THE VALUE PROPOSITION FOR SYNCHROPHASOR TECHNOLOGY

ITEMIZING AND CALCULATING THE BENEFITS FROM SYNCHROPHASOR TECHNOLOGY USE

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Disclaimer

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This paper was written by Alison Silverstein (Project Manager, North American Synchrophasor Initiative) and PNNL employees Mark R. Weimar, PhD., and Joseph Petersen. This effort was supervised and managed by Jeffery Dagle, P.E., and Eric S. Andersen, PMP.

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Reviewers and contributors included:

- David Bertagnolli (ISO-NE)
- Dennis Naef (BPA)
- David Ortiz, PhD (DOE-OEDER)
- Abhishek Somani, PhD (PNNL)
- David Schooley (Commonwealth Edison)
- Tony Weekes (Manitoba Hydro)

Executive Summary

This report provides the methodology for identifying and estimating the benefits of using synchrophasor technology to enhance grid operations and planning. The methodology is intended to help entities develop defensible estimates of the the benefits derived from synchrophasor data and applications. The report outlines how to estimate the annual benefits that can be realized by using synchrophasor technology, relates them to synchrophasor data applications, and explains how to calculate and sum the value of these monetary and non-monetary benefits over time. The study identifies benefits from improvements in grid resilience and reliability, cost savings, increased efficiency and throughput, and environmental benefits from increased electricity generation from renewable resources.

The benefits of synchrophasor data analysis and use occur because synchrophasor measurement technology uses digital processing of electricity wave-forms, synchronized to a universal time source, to record system conditions at high speeds and provide real-time situational awareness of the electrical grid. Phasor measurement units (PMUs) can report as many as 60 measurements per second, while SCADA (supervisory control and data acquisition) provides a measurement every 4 seconds. This high-speed monitoring can detect and record events that SCADA misses, enabling much better visibility into grid conditions and the performance of specific assets such as power generators. PMUs used with high-speed data networks, high-quality data analytics, and active system management can provide improved reliability, environmental benefits, cost savings, and improved efficiency and throughput of the electricity grid.

Synchrophasor technology improves grid resilience and reliability by reducing the number and duration of outages, as well as reducing the number of customers affected by outages. It can help to decrease the time required to restore service through faster line reclosing, faster blackstart, faster island resynchronization, faster forensic analysis, and smoother generator synchronization. Oscillation detection and actions to restore grid stability can reduce outages. Outage reductions also occur from identifying potential equipment failures and fixing them before they occur.

In addition to improving grid resiliency and reliability, synchrophasor technology can increase savings to transmission owners and customers. Cost savings are primarily derived from congestion reduction, reduced labor costs associated with reduced forensic analysis, and model validation. Cost savings can also arise from reduced fossil energy use as more renewable energy is allowed onto the grid. Lastly, cost savings can arise from deferred or avoided capital acquisition. Many of the efficiency and throughput benefits make sense in principle, but this report does not provide a methodology to calculate them because they involve relatively small amounts of energy and would require significant extrapolation from currently available facts.

Environmental benefits occur because synchrophasor technology can increase the amount of intermittent renewable energy that can be accommodated by the grid. This avoids some fossil fuel consumption and its associated pollution emissions.

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Section 1 – The synchrophasor benefits calculation framework

Synchrophasors provide many benefits to the electricity grid system. Articulating the value of those benefits helps us assess the results of past investments in synchrophasor technology and weigh new project opportunities. This document outlines the annual benefits that can be realized by using synchrophasor technology, relates those to synchrophasor data applications, and explains how to calculate and sum the value of these monetary and non-monetary benefits over time. But the importance of this study lies in its documentation of the framework and methodology for estimating synchrophasor value, which enable users to systematically identify and quantify value appropriate to the specifics of their own projects.

These benefits arise because synchrophasor measurement technology uses digital processing of electricity wave-forms, synchronized to a universal time source, to record system conditions at high speeds and provide real-time situational awareness of the electrical grid. Phasor measurement units (PMUs) can report as many as 60 measurements per second, while SCADA (supervisory control and data acquisition) provides a measurement every 4 seconds. This high-speed monitoring can detect and record events that SCADA misses, thereby enabling much better visibility into grid conditions and the performance of specific assets such as power generators. PMUs used with high-speed data networks, high-quality data analytics, and active system management can provide improved reliability, environmental benefits, cost savings, and improved efficiency and throughput of the electricity grid.

Most justifications of synchrophasor technology to date have asserted benefits based on anecdotal evidence, rather than by developing specific numerical estimates for those benefits. This study is a first attempt to identify an extensive suite of synchrophasor technology benefits in specific, quantifiable terms and metrics. The authors encourage readers and users to share their feedback and insights on the usefulness of these metrics and calculation methods, and to share their synchrophasor project benefits analyses. Such feedback will be used to modify and improve the benefits estimation study and methods for future synchrophasor users and investors.

1.1 Benefits and value metrics of synchrophasor technology use

The specific, quantifiable benefits that can be realized from synchrophasor technology use are listed in Table 1-1, which summarizes the major categories of synchrophasor benefits. As should be expected in an industry that places high value upon reliability, the benefits of synchrophasor technology use can be calibrated in terms that include increased reliability and resiliency derived by reducing outages, the number of unserved customers and the cumulative length of time that they are unserved, and outage costs; cost savings from reduced labor and energy costs; increased grid throughput and efficiency; and increased environmental benefits from higher renewables usage and the associated pollution avoided.

Table 1-1 – Synchrophasor benefits and value metrics

Synchrophasor Benefit	Synchrophasor Value Metrics
Reliability and resiliency benefits	
Reduction in major outages	Number major outages
Reduction in minor outages	Number minor outages
Fewer customers affected by outages	Number customers
Fewer equipment failures and catastrophic emergencies	Number of equipment failures Number of catastrophic equipment emergencies
Faster service restoration	Number of outage hours avoided
Faster line reclosing	Number of outage hours avoided MWh energy flows enabled
Smoother generator synchronization	Not known
Faster black-start restoration and synchronization	Number of outage hours avoided Customers affected
Faster island restoration	Number of outage hours avoided, Customers affected
Faster forensic event analysis and lessons learned	Not quantified (NQ)
Backup communications network and data for loss of SCADA system	NQ
Cost savings	
Congestion reduction	$ value of more efficient dispatch
Labor cost reductions	Staff hours saved $ value of worker hours saved
Reduced energy use	MWh and value of MWh saved

Fuel and hydro savings (includes operation and maintenance [O&M] costs)	MWh realized from generation efficiency
	$ value of fuel savings
	$ value of O&M savings

Capital savings	$ capital value of assets not built $ net present value of capital investments delayed
Grid throughput and efficiency benefits	
Enhanced energy flows	Bottleneck facilities relieved; MWh of incremental flows from bottlenecks reduced
Increased energy flows	MWh of increased energy from fewer outages
Better reactive power management	NQ
Environmental and policy benefits	
Increased delivery and use of renewable generation	Incremental renewable MWh
Decrease in net carbon emissions	Incremental tonnes of pollutants not issued from fossil generation

The greatest benefits of synchrophasor technology are related to improved grid reliability and resiliency. Major reliability benefits occur because the more granular data and keener analytics available from synchrophasor systems enable earlier detection and analysis of potentially dangerous grid conditions. They also enable early identification of potential causes and mitigation options for those conditions, which enhance resiliency as well as reliability. Synchrophasor technology allows operators and planners to gain a better understanding of system performance and relationships from improved model validation. It can improve operational tools and operators' instincts with synchrophasor-based training and tools, including visualization, alarms, and alerts. These should help grid operators avoid major and minor outages, reducing the number of customers and customer-hours of service disruption and speeding system restoration time. In the event of a major disturbance, engineers can use synchrophasor data to analyze the event and identify root causes quickly, thereby enabling the industry to implement relevant mitigations and improvements that may prevent similar disturbances in the future (Patel et al. 2010; CAISO 2011; Carter et al. 2010).

Cost savings arise from equipment savings, labor savings, and other avoided costs. With synchrophasor data-based model validation, generators and transmission owners can spend less time and money on physical generator testing and modeling, with no lost revenue from plant down-time. Synchrophasor data and analytics enable identification of potential equipment failures before they occur, thereby supporting conditioned-based maintenance that should reduce catastrophic equipment failures and direct maintenance costs (NASPI March 2015).

