year acceleration is to give ratepayers $302 million per year more of

37 KEMA (2010), *op. cit.*

benefits in 2020 than they would have had without PIER (all numbers in year-2010 dollars). This calculation includes $79 million in reduced cost of electricity, still compensating for the annual cost of all PIER electric RD&D to ratepayers, plus $222 million in reliability benefits. If long-distance load balancing works out, electricity costs could drop an additional $16 million per year.

Table 2: Point Estimates of Benefits Given Different Approaches to Attribution (Year 2010 Dollars)

Approach	Real Year 2020 Annual Net Benefit	Annualized Real Net Benefits Over the 2011 – 2030 Period	Ratio of Benefits to All Costs Including Deployment
Full attribution to PIER as essential partner chipping in for public good	$388 million	$260 million per year	23: 1
Same, but allowing for Californians' contributions to another partner, DOE	$388 million	$259 million per year	21 : 1
Suppose PIER sped up deployment 7 years but did not affect value	$302 million	$131 million per year	12 : 1

Source: *California Energy Commission*

GLOSSARY

Term	Definition
California ISO	California Independent System Operator
CERTS	Consortium for Electric Reliability Technology Solutions
CIEE	California Institute for Energy and Environment
COI	California-Oregon Intertie
DOE	U.S. Department of Energy
E3	Energy & Environmental Economics, Inc.
EPRI	Electric Power Research Institute
HMG	Heschong Mahone Group
LBNL	Lawrence Berkeley National Laboratory
PMU	Phasor Measurement Unit
PV	Photovoltaic
RTDMS	Real-Time Dynamics Monitoring System
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
WECC	Western Electric Coordinating Council
WISP	Western Interconnection Synchrophasor Program

REFERENCES

Amin, S. Massoud. (January 2011). "U.S. Electrical Grid Gets Less Reliable," *IEEE Spectrum.* Retrieved July 6, 2012, from http://spectrum.ieee.org/energy/policy/us-electrical-grid-gets-less-reliable

Bravo, Richard, Robert Yinger, Dave Chassin, Henry Huang, Ning Lu, Ian Hiskens, Giri Venkataramanan. (2010). *Final Report: Load Modeling Research. Lawrence Berkeley National Laboratory. Retrieved from http://uc-ciee.org/downloa*ds/LM_Final_Report.pdf.

Brown, Merwin, Larry Miller, Alexandra von Meier, Lloyd Cibulka, Lorraine Hwang. (2012). *Modernizing the Transmission Grid: Research to Improve Infrastructure, Operations, and Planning*. California Institute for Energy and Environment. Retrieved from http://uc-ciee.org/downloads/Transmission_Research.pdfCalifornia Independent System Operator. (2010, December). Smart Grid Roadmap and Architecture. Retrieved from http://www.caiso.com/2860/2860b3d3db00.pdf.

Carrerras, B. A., D. E. Newman , I. Dobson, and A. B. Poole. (2000). *Initial Evidence for Self-Organized Criticality in Electric Power System Blackouts*. Presented at the International Conference on Systems Sciences, Hawaii: IEEE. Retrieved from http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&arnumber=926768&contentType=Conference+Publications.

Chen, J., J. S. Thorp , and M. Parashar. (2001). *Analysis of Electric Power System Disturbance Data*. Presented at the International Conference on System Sciences, Hawaii: IEEE.

Energy and Environmental Economics. (2009). Benefits of Synchro-Phasor Program.

Energy and Environmental Economics, Heschong Mahone Group. (2008). *Time Dependent Valuation of Energy for Developing Building Efficiency Standards: 2008 Time Dependent Valuation (TDV): Data Sources and Inputs.*

Hamachi-LaCommare, Kristina and Joseph H. Eto. (2004). *Understanding the Cost of Power Interruptions to U.S. Electricity Consumers* (No. LBNL-55718). Lawrence Berkeley National Laboratory. Retrieved from http://certs.lbl.gov/pdf/55718.pdf

Hines, Paul, Jay Apt, and Sarosh Talukdar. (2009). "Large Blackouts in North America: Historical Trends and Policy Implications." *Energy Policy*, 37.