Synchrophasor technology can yield labor savings in several ways. Reducing equipment failures should reduce crew labor costs, including overtime, and enable more cost-effective equipment acquisition and inventory management. Fault location using PMU data should reduce crew field time spent hunting for an outage location. Additional costs savings occur in forensic analysis, with PMU data enabling construction of a sequence of events within hours rather than after months of engineering effort. This lets engineers model and analyze the disturbance more quickly, saving additional labor hours (Carter et al. 2010).

PMUs allow the grid to operate more efficiently. Grid managers can use synchrophasor systems for congestion management and dynamic line loading, getting greater utilization from existing transmission assets (CEC 2013). This can reduce line losses, delivered energy costs, and total generation requirements, ultimately requiring fewer barrels of fuel to provide the same amount of delivered electricity. The increased efficiency may occasionally lower capital costs for transmission lines and generation assets. Also, better recognition and use of active and reactive power needs can improve grid utilization. However, this is one of the most challenging benefit sets to estimate and quantify (Hurtgen 2012).

Environmental benefits of synchrophasor use occur because PMU data and analytics help grid planners and operators manage intermittent generating resources such as wind and photovoltaics (PV) without compromising reliability. This enables an incrementally greater use of renewable generation, with associated carbon emission reductions as wind and PV replace fossil generation. At the same time, fossil fuel costs decline incrementally because renewable generation is displacing fossil generation (net of renewables integration requirements) (NASPI 2012).

Some synchrophasor benefits are easier to articulate and quantify than others. Some of the benefits listed in Table 1-1 are obvious and clear in principle, but difficult to quantify in terms of value. Those benefits are indicated as being not quantifiable (NQ) in the table above.

1.2 Mapping applications to benefits

Table 1-2 maps the major synchrophasor applications to these benefits. Recent experience of synchrophasor technology users indicates that estimating the value created by synchrophasor applications is complex due to several factors, as follows:

- Many of these benefits are realized due to a combination of synchrophasor applications (for instance, oscillation detection plus voltage stability monitoring plus visualization), rather than through the use of only a single application.
- Few of these benefits can be realized if the synchrophasor data are used only for monitoring, observation, and analysis. Rather, most of these benefits can only be realized if the synchrophasor user actually uses the analytical results to effect specific changes and improvements in grid operations or models. Without specific action in response to the synchrophasor-enabled insights—such as through operator- or engineer-directed intervention, automated protection and control, or model modification—few of the potential benefits will be realized.
- Because of these two considerations, there is a risk of double-counting synchrophasor benefits by attributing the same impacts or benefits to multiple applications.
- While some of these benefits are clearly valid in theory, it is difficult to estimate or attach specific metrics or numbers to them.

For these reasons, few users have yet attempted to document and quantify the beneficial impacts of synchrophasor use in a broad and rigorous fashion.

In the study described here, the value analysis is organized and presented in terms of common benefits rather than by applications, specifically to help users think through the applications in a way that reduces the possibility of double-counting benefits.

Table 1-2 – Synchrophasor benefits and applications

Synchrophasor benefit	Synchrophasor value metrics	Applications contributing to or delivering each benefit
Reliability and resiliency benefits		
Fewer and shorter outages	• Number of outages	• Real-time visualization • Oscillation detection • Voltage stability monitoring and management • Operator decision support • PMU-based alarms and alerts • Operator training • Model validation • Forensic event analysis • Automated system protection • Synchrophasor-aided state estimation
Fewer customers affected by outages	• Number of customers	• Real-time visualization • Oscillation detection • Voltage stability monitoring and management • PMU-based alarms and alerts • Operator decision support • Operator training • Model validation • Forensic event analysis • Automated system protection • Synchrophasor-aided state estimation
Fewer equipment failures and catastrophic emergencies (including generators and transmission equipment)	• Number of equipment failures • Number of catastrophic equipment emergencies • Number of outage hours avoided, number of customers affected, value of outage reduced	• Event analysis • PMU-based alarms and alerts • Model validation • GMD-GIC (geomagnetic disturbance-geomagnetically-induced current) event detection
Faster service restoration	• Number of outage hours avoided • Number of customers affected • Value of outage reduced • Labor hours saved	• Fault location • Phase angle monitoring • PMU-based alarms and alerts • Model validation

Synchrophasor benefit	Synchrophasor value metrics	Applications contributing to or delivering each benefit
Faster line reclosing	• Labor hours saved • MWh energy flows enabled • Revenue earned • Number of outage hours avoided • Number of customers affected • Value of outages reduced	• Phase angle monitoring • Real-time visualization
Smoother generator synchronization	• Outage hours reduction	• Phase angle monitoring
Faster black-start restoration and synchronization	• Hours saved • Customers affected	• Phase angle alarming • Real-time visualization
Faster island restoration	• Outage hours reduction • Customers affected	• Phase angle alarming • Real-time visualization • Operator training and event simulation • Model validation
Faster forensic event analysis and lessons learned	Not quantifiable	• Forensic event analysis • Model validation
Backup communications network and data for loss of SCADA system	Not quantifiable	
Cost savings		
Congestion reduction	• $ value of more efficient dispatch	• Voltage management • Real-time visualization
Labor cost reductions	• Staff hours saved • $ value of worker hours saved	• Model validation • Event analysis • Forensic event analysis • PMU-based alarms and alerts
Reduced energy use	• MWh • $ value of MWh saved • % line losses avoided	• Congestion management & dynamic line loading • Voltage stability monitoring and management • Automated protection systems • Renewables integration • PMU-based alarms & alerts • PMU-enhanced state estimation
Fuel and hydro savings (includes O&M costs)	• MWh realized from generation efficiency • $ value of fuel	• Congestion management & dynamic line loading • Voltage stability monitoring and management

Synchrophasor benefit	Synchrophasor value metrics	Applications contributing to or delivering each benefit
	savings • $ value of O&M savings	• Automated protection systems • PMU-based alarms & alerts • PMU-enhanced state estimation
Capital savings	• Assets not built • $ net present value of capital investments delayed • $ value of equipment damage and replacement averted	• Congestion management & dynamic line loading • Voltage stability monitoring and management • Automated protection systems
Grid throughput and efficiency benefits		
Enhanced energy flows	• Bottleneck facilities relieved • MWh of incremental flows from bottlenecks reduced • MWh of increased flows due to fewer/shorter outages	• Congestion management & dynamic line loading • Voltage stability monitoring and management • Automated protection systems • PMU-based alarms & alerts • PMU-enhanced state estimation • Model validation
Better reactive power management	Not quantifiable	• Voltage stability monitoring and management • Automated protection systems
Environmental and policy benefits		
Increased delivery and use of renewable generation	• Incremental renewable MWh	• Congestion management & dynamic line loading • Voltage stability monitoring and management • Automated protection systems • PMU-based alarms & alerts • PMU-enhanced state estimation • Model validation
Decrease in net carbon emissions	• Incremental tonnes pollutants avoided from fossil generation	• Congestion management & dynamic line loading • Voltage stability monitoring and management • Automated protection systems • PMU-based alarms & alerts • PMU-enhanced state estimation • Model validation

1.3 Study overview

Section 2 discusses how to use this benefits estimation methodology. Section 3 reviews each of the benefits in turn and offers a method for calculating each benefit (to the degree that it can be quantified at this time). Section 4 discusses the methodology for converting annual benefits to project lifetime benefits. This explanation includes documentation for the calculation method for each quantifiable benefit. Where possible, this section offers one or two specific illustrations that lay out how a synchrophasor project has used specific applications to realize this benefit, with actual or representative estimates of the value of that benefit for that project application.

Section 2 – How to use this valuation methodology

This section offers suggestions and cautions to guide analysts in using the framework and methodology offered in this report.

Benefits, not costs – This study estimates the benefits of synchrophasor use based on accepted methods of calculating benefits used in other areas of electricity and energy analysis (for instance, in energy efficiency, transmission, and smart grid benefit-cost analyses). This study presents just one side of a cost-effectiveness analysis; it does not attempt to estimate synchrophasor project costs, because those costs are changing rapidly and are highly project-specific.

Many benefits, not just dollars – Many electric industry cost-benefit analyses attempt to convert every benefit into dollar terms (Haddad et al. 2012). But synchrophasor technology adoption is being driven principally by the need to maintain and improve grid reliability in the face of growing operational challenges, without significantly increasing operating and capital costs. Electric system analysts should not lose sight of non-dollar benefits. Goals such as customer outage hours and power quality, worker safety, renewable megawatt-hours enabled, and carbon emissions avoided are important societal and electric policy goals that should be valued in their own rights. Reasonable reliability estimates are easier to delineate than it is to translate those reliability impacts into dollar-denominated impact estimates.

Benefits over time – Synchrophasor systems are relatively new and are evolving quickly. Unlike traditional long-lived utility capital projects, these systems combine capital equipment with complex information and communications technology elements. Whatever time horizon is used, the cumulation of benefits should list and sum the various benefit streams over time, and not force the non-financial benefits into net present valued dollars (Keeler and Cretin 1982).

Appropriate time horizons for synchrophasor benefits estimation are discussed further below.

Specific, not general – This study offers a methodology for valuing the benefits of synchrophasor technology, but it does not attempt to assert a sweeping summary number for the value of those benefits. To date, only a few studies have outlined a broad business case or benefits valuation for synchrophasor technology (Novosel et al. 2007; Carter et al. 2010). Most of those were prepared before much synchrophasor technology had been deployed, and the benefits were still hypothetical and assumed big impacts with wide applicability. More recent work has been very narrow in scope, with individual project owners estimating or documenting the benefits from a single synchrophasor technology application.[1]

[1] For example, the Western Electricity Coordinating Council (WECC) analysis of how synchrophasor technology could be used to increase the throughput of the California-Oregon

One exception is the recent California Energy Commission (CEC) staff study (Kandel 2014). That study was prepared to show the significant return from the CEC's investments in developing and deploying synchrophasor technology. It estimates those benefits based on the assumed impacts of widespread synchrophasor usage through 2030, using mature technology and applications that affect all California electric users. That draft study estimates that,

> … synchrophasor technologies should save Californians from $210 million to $360 million in customer outage costs. 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 should the technologies prove fruitful in avoiding firming power costs and allowing transmission line rerating" (Kandel 2014).

The study uses alternate approaches to calculate the value of avoided customer outages and estimates the net present value benefits from synchrophasor use in California to be $2.7 billion, with annualized benefits of $260 million per year (Kandel 2014).

This study is more modest in scope. It assumes that the principal users of this methodology will be analysts who are trying to estimate the value that could be produced by a specific synchrophasor project being undertaken over a limited footprint for specific applications and purposes; for instance, a new synchrophasor deployment contemplated by a transmission owner that needs to integrate wind generation, manage voltage, comply with North American Electric Reliability Corporation (NERC) modeling and balancing reliability standards, monitor transmission assets for condition-based maintenance and asset commissioning, and share real-time operational data with its reliability coordinator. For that analysis, the analyst would identify the specific benefits associated with those applications, develop estimates for the components of each benefit that are appropriate for the location and scope of the project (e.g., regionally appropriate energy and labor costs, number of grid constraints limiting local renewables delivery, and region-specific incremental carbon emissions per megawatt-hour of fossil generation displaced by renewables), and roll those up through the appropriate benefits calculations to estimate the project's value.

<u>Conservative, not aggressive</u> – This study is an early effort to document value, which is only beginning to be recognized, of using an emerging technology. At this stage, it is useful to establish a valuation methodology with conservative, defensible estimates of the value of synchrophasor technology in specific uses. As the industry gains more experience using synchrophasor technology in different ways, measures the results of those uses, and shares those results, it will be easier to find source material and defensible values for each application and type of benefit, and it is likely that the magnitude of estimated benefits will increase over time.

Intertie (link), Bonneville Power Administration's (BPA) reporting on the costs avoided and generator revenue retained from performing synchrophasor-based model validation (link), and various accounts from Smart Grid Investment Grant recipients about the beneficial impact of specific synchrophasor technology uses within their organizations.

Estimating what did not happen – It is not easy to estimate counterfactuals for low-probability events for which we have limited experience. For example, how many blackouts might there have been if phase angles were not monitored more closely?[2] How many instrument transformers might not have exploded if we had monitored phase angle, current and voltage more closely in substations to detect anomalous behavior? This study attempts to look at actual data and extrapolate from documented user experiences with synchrophasor technology to develop counterfactuals and make conservative estimates for the near-term impact of synchrophasor technology.

Pace of reliability improvements – Many of the impacts of synchrophasor technology on reliability, such as those from model improvements and oscillation detection, may take effect with large impacts fairly quickly. For instance, many transmission asset models may be improved within the first six months of synchrophasor use; alarm and limit settings will be improved within a year; and event analysis efficiencies could be noticed within three months. After that, many categories of benefits may remain relatively flat rather than increasing steadily over time.

A synchrophasor system being planned today will have specific applications and reliability goals. The analysis of reliability and other benefits should start by trying to quantify the impacts of those known uses and goals, recognizing that synchrophasor technology can reduce but not eliminate outages. But new synchrophasor data uses and benefit opportunities are being developed and maturing each year, so while one benefit stream may flatten out, another may start up in later project years. It is entirely appropriate to hypothesize and itemize future benefit streams from these evolving uses, such as the potential benefit of using PMUs as an early warning mechanism for geomagnetic disturbance-caused currents, or for condition-based asset monitoring and maintenance.

Deterministic versus probabilistic – For the sake of simplicity, this study offers only deterministic methods for how to estimate synchrophasor benefit. But since there is so much uncertainty about how these benefits could play out over time, it would be reasonable to modify the deterministic estimates with some confidence band approach. This could be done by assigning probabilities of occurrence to different benefit outcomes, or applying an upper and lower range of outcomes to the most important benefits.

The goal of this study is to offer a sensible and defensible methodology for value estimation. As North American electric entities and others gain more experience using synchrophasor technology, more details and data will become available for documenting and calculating the value of synchrophasor technology.

[2] The Midcontinent Independent System Operator (MISO), for instance, estimated that synchrophasor applications would reduce 2003 magnitude blackouts from 1 in 20 years to 1 in 30 years (MISO 2015).

Section 3 – Synchrophasor benefits and valuation examples

In this section we review each set of benefits and outline the calculation methods and data needs for each type of benefit. Wherever possible, the discussion identifies specific numbers and source materials that could be used to quantify and estimate the value of this benefit.

Table 3-1 maps the major synchrophasor applications to classes of benefits. As the table reveals (reading down the benefits columns), significant overlap exists between many of the applications and the benefits they deliver. But it is rare that a single synchrophasor application can claim the credit for avoiding an outage or reducing costs. For example, a host transmission owner or reliability coordinator might have used the combination of synchrophasor-based wide-area situational awareness with voltage monitoring, oscillation detection, and improved alarms and alerts to spot a growing grid problem and avoid an outage.

Most documents about synchrophasor technology approach the topic by describing specific applications. But companies invest in synchrophasor technology to achieve specific goals such as improving reliability and reducing costs, not because they want the applications for their own sakes. Therefore, this analysis approaches the benefits of synchrophasor technology from the end goals of reliability, grid utilization, cost savings, and environmental impact, rather than itemizing the applications directly. This approach allows us to avoid double-counting or exaggerating benefits by claiming the same benefit for more than one application.

Relevant applications are summarized in the introduction and mentioned in the discussion of specific metrics; if the reader wants to learn more about specific applications, numerous resources are listed in the footnotes and reference list.