KEMA. (2010). *Benefits Assessment of Seven PIER-Sponsored Projects* (Final Draft No. CEC 500-06-014).

Lawton, L., M. Sullivan, K. Van Liere, and A. Katz. (2003). *Characteristics and Trends in a National Study of Consumer Outage Costs*. San Francisco: Population Research Systems, LLC.

Lineweber, David and Shawn McNully. (2001). *The Cost of Power Disturbances to Industrial & Digital Economy Companies* (No. EPRI TR-1006274). Madison, WI: Primen

Novosel, Damir. (2007). *Phasor Measurement Application Study (Final Project Report)*. KEMA. Retrieved from http://uc-ciee.org/downloads/PMTA_Final_Report.pdf

Novosel, D., B. Snyder, K. Vu. (2006). *A Business Case Study on Applying Phasor Measurement Technology and Applications in the WECC.* California Energy Commission Public Interest Energy Research Program

Pacific Gas and Electric. (2000). *Value of Service (VOS) Studies*. Presented at the ISO Grid Planning Standards Subcommittee, San Francisco.

Southern California Edison. (1999). *Customer Value of Service Reliability Study*. Rosemead.

Sullivan, Michael J., Matthew G. Mercurio, Josh A. Schellenberg, and Joseph H. Eto. (2010). *How to Estimate the Value of Service Reliability Improvements*. Power and Energy Society General Meeting, IEEE. Retrieved from http://escholarship.org/uc/item/8gz990pz.pdf

Talukdar, N., J. Apt, M. Ilic, L. B. Lave, and M. G. Morgan. (2003). "Cascading Failures: Survival Versus Prevention." *The Electricity Journal*, 16(9), 25–31.

U.S.-Canada Power System Outage Task Force. (2006). *Final Report on the Implementation of the Task Force Recommendations.* Natural Resources Canada, U.S. Department of Energy.

U.S. Small Business Administration, Office of Advocacy. (2008). "Small Business Profile: California." Retrieved from http://archive.sba.gov/advo/research/profiles/08ca.pdf

Western Electricity Coordinating Council. (n.d.). "WISP Project FAQs." Retrieved from http://www.wecc.biz/awareness/Documents/WISP project FAQs 05-05-10.pdf

Woo, Chi-Keung and Roger Pupp. (1992). "Costs of Service Interruptions to Electricity Consumers." *Energy*, 17(2), 109–126.

APPENDIX A:
ASSORTED CALCULATIONS

Annualized California Share of WECC-Wide Savings

E3 estimated a present value of $1,220,540,494 to $3,510,982,465 worth of reliability attributable to synchrophasor deployment, for all of the Western Electricity Coordinating Council in year 2008 dollars, as the present value of 40 years of benefits discounted at 11.8 percent. This translates to $145,705,695 to $419,134,093 per year. For 2020, a year when California will have stringent renewables standards to meet, the Energy Commission is forecasting base case electricity loads for California and WECC of 326,508 GWh and 1,021,649 GWh. California's share is thus 32 percent. Multiplying the annualized estimates by 32 percent then by 1.02 to bring year 2008 dollars to year 2010 dollars yields $46 million to $134 million.

Sectoral Weights Used to Estimate Cost of Customer Outages

This section derives the weights used to change LBNL's estimates of cost per sector into a single estimate of customer outage costs.

In 2009, homes used 32 percent of electricity in California, while commercial and industrial businesses used 52 percent, meaning homes used 32/ (32+52) =38 percent of the electricity used in the three sectors LBNL addressed. Businesses used the remaining 62 percent. That 62 percent gets split into small business usage (52 percent of 62 percent) and medium to large business (48 percent of 62 percent), approximating based on the fact that 52 percent of the California private sector workforce is employed in small businesses.[38] The resulting weights of 38 percent, 32 percent, and 30 percent get multiplied by the residential, small business, and not-small business cost estimates.

Probabilistic Combination of Reliability Value Estimates

Table 1 lists five estimates of the avoided cost of customer outages due to synchrophasor research and deployment. The average of the midpoints of the estimates is $287 million.

To find central tendencies, each estimate was converted into a probability distribution. The four ranges were converted into uniform distributions from the minimum to maximum value, while the point estimate of $133 million was treated as normally distributed with a standard deviation of 30 percent of the mean value.

To combine the five probability distributions into one, 100,000 average draws were created by drawing one number from each of the five distributions and averaging the five numbers. These 100,000 averages constituted the average distribution. The mean and median were both $287 million. The first and third quartiles of this average distribution were $214 million and $358

---

38 U.S. Small Business Administration, Office of Advocacy. (2008). *Small Business Profile: California.* Retrieved from http://archive.sba.gov/advo/research/profiles/08ca.pdf.

million, respectively. This means most estimates fell in the neighborhood of $214 million to $358 million (between or near the estimates), rounded in the main document as $210 million to $360 million.

Alternative Approach: Direct Probabilistic Development of Reliability Value

This approach estimates reliability benefits directly as expected cost of outages times how much synchrophasors will help avoid those outages. The latter sum is unknown, and estimates have ranged from 10 percent to 50 percent. The customer outage avoidance rate, therefore, is drawn from a uniform distribution, with an equal probability of choosing any number between 10 percent and 50 percent.

As for cost of avoided customer outages, six estimates are possible:

1. Primen's paper for Electric Power Research Institute (EPRI) estimates California firms lose $13.4 billion to $20.4 billion per year from customer outages and power quality events. One million draws from that spread were taken. In this appendix, a draw from a spread means a draw from a normal distribution with 95 percent confidence intervals ending at the given values ($13.4 billion and $20.4 billion). Each draw of total customer outage cost was divided by a draw around 10 because around one tenth of customer outages begin on transmission lines. In this appendix a draw around x means a draw from a normal distribution of with mean x and a standard deviation of x/3.

Primen's estimate is given a weight of two, as it is based on one survey (one point) and uses California respondent data (second point).

2. LBNL estimated an $8.1 billion cost to California of customer outages, based on a meta-analysis of 24 studies. One million draws were made around that number (same definition as above, with standard deviation of $8.1 billion/3). Each was divided by around 10 to get the cost of customer outages beginning on transmission lines.

This LBNL estimate (LBNL 1) is given a weight of 24, as it is based on 24 surveys.

3. The California share of E3-estimated costs is $47 million to $137 million per year in major (hence transmission-level) outages. Draws were taken between $47 million and $137 million, using a uniform distribution that gives equal probability to every possible value between the two endpoints. The cost estimates were posited rather than linked to survey data; hence, the E3 estimate is given a weight of one half.

The following three estimates are based on size times customer outage frequency times cost per unserved kWh. KEMA found an expected California customer outage size of 3.839 million kWh using data from the North American Electric Reliability Corporation – a draw around this number is taken. Customer outage frequency has been analyzed as averaging around 1.56, as noted by KEMA,[39] a draw around this is also taken. The third element is cost per unserved kWh: Three estimates are available for this.

4. The most well-supported estimate is the weighted average based on the LBNL meta-analysis of 28 studies, which yielded a range of $100 to $550 per unserved kWh. Each draw for the LBNL range is drawn as if that range were the 95 percent confidence interval of a normal distribution. This LBNL-based distribution (LBNL 2), then is (around 1.56) x (around 3.839 million) x (a spread from $100 to $550).

The LBNL2 distribution is given a weight of 28, as it is based on 28 surveys.