Table 3-1 – Benefits of synchrophasor technology, by application

	Better grid reliability	Better grid throughput and usage	Better grid economics and cost savings	Better environmental impact/more renewables
Real-time operations and operations support tools				
Visualization & wide-area situational awareness	X	X		X
Oscillation detection	X	X	X	X
Phase angle monitoring	X	X	X	X
Voltage stability monitoring	X	X		X
Event detection	X	X		X
Event management	X	X	X	X
Islanding detection and restoration management	X		X	
Automated protection and controls	X	X		X
Off-line tools				
Model validation and improvement (generator, load and system models)	X	X	X	X
State estimation and linear state estimation	X	X	X	X
Equipment mis-operations diagnosis	X	X	X	X
Post-event analysis	X		X	X
Operator training	X		X	

3.1 Reliability and resiliency benefits

Synchrophasor technology improves grid reliability in many ways (as described in the list below), almost all of which should end up affecting the number, duration, and severity of electric disturbances and outages:

- Inadequate wide-area monitoring and situational awareness has been a contributor to numerous major and minor blackouts. High-speed, real-time synchrophasor data enables much better monitoring, trending, and visualization, which allows grid operators to identify problematic situations and craft better responses.
- System operating limits and alarms and alerts for potentially hazardous conditions are essential operating tools. Baselining analysis of historic synchrophasor data can be used to set system operating limits (SOLs) and update alarms and alerts, while pattern recognition and data mining of those records can be used to inform real-time, synchrophasor data-based operator decision support tools.
- NERC has identified protection system mis-operations and equipment mis-operations as significant causes of bulk electric system disturbances, and made it an industry priority to address the issues underlying these problems (NERC 2015 pp. 8, 10–11, NERC 2014). Synchrophasor data can be used to identify and help remedy many of these problem causes.
- Small signal stability issues are on-going threats to the reliability and stability of the grid. An unstable oscillatory mode can cause large amplitude oscillations that can lead to large-scale blackouts. PMU data and analytical tools enable analysts to identify active oscillatory modes and determine whether oscillations are damping safely. Once oscillations have been identified, analysts can develop mitigation measures as needed.
- Phase angle monitoring can be used to monitor and improve the speed and accuracy of line reclosing and generator synchronization.
- Once a grid disturbance occurs, synchrophasor data can be used for event analysis to determine its cause, manage grid islands, and coordinate black-start synchronization and restoration (Sharma et al. 2009).
- Following a grid disturbance, synchrophasor data can be used for forensic event analysis to find the cause of the disturbance, simulate the event, and determine potential future remedial actions.
- Many grid events occur because the models used to plan and monitor grid operation do not accurately predict grid behavior under various grid disturbance conditions. PMU data are being used for model validation, producing notably better models of generators and grid assets at lower analytical cost with rapid update capability (Silverstein et al. 2015; Overholt et al. 2014; WECC Jul 2012).

In the electric industry, resilience has been defined as the ability to "reduce the magnitude and or duration of disruptive events" (NIAC 2010). The National Association of Regulatory Utility Commissioners' definition of resilience refers to the robustness and ability to recover, avoid, or minimize service interruptions during extraordinary or hazardous events (Cody 2014). Grid resilience becomes increasingly important because of the higher incidence of severe weather-related damage due to climate change. Severe weather outages cost between $18 and $33 billion annually including lost wages, production, and damage to the grid (EOP 2013).

Grid resilience and reliability are closely related. The synchrophasor applications that improve reliability also improve resilience by reducing the number and duration of electrical outages (via faster reclosing, better electrical island management, and better black-start restoration) and the number of customers affected. Use of synchrophasors allows operators to identify and mitigate reliability concerns and disturbances. These attributes allow the grid to be more resilient and less likely to succumb to severe weather events. In addition, the use of synchrophasors enables operators to "see" equipment vulnerabilities such as transformer failures before they occur. This could allow operators to position equipment to reduce the likelihood of equipment damage, so that equipment often can be fixed or replaced without outage time (EOP 2013).

Table 3-2 summarizes the benefits and calculation methods for the reliability benefits discussed in this section. The specific reliability benefits and their calculation methods are discussed below. Most of these discussions offer one or more examples of representative synchrophasor uses and estimated benefit components for each benefit calculation. Following the summary discussion, each of the reliability benefits is discussed along with suggestions for calculation methods and data sources.

Table 3-2 – Reliability and resiliency benefits calculations

Benefit	Benefit metric	Calculation method
Reduction in major and minor outages	Number major and minor outages avoided	Estimated number of outages avoided annually by using synchrophasor technology
Fewer customers affected by outages	Number of customers	Reduced number of outages * reduced number of affected customers
Outage time	Avoided minutes of customers being out of service	Number outages reduced * reduced amount of time
Fewer equipment failures and catastrophic emergencies	Number of equipment failures avoided	Estimated number of equipment failures avoided through condition-based monitoring and early detection
	Number of potential catastrophic equipment emergencies avoided	Estimated subset of equipment failures avoided that could have resulted in catastrophic damage
	Number of outage hours avoided/reduced	Number of equipment failures avoided * number of customers served by that equipment * average number of hours for equipment replacement or repair effort per failure
Faster service restoration	Number of events where service restoration accelerated	Estimated number of events where service restoration accelerated
	Number of customers affected	Sum of (events * number of customers affected/event)
	Number of outage hours avoided or reduced	Sum of (events * number of customers affected/event * minutes of outage reduced from faster service restoration)
Faster line reclosing	Number of events with faster line reclosing	Count number of events when PMUs enabled faster line reclosing

Benefit	Benefit metric	Calculation method
	Time saved	Sum of (minutes saved from average faster line reclosing event * number of events)
Smoother generator synchronization (routine, not black-start)	Number of events when generator synchronization was expedited by synchrophasor monitoring)	Count or estimate number of events per year
Faster black-start restoration	Number of black-start events	Estimate number of black-start events
	Number of customers affected by outage requiring black-start	Estimate number of customers affected based on black-start exercise
	Time black-start effort reduced by using PMUs for black-start resynchronization	Reduced minutes or hours based on experience of black-start restoration
Faster island resynchronization	Shorter operational time islanded	Estimate time saved based on black-start exercise, Hurricane Gustav example, or other experience
	Reduced number of customers affected	Numbers of customers in the island
Faster forensic event analysis and lessons learned	Time saved in faster event reconstruction and modeling relative to pre-PMU event analyses	Estimate time compared to 2003 Blackout investigation
Backup communications network and data for loss of SCADA	NQ	NQ

3.1.1 Calculating the benefit of reduced customer outages

Synchrophasor technology users hope to reduce the number and magnitude of outages, shorten the length of outages, and reduce the number of customers affected. As outlined in Table 3-1, the reliability metrics associated with outages are the reduction in:

- the number of major and minor outages that occur,
- the magnitude or severity of those outages in terms of customers affected,
- the time duration of those outages,
- the number of customer-minutes out of service, and
- the financial value of the customers' inconvenience and societal discomfort.

The first way to estimate the value of reduced customer outages can be calculated using the above factors:

> Number of customer hours out of service = reduced number of outages due to synchrophasor technology * number of customers affected by those outages * time duration of the outages

Value of customer outages = reduced number of customer outage hours attributable to synchrophasor technology use * average financial value of customer outage per hour

The second approach modifies outage analyses developed by Lawrence Berkeley National Laboratory (LBNL), which determine the value of total customer outage costs using System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) values. Since SAIDI and SAIFI estimates are dominated by distribution-level events,[3] the modification requires recognizing only those transmission-level outages that active synchrophasor management could impact.

The first step is to estimate how much the use of synchrophasor tools could reduce the number and length of outages. The second step estimates how much these tools could reduce the number of customers impacted by outages. The last step determines the value of the outage time.

Estimating synchrophasor impacts on outages – The analyst needs to evaluate recent and current region-specific outage data and consider whether the use of synchrophasor technology could have enabled grid operators to identify and avoid at least a few of the outages. Data on past outages could be used to estimate the number of major and minor outages[4] attributable to Bulk Electric System (BES) problems,[5] the number of customers affected by each type of outage, the duration of the outages, and therefore the number of customer-minutes of outages.[6] Lacking specific experience with synchrophasor technology, but given the information in Section 2.3 below on the numerous ways that synchrophasor technology can be used to improve BES reliability, the analyst could estimate the reliability impacts.

Table 3-3, a NERC summary of bulk power system-related outages, lists the number of outages, number of customers affected, outage durations, and the general causes of those

[3] SAIDI and SAIFI were developed by IEEE in Standard P1366, "Guide for Electric Distribution Reliability Indices," and most of the events that cause customers to experience electric outages arise at the distribution level where synchrophasor technology is not yet widely used.
[4] This study uses the "alert criteria" for the Energy Information Administration's Form OE-417 Electric Disturbance Report, in which "major outage" means outages that affect more than 50,000 customers, and minor outages affect fewer than 50,000 customers.
[5] Most current uses of synchrophasor technology are to support bulk electric system reliability, so it is appropriate to exclude outages caused by distribution systems. Eventually, as more transmission owners use PMU data to monitor events and equipment on individual transmission circuits, those entities will be realizing circuit-specific distribution-level reliability benefits.
[6] In 2009, before the Western Electric Coordinating Council (WECC) had significant experience with synchrophasor technology, it estimated that the proposed Western Interconnection Synchrophasor Project would avert two major outages (lasting 8 hours and affecting over 500,000 customers each) over a 40-year project life. The WEEC used estimates for the distribution of customer classes and the cost to customers of an 8-hour outage to estimate the net present value of the avoided outages at somewhere between $1.2 and 3.5 billion in 2008 net present value (WECC 2009, pp. 35–36).

outages for 2010 through 2014. The analyst could use these data as a starting point for approximating the metrics below.

Table 3-3 – Duration of outages, number of customers affected, and outages by NERC region

Year	Momentary	>5 - <=30 min	>30 - <=60 min	>1 - <=4 hours	>4 - <=8 hours	>8 - <=16 hours	>16 - <=24 hrs	>1 - <=2 days	>2 - <=3 days	>3 - <=4 days	>4 days	NA
						Length of Outage						
						Number of Outages						
2014	42	12	15	20	18	14	18	21	13	4	13	24
2013	37	11	10	33	14	8	9	22	14	9	6	1
2012	47	13	6	27	16	10	12	23	15	3	24	
2011	57	7	8	38	38	17	29	56	24	6	25	2
2010	2	4	8	15	16	11	2	24	12	6	20	3
						Number of Customers Affected						
2014	1,159,125	-	145,951	930,581	1,047,684	1,943,165	1,253,742	1,222,102	1,421,247	646,277	912,580	6,168,493
2013	83,632	500,657	412,000	515,641	811,600	403,627	518,838	2,207,344	1,300,149	950,825	1,124,000	
2012	30,379	11,963	29,250	1,264,205	1,261,341	532,998	900,460	2,209,219	2,682,379	5,061,354	8,696,891	
2011	774,300	11,000	28,714	1,359,948	712,575	1,133,856	1,614,165	8,644,130	6,175,658	533,833	4,984,640	220,000
2010	36,011	2,674	373,737	565,519	388,127	789,801	138,000	2,241,567	1,139,731	1,029,134	4,736,314	250,514

Outages by NERC Region 2010-2014

	RFC	TRE	SERC	WECC	MRO	NPCC	ERCOT	SPP	FRCC	Other
2014	57	16	37	63	22	15	3	1		3
2013	45	5	22	59	8	20		6	3	6
2012	74	8	25	49	3	26		8	1	2
2011	94	15	46	77	4	44		21	3	3
2010	45	5	18	31	6	9		8	1	

Include 3 outage in Ercot for 2014

	50000 Customers or more	Load Shed	Cyber Attack	Physical Attack	Weather	Earthquake	Equipment	Islanding	Distribution or Transmission System Interruption	Fault	Fuel Supply	Public Appeal Reduce Demand
2014	70	2	3	76	71	1	1	14	4		18	26
2013	59	8	2	78	53		4	13	4	1	6	1
2012	77	5	3	86	81		3	6	4		5	5
2011	139	13	7	114	135	1	3	4	4	1	7	18
2010	71	11			75		6	10	3	1	3	16

Source: Office of Electricity Delivery and Energy Reliability, U.S. Department of Energy. "Electric Disturbance Events (OE-417)." Accessed September 2015 at http://www.oe.netl.doe.gov/oe417.aspx

Estimating customer impacts – The number of customers affected by outages with and without synchrophasor technology could be estimated based on recent outage statistics (for instance, the U.S. Department of Energy OE-417 reports or the NERC Transmission Availability Data System data) or the company's own data on historic outages. With data on the causes of recent outages, the analyst could identify the specific outages and causes that might have been avoided or reduced had synchrophasor technology been in use when the outage occurred.[7] Alternatively, the analyst could look at a general data source such as Table 3-2, a summary of OE-417 data. The analyst could then estimate the number of BES-related major and minor outages (modified by region) and estimate how many of them might have been avoided or reduced by using synchrophasor technology. DOE's OE-417 Electric Emergency and Disturbance Reports[8] give outage-specific duration and

[7] The Appendix to the NERC ACSETF report, "AC Substation Equipment Failure Report" (December 2014), indicates how many outage events occurred due to different types of substation equipment failures (see Appendix Figures 17 and 18), and gives the average duration of the sustained outages (Appendix Tables 9 and 10).

[8] Available at http://www.oe.netl.doe.gov/oe417.aspx.

customer counts, so they could be used to construct an average or representative customer count and outage duration. Actual or average customer counts for different types of outages would then be multiplied by the number of outages avoided to get the estimated number of customers benefiting from synchrophasor-avoided or -shortened outages.

Customer outage minutes avoided – This follows from the number of outages and number of customers affected by those outages. A simple approach would use historical average outage durations for the major and minor outages avoided and hypothesize that synchrophasor technology could shorten those outages by an average of a short time period per outage (as from fault location, faster line reclosing, island management, and more effective black-start restoration).

Dollar impact of outages avoided – This places a financial value on customer outage inconvenience, including actual costs (such as those from damaged equipment or lost sales) or harm avoided. Economists have conducted various studies to estimate the value of lost load and routinely multiply the number of customers affected by the value of lost load per minute by the minutes of outage reduced to estimate the cost of outages. To extend this method for synchrophasor impacts, the analyst would estimate the number of residential, industrial, and commercial customers affected by the estimated reduction in outages attributable to synchrophasor technology, and multiply the minutes of outages avoided for each customer group by a value of lost load appropriate for that customer group.

There are several estimates for the value of customer load as reflected in the cost of being out of service. These include the following:

- $/power customer/hour, from LBNL (LaCommare and Eto 2006);
- individual utility estimates (PacificCorp 2015; Carter et al. 2010); and
- Sullivan 2015 value of service study (Sullivan et al. 2015).

Alternative calculation approach – The alternative approach to calculating customer outage value uses estimates of transmission outages as a percent of total outages and multiplies that by the total value of all customer outages. This approach requires the analyst to start with all outages and remove the outages that are caused by distribution-level events to determine those associated with the BES, and then to determine what subset of those outages could be reduced by active synchrophasor management. The number of customers and the reduced outage duration would be multiplied by the value of the reduced amount of outages.

To determine is the percentage of transmission outages reduced by the use of synchrophasor technology, the analyst should look at experience within the analyst's own company or documented experience at other companies. The literature offers a range of values for how much synchrophasors can reduce transmission-caused outages. Massoud

Amin (2011)[9] estimates that synchrophasors can reduce transmission-level outages by 31% to 41%. At least one estimate indicates that transmission-level estimates are about 10% of total outages (Campbell 2012). Another estimate indicates that synchrophasors would only prevent 50% of the preventable outages. These could be combined to estimate that 1.5% to 2.0% of total outages could be prevented using synchrophasor technology. A study by MISO indicates that the probability of large-scale events such as the 2003 Northeast event could be reduced from 1 in 20 years to 1 in 30 years (MISO 2015). The decrease in the frequency of major outages translates to a reduction from 5% to 3.33% or a 1.67% decline. Again, the values used for the estimated reduction should be based upon experience in the number and length of outages reduced and the number of customers affected.

The other information required for this approach is the total customer outage value. The total customer outage value depends on assumptions about the number of outages, the number of customers by customer class, the duration of the outage, when the outage occurs seasonally, and the time during the day at which the outage occurs. The literature offers several sources for such an estimate. One easy approach is to use LBNL estimates. LBNL developed the Interruption Cost Estimate calculator to estimate outage costs based on utility-level reliability information (SAIFI and SAIDI data).[10] The Energy Information Administration (EIA) collects the reliability data (EIA 2015). The data for utilities in the transmission area must be aggregated to address the appropriate transmission area to determine the total cost of outages in that area. The EIA also indicates the number of customers affected by the outages. The total reduction in customer outage value due to active use of PMU data at the transmission level is the percentage the analyst estimates for the company, which is multiplied by the total customer outage values.

The extent to which synchrophasors reduce outages and outage impacts should be revisited over time as experience with the technology increases, the body of documentation on successful synchrophasor use grows, and the balance of customer reliance on the BES evolves.