5. The Heschong-Mahone Group (HMG) estimate of $42 per unserved kWh is combined with outage size and probability in the same way. The HMG distribution is (around 1.56) x (around 3.839 million) x (around 42).

The HMG distribution is given a weight of 5, as it is based on two California-specific surveys (2 points each) and 1 general paper (dated, hence 1 point).

6. The KEMA distribution is created like the HMG distribution but using a customer outage cost of around $13. Its customer outage cost is posited, rather than based on surveys, but the value was chosen with attention to past, albeit dated, studies. It is given a weight of 1.

To summarize, there are six probability distributions for costs of outages to Californians. Each one will be multiplied by a distribution of draws between 10 percent and 50 percent, representing the unknown percentage reduction in outages due to synchrophasor technologies. A weighted average of these six distributions is taken, with higher weights given to studies based on more real survey data.

The results in a distribution with mean around $410 million per year, median around $350 million per year, and first and third quartiles around $220 million and $540 million.

---

39 They cite Chen, J., J.S. Thorp, and M. Parashar. (2001). "Analysis of Electric Power System Disturbance Data." Presented at the International Conference on System Sciences, Hawaii: IEEE.

APPENDIX B: SYNCHROPHASOR-RELATED WORK FUNDED BY PIER

Table 3: PIER Synchrophasor Projects Through 2011

Contract	Amount	Description
500-97-012	$150,000	Phasor Measurement Units (Edison Technology Solutions/SCE, 1/7/98 – 6/30/04)
150-99-003	$1,150,000	Microgrid Amendment to Electric System Reliability Enhancements contract (LBNL, 6/1/00 – 9/30/05)
BOA-99-206-P	$235,200	Phasors (LBNL, 6/1/00 – 9/30/05)
BOA 130	$258,000	Public Interest Technology Assessment of Phasor-Based, Real-Time Dynamic Information Systems (Phasor Business Case) (KEMA, 1/1/06 - 6/30/07)
MRA-053	$231,128	Enhancement of Transmission State Estimation Results Using Real Time Phasor Measurement Data at SDG&E (SDG&E, 9/30/06 – 2/28/09)
MRA-054	$609,467	Advanced Protection Systems Using Wide Area Measurements (Virginia Tech, 10/14/06 – 9/30/10)
500-07-037, Task 3.2	$180,000	Oscillation Detection and Analysis (PNNL, 9/2/08 - 9/2/09)
500-07-037, Task 3.3	$360,000	Application of MANGO in Western Interconnection (PNNL, 9/2/08 – 1/8/10)
500-08-048	$1,699,149	Advanced Phasor Applications for Real Time System Operations Initiative Phase III (Electric Power Group, 11/20/08 – 3/31/10)
BOA-99-206-P	$235,200	Phasors (LBNL, 11/20/08 – 3/31/10)
500-08-054	$550,000	Synchrophasors for the Integration of Renewables (LBNL, 6/30/09-3/31/13)
MRA-02-085	$200,000	DOE Application of Advanced Wide Area Early Warning Systems with Adaptive Protection (CIEE, 7/19/2010 – 6/30/2011)
PIR-10-068	$999,743	CAISO Synchrophasor Technology Investment & Implementation (Electric Power Group, 4/1/11 - 12/31/13)
500-07-037, Task 4.1	$180,000	Adaptive Relaying Technology Development, (Virginia Tech, 9/2/08 – 9/2/11)
BOA 20-21	$88,050	Real-Time Grid Reliability Management Phases 1A & 1B

Contract	Amount	Description
BOA 20-24	$172,065	
MRA 036	$1,600,000	Real-Time Applications of Phasors for Monitoring, Alarming and Control (RTDIS Phase 1, LBNL)
MRA-041	$2,500,000	Real Time Dynamic Information Systems (RTDIS Phase 2) (LBNL, 1/1/06 – 6/30/07)
	$11,398,002	TOTAL

Source: *California Institute for Energy and Environment, California Energy Commission*