3.1.2 Synchrophasor technology impact on outages

Outage causes – NERC's "State of Reliability 2015 Report" indicates that the bulk of severe bulk power system disturbances and highest stress days were the result of extreme weather events (including hurricanes, thunderstorms, winter storms, and the polar vortex) (NERC 2015, p. 17). Synchrophasor technology cannot change the number or magnitude of extreme weather events, but it can help transmission owners and grid operators reduce the impact of those events on customer outages by improving situational awareness, enhancing analysis of mitigation options, and shortening system restoration times.

[9] Note that Amin's conservative estimate of the potential impact of synchrophasor technology in reducing transmission-level outages predates much of the current usage and knowledge gained from the extensive synchrophasor deployments, which are discovering a wider span of impact.
[10] The calculator can be accessed at http://www.icecalculator.com/.

In addition, NERC has noted that BES equipment mis-operations and failed substation equipment are significant causes of BES disturbances, and has identified them as top-priority reliability issues (NERC 2015, 2014). NERC reports indicate that as BES elements fail, the failures increase the severity of transmission outages. To address this problem, several leading synchrophasor users are using anomalous PMU data patterns to identify mis-operations and imminent failures in capacitors, instrument transformers, and transformers within their substations, and using that information to fix or replace the equipment before it fails (Silverstein 2015).

Once synchrophasor technology is being used for real-time system operations, operators may be able to reduce the magnitude or scope of BES outages as well as the frequency or probability of outages. This could occur because with synchrophasor-enabled oscillation detection and voltage stability management, combined with phase angle monitoring and better situational awareness, operators can identify emerging problems and take early action to restore degrading system conditions before a disturbance occurs. Where this practice is followed, the number of major and minor outages caused by oscillation and voltage issues could be diminished or averted, and this impact can be estimated.[11]

NERC has also identified protection system mis-operations as a significant cause of outages, and reports that these transmission system events are more severe than other transmission events (NERC 2015, 2014). NERC staff identified over 2,000 mis-operations per year from 2011 through 2013, with 1 in 10 system protection operations involving a mis-operation. They concluded that the three most common causes of protection system mis-operations are "incorrect setting/logic/design errors, communication failures, and relay failures/mis-operations" (NERC 2014).

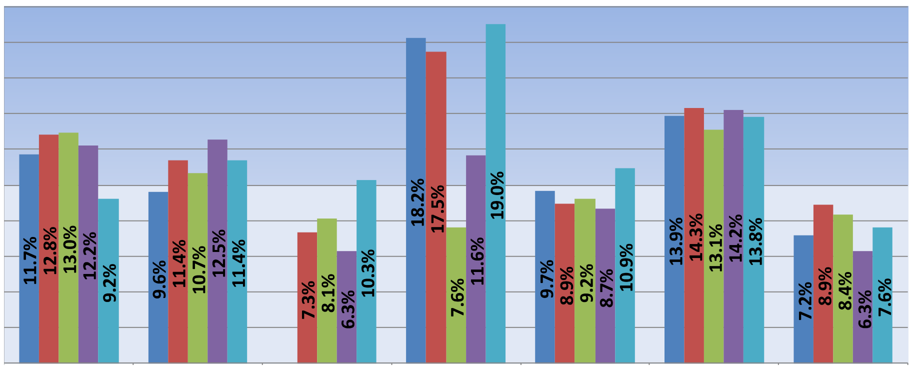
PMUs dispersed across the grid can be used to monitor protection system operations and verify whether a protection system operation performed as intended. Several transmission owners routinely check their PMU records after every event that involves a transmission system protection operation to determine whether the protection operation occurred and whether it operated as expected. This enables them to identify and correct individual equipment failures and malfunctions (which could include communications failures) and erroneous settings or logic errors early on, rather than only discovering a mis-operation after it has caused a significant disturbance.

The NERC analysis reports the rate of protection mis-operations by region (see Figure 3-2 below), and gives counts for the number of mis-operations over the study period. An analyst could use these data to estimate the potential number of mis-operations in the region of interest and project a percentage reduction in that rate due to an aggressive synchrophasor-based protection system operation monitoring, quality control, and correction program. Because transmission outage events triggered by protection system

[11] See Table 3 in the NERC "AC Substation Equipment Failure Report," which indicates that there were 602 transformer and 105 instrument transformer equipment failures during the study period.

failures have a disproportionately high effect on outage severity,[12] the use of synchrophasor technology to reduce the number of protection mis-operations over time should reduce both the number and severity of transmission-related outages. The transmission operator could estimate the potential or actual impact of synchrophasor monitoring upon the number of protection system mis-operations.

Figure 3-2 – NERC-calculated mis-operations rate by reliability region



Source: NERC Staff Analysis of System Protection Misoperations, December 2014, p. 2.

The benefits of synchrophasor reliability applications are going to be area-specific, reflecting variations between areas in the following:

- the probability, causes, and lengths of outages in each area;
- the numbers and types of customers affected by those outages (Sullivan et al. 2015);
- the extent to which synchrophasor systems in the area are being used actively for grid management; and
- whether the operator or owner recognizes the impacts of synchrophasor use on major and minor outages (Novosel et al. 2007).

3.1.3 Fewer equipment failures and fewer catastrophic failures

Synchrophasors can improve grid reliability by enabling diagnosis of many impending equipment failures before an actual failure. Utilities can use such synchrophasor-based detective work and mitigation efforts to reduce the need for and avoid costs associated with additional wear and tear and reduce the potential for future outages (NASPI March 2015). Oklahoma Gas & Electric has used synchrophasor data to find loose connections in the potential circuits at fuses and terminal blocks, including loose Coupling Capacitor Voltage Transformer (CCVT) safety switch fuse connections. Similarly, Dominion engineers monitored the fluctuations in the synchrophasor recordings from the C-phase of

[12] Specifically, NERC reports that, "… more than 68 percent of transmission events have misoperations associated with them that either initiated the event or caused the event to be more severe." (NERC 2015, p. 47).

a three-phase transformer not tracking well with the A and B phases and found that a capacitor in the CCVT was failing. This capacitor failure could have caused an explosion releasing shrapnel several yards in all directions, creating a safety hazard for personal and potentially damaging other substation equipment. With PMU data, Dominion staff found the failure signs four days before the SCADA system triggered a failure alarm (NASPI March 2015).

Duke Energy (2015) indicated that approximately 50% of customer-minutes lost can be attributed to equipment failure; the average outage time is 93 minutes shorter if the outage is planned versus unplanned, and the costs of replacement are 25% lower than for unplanned outages (Sweezer-Fischer 2015).

Apart from reliability improvements, using synchrophasor technology to reduce equipment failures yields savings in equipment and labor costs as well. These are discussed in the Cost Savings section below. There will also be savings associated with reduced equipment repair and reduced damage to other equipment due to preventative maintenance and the reduced labor required as a result of preventative maintenance.

3.1.4 Faster service restoration

Synchrophasor technology can help expedite outage detection and service restoration, which is highly valuable for the transmission owner and its customers. This is made possible because analysts can use the synchrophasor data to locate faults, perform phase angle monitoring for line reclosing, test and commission equipment after repairs, and verify line flows and grid conditions before, during, and after the outage. They can also use the recorded phasor data in synchrophasor-enhanced simulation models to test alternate restoration strategies. After major blackouts, synchrophasor monitoring can be used to manage black-start restoration and generator resynchronization to the grid. The primary result of this benefit is reduced outage time and reduced outage-related costs to customers; these are covered in the outage section above and will not be revisited here given the risk of double-counting time savings (NASPI June 2015). The analyst needs to estimate the reduction in the number of minutes and customers affected by faster service restoration through the use of synchrophasor technology for tasks such as line reclosing, generator synchronization, and black-start resynchronization.

Savings will also be associated with reduced labor required due to the faster service restoration and the amount of megawatt-hours that will be able serve demand and otherwise would not have been delivered. These are discussed in the Cost Savings section.

3.1.5 Faster line reclosing

After a major fault, it is crucial to minimize the amount of time a line is out of service and ensure that once the fault clears, the line can reclose as soon as possible. Using phase angle monitoring, operators can verify that the two line segments are in a safe state to close. Without PMU data, SCADA data and state estimators cannot identify this condition with great precision. If the operator closes a line while the phase angle is in an unsafe state, protection equipment should reopen the line, and the reclose process must start again. In some cases, this can require only seconds; in other cases, it may take many minutes and trigger an automated system protection scheme (SPS) because the immediate reclosure did not happen within the SPS time window. Synchrophasor-enabled phase angle monitoring enables much faster line reclosing with a high degree of certainty and confidence, which lets the operator bring the system back to a safer operating state with higher throughput. For example, the Imperial Valley – North Gila 500 kV line tripped and locked out in 2013. Using phase angle monitoring with PMUs, operators were able to reclose the line without risking equipment damage because they could see that the phase angle at 37.2-degree separation was within the 50-degree limit for reclosing (Peak Reliability 2014).

It is difficult to identify specific metrics for the value of line reclosing that are separate and distinguishable from better grid operation and shorter outages. At this early stage of synchrophasor adoption, the most immediate metric to count may be the number of line reclosing events that are managed successfully using synchrophasor technology.

3.1.6 Faster generator synchronization

Automated generator synchronization using PMUs can reduce outage time due to faster matching of voltage magnitudes reducing the potential for restart faults (Seeley et al. 2012; Patel et al. 2010). While this enables faster generator availability and potentially better frequency management, it is difficult to quantify specific benefits from this application. Counting the number of generator synchronization events using synchrophasor technology might be a useful early metric to express this metric, and generation owners and dispatch desks may be able to estimate the time saved (and hence, shortened outages) in the synchrophasor-expedited synchronization process.

3.1.7 Faster black-start restoration

NERC Standard EOP-005-2 directs that plans, facilities, and personnel need to be prepared to enable systems restoration from black-start resources and maintain reliability during restoration. Restoration plans require activities to restore the outage area to service, coordinating reconnection of parallel electrical islands to the main grid without creating more stability issues (NERC ca 2013).

The restoration process can be expedited by using synchrophasor data and tools; the PJM Interconnection (PJM), Electric Reliability Council of Texas (ERCOT), and other entities have been using their synchrophasor networks as part of their black-start exercises, using phase angle monitoring in particular for generator resynchronization and line reclosing and frequency monitoring for load-to-generation rebalancing. The use of synchrophasor data to detect power system oscillation and voltage instability is also useful for system restoration (PSRC 2013). Faster black-start operations allow faster restart of the system, thus reducing the outage time and outage cost.

The Salt River Project implemented synchrophasor technology to provide greater system visualization over the traditional SCADA system and synchronize the connection of differing power systems during black-start testing. The black-start required the synchronization of two thermal and hydro units. During this connection of the thermal and hydro units, synchrophasors were used to monitor the frequency and slip differences between the systems to determine an appropriate interconnection moment. With both systems online, the phase angle between the thermal and hydro systems could be monitored to ensure that the systems were within the phase angle difference tolerances (PSRC 2013).

Since many reliability coordinators are using synchrophasor tools for black-start restoration exercises, it should be possible to estimate from those drills the amount of time that could be saved when using synchrophasor data to manage an actual system black-start event. The time saved can be used to estimate the amount of customer outage time avoided, the financial value of that lost time to customers, and the value of that shortened outage time in terms of energy flows enabled.

3.1.8 Faster island resynchronization

Reliability coordinators (RCs) and transmission operators (TOPs) must identify events that result in system islanding and engage in appropriate restoration activities. The RC and TOPs are required to identify when such system outages and islanding may occur; analyze the potential cause and the resulting response of the system; determine steps that will return the power system to acceptable operating conditions; and coordinate with other entities to ensure that the appropriate actions are taken to restore the system to normal operation (NASPI June 2015). Synchrophasor technology makes these tasks easier.

Real-time, highly granular PMU data reveal when the voltage angle and frequency of the power system are not synchronized, and can identify when an electrical island has formed. The PMU data can then be used to determine how and why the island formed, its electrical location, and whether the island has excessive generation or excess load (high or low frequency). Following a major power grid disturbance, RCs and TOPs are required to identify unacceptable operating conditions of generators and transmission facilities that remain operational. Failure to trip islanded generators can potentially pose multiple problems including personnel safety hazards, out-of-phase reclosing, and degradation of the power quality within the island. With proper action, the synchrophasor data can be used reduce outage time (PSRC 2013).

As an extreme example, Hurricane Gustav brought down a 230 kV transmission line in Louisiana on September 1, 2008, at 2:49 p.m. After approximately 20 minutes, Entergy discovered through analysis of data from numerous PMUs installed in the area that there was an electrical island operating in South Louisiana, wholly separate from the rest of the interconnection. Entergy was able to monitor real-time changes in the island that would not have been detected by the traditional SCADA system, and used the PMU data to adjust generator controls within the island to keep it intact for 33 hours while staff developed a restoration strategy. On September 2 at 11:21 p.m., the electrical island was reconnected to the Eastern Interconnection without incident or loss of generation or load. Entergy believes that the entire island would have been lost and all of its customers within the island blacked out without the PMUs, which were also instrumental in the resynchronization and reclosure process (Galvan et al. 2008).

In a less dramatic example, Florida Power & Light placed PMUs on the remote source and distributed generation end. It used the synchrophasor data to island out-of-phase distributed generation using adaptive load shedding (Sweezer-Fischer 2015).

3.1.9 Faster forensic analysis and lessons learned

After significant grid disturbances, analysts from NERC and the Federal Energy Regulatory Commission (FERC) conduct a forensic analysis of what caused the outage, and develop detailed recommendations for how industry members should address the contributing factors for that outage, to reduce the likelihood that they contribute to future disturbances (NERC 2012). The forensic analysis and resulting recommendations address narrow, company-specific issues as well as broad industry practices. The recommendations can span how to improve situational awareness, needed changes in reliability standards, daily operations and planning procedures, BES equipment, SOLs and interconnection operating limits. Collectively, these recommendations improve future system planning and operations and reduce the likelihood of future disturbances (Silverstein 2014). Forensic event analysis enables the industry to make and implement better reliability recommendations more quickly, which may enhance grid reliability.

3.1.10 Backup network and data source for SCADA failure

All transmission system operations use SCADA and Energy Management System (EMS) data. Few of these entities have wholly redundant data collection and communication systems that can replace SCADA if the systems fail due to natural disaster or intentional cyber-attack. But an extensive PMU deployment and a stand-alone synchrophasor network essentially create a separate system that collects grid condition information in the form of PMU data, and delivers it into control room applications. Few such networks would offer communication and control capability back from the control room to BES devices, and so could not fully replace a failed SCADA-EMS system. But using a synchrophasor system as a backup method to collect and receive grid condition information offers a significant—but unquantifiable—reliability benefit for grid operators.

As a point of information, it is worth noting a recent analysis prepared for NERC on EMS outages. This analysis found that in the 11 months ending in August 2014, there were 74 events in which operating entities lost their SCADA, control, or monitoring functionality for 30 minutes or more, or lost sufficient monitoring and control capability (that occur with communications failures) that they were unable to make operating decisions for 30 minutes or more (Tirupati 2014, slides 3–4). In these cases, the mean time to restore the EMS was 60 minutes (Tirupati 2014, slide 9). Because many synchrophasor systems (particularly RCs) deliver PMU data over a separate network from that which carries SCADA and EMS data, these entities might be able to receive and use the PMU data for situational awareness in lieu of the EMS.

3.2 Cost savings

Table 3-4 summarizes the benefits and calculation methods for the cost savings discussed in this section. The specific cost savings and their calculation methods are discussed below. Most of these discussions offer one or more examples of representative synchrophasor uses and estimated benefit components for each benefit calculation.

Table 3-4 – cost savings calculations summary table

Benefit	Benefit metric	Calculation method
Congestion reduction	$ value of more efficient dispatch	Change of MWh flow enabled by synchrophasor-based change in transmission capacity * $ value of those MWh
Labor cost reductions	Calendar time saved (days, hours, months)	Time saved and number of workers affected
	$ value of worker hours saved	Time saved * labor cost/hour for affected workers
Reduced energy use	MWh	MWh not used due to synchrophasor-based efficiencies
	$ value of MWh saved	MWh saved * $ value of saved energy (could be time-varying)
	% line losses avoided	NQ
Fuel and hydro savings (includes O&M costs)	MWh realized from generation efficiency	MWh saved
	$ value of fuel savings	MWh saved * $ value of fuel not used for that generation
	$ value of O&M savings	NQ
Capital savings	Assets not built	Specific capital assets avoided thanks to synchrophasor-based change in transmission capacity or capability
	$ net present value of capital investments delayed	$ net present value of capital assets avoided or delayed
	$ value of equipment damage and replacement averted	Assets not damaged thanks to synchrophasor-based condition-based monitoring and early replacement or repair
		$ value of equipment not damaged due to catastrophic equipment failures not averted through synchrophasor-based asset monitoring
Standards compliance	Standards compliance	Identify relevant standards; compare compliance validation method and time requirement to non-synchrophasor-based method; calculate labor savings.

3.2.1 Congestion reduction

Traditionally, off-line models are used to represent present grid conditions, but do not have the capabilities to respond to real-time, system-level impacts on the grid (Silverstein et al. 2015). Grid operators use these models with estimates of anticipated conditions, and develop line limits and nomograms to recognize and manage energy throughput relative to safe thermal and voltage stability limits. But nomograms and fixed line limits often create congestion on the grid, making low-cost energy unable to flow through the point of congestion because of the limit, and leave available transmission capacity unused in real time (Patel et al. 2010).

In the Eastern United States, PJM and others are looking at how to implement PMU-based dynamic line loading and congestion management schemes. These schemes would link real-time operational limits at key points on the grid to actual measured conditions rather than models and standing rules. Once implemented, these applications could reduce congestion costs by millions of dollars each year, and those savings could go straight to customers. PJM reported its total congestion costs to be $1.9 billion for 2014 (Monitoring Analytics 2015). The portion that can be reduced by synchrophasors would be the value of this benefit.

With PMU monitoring at key points across the grid, operators can use phase angle and voltage stability monitoring to determine actual grid conditions in real time. In many cases, this may reveal that there is more transmission capacity available at bottleneck points than the model-based limits allowed. Using these calculations for dynamic line loading and congestion management may lead to net lower energy costs (because more energy can flow and uneconomic, out-of-order dispatch is avoided). Because wind energy in particular is often constrained by operating limits, this may enable greater delivery of wind energy (Hurtgen and Maun 2012).

The net savings can be calculated by estimating the additional energy flow enabled by the use of synchrophasor technology, multiplied by the average value of those kilowatt-hours (based on seasonal Locational Marginal Prices (LMPs) in competitive wholesale market locations, or system lambda estimates in non-market regions).

> Net savings from congestion = MWh incremental energy flow * average or time-specific value of MWh based on LMPs or system lambda

It is worth noting that on occasion, using PMU data to recalculate line limits and available transmission capacity may reveal that the limits in use based on modeled calculations have been too generous; continuing electricity flows at that level may be placing greater strain on the bulk electric system. In those circumstances, the use of synchrophasor data would yield more constrained flows and reduce rather than increase cost savings from congestion management.

3.2.2 Labor cost reductions

Synchrophasor technology offers great value by reducing the amount of time that electric industry workers must spend to accomplish needed tasks at better performance levels. Examples of the time and labor savings to be realized using synchrophasor technology include the following:

- using PMU data for ongoing, automated generator model validation in lieu of physical generator testing every five years

- using PMU data to monitor interconnection and balancing area frequency to satisfy NERC standard BAL-003-1
- using synchrophasor technology for fault location, which may shorten field crew travel time to repair
- using PMU data for forensic event analysis
- using PMU data for ongoing event analysis and identification of mis-performing equipment.

Experienced electric industry engineers and field crews are a scarce and limited resource, and an expensive one. The Bureau of Labor Statistics reports that within the electric industry, mean wages for electrical engineers in 2014 were $43.48 per hour and $90,440 per year; line crew pay averaged $33.23 per hour and $69,120 per year (BLS 2015).[13] Within the utility industry, employee benefits are worth an average of 39% of the total compensation package, or another 64% on top of the employee's salary; so, if synchrophasor technology can be used to save an hour of an engineer's time, that could mean a labor savings of $43.48 * 1.64 = $71.31.

Electric worker pay varies significantly with the worker's experience, training, and location; for instance, journeyman hourly wages for outside linemen in California were $47.87 in 2012 (Parker 2012). The analyst should use fully loaded (including benefits) hourly pay figures that reflect company or regional worker compensation to estimate labor savings associated with a synchrophasor project.

Forensic event analysis example – Consider the example of labor savings associated with using PMU data for forensic event analysis after a major grid disturbance. The availability of synchrophasor data has shaved months of time from forensic event investigations because the initial sequence of events and modeling data can be compiled within hours rather than months. In 2003, after the August 14 blackout of the Northeast U.S. and Canada, NERC, DOE, and FERC pulled together a group of over 20 engineers from across the electric industry and federal government to look through millions of data points in control room, SCADA, and relay records from many sources to compile the sequence of events for the blackout. Lacking PMU data, the intensive initial effort to build the sequence of events lasted for over six weeks, after which a smaller team of three or more engineers spent five more months reexamining and refining the analysis. The formal analysis and recommendations were not released until April 2004. Modeling and analysis continued for another year. In contrast, after PMUs were installed, NERC was able to compile the sequence of events for the 2011 Southwest outage and the 2015 Washington D.C. metro disturbance within less than 24 hours. A detailed forensic report and reliability recommendations were released the following year.

A representative calculation of the labor savings derived from using PMUs to build the sequence of events for a large grid disturbance involves the following:

[13] Payscale.com reports that the national average total annual pay after overtime and bonuses ranges from $45,000 to $98,000 for a journeyman lineman.

Hours saved = 20 engineers for six weeks (20 * 240 hours) plus 4 engineers at five months (4 * 866 hours) = 8,264 hours

Fully loaded cost per engineer = $43.48/hour plus benefits at 64% = $71.31/hour (assuming national average hourly compensation rate with no overtime pay)

Total cost to build disturbance sequence of events w/o PMU data = 8,264 hours * $71.31/hour = $589,306 worth of labor and benefits over seven months

Time saved = six months or more.

This half million dollars in labor costs could be compared to the effort to compile a sequence of events after a major disturbance today. Within an hour or two after the start of the event, the involved transmission owners and RCs send files of all their SCADA and PMU data to NERC; two to four NERC engineers compile the data into the sequence of events and check it; and the events and initial cause can be determined within 24 to 48 hours of the event.

<u>Model validation example</u> – With the advent of automated model validation routines that can use PMU data to test and validate a generator model, there is less need for generation owners to hire a consultant to conduct physical tests of the generator (which can cost $50,000 per test engagement), and less need for engineers at the transmission owner or RC to examine the generator test results and compare them to the generator model. Instead, with PMU data and automated model validation procedures, such models can be continuously updated and made more accurate every time a grid disturbance occurs. Although the new procedures still require scrutiny by an experienced engineer, the processes could mean a savings of two to four days of engineering work per generator per year—time that could be used for more productive work. Calculating the associated savings involves the following:

Hours saved = 1 engineer for two days = 16 hours

Fully loaded cost per engineer = $71.31/hour

Total labor cost saved per generator for physical testing and model updating = $1,141

Time saved = two days or more.

<u>Fault location example</u> – PMU data have sufficient locational and time granularity that they can be examined immediately after a fault to determine the location of the incident. If the transmission owner lacks other smart grid fault location methods, PMU data analysis enables faster dispatch of field crews to the fault location, thereby reducing the crew's field investigation time hunting for the fault and shortening the time required for service restoration. Supposing this saves one hour per fault event, and faults occur 100 times per year across the service territory, calculating the associated savings involves the following:

Hours saved = 100 faults per year at one hour per fault and one crew with two linemen per fault = 200 hours

Fully loaded cost per lineman = $33.23/hour average national wage with 64% benefits = $54.50/hour

Total labor cost = $10,899 per year

Time saved = 100 hours or more of outage time.

Detecting failing equipment before catastrophic failure – Work by Dominion Virginia Power, American Transmission Company (ATC), and others indicates that it is possible to use PMU data to identify deteriorating performance within transformers as much as three days before they fail (NASPI March 2015). This enables the alert transmission owner to acquire replacement equipment and send crews in to replace the failing equipment before a possible catastrophic failure (or to take the unit out of service and pull crews away from the facility until after the failure occurs); in such an event, the transformer could explode, emitting shrapnel that could harm other equipment in the substation and injure any personnel onsite. An emergency equipment replacement task could entail extensive overtime work; thus, the labor-saving calculation shown above would require an overtime mark-up as well as an increase in the number of hours and workers required for the replacement task.

An alternate way to handle a pending potential transformer or current transformer failure is to ban crews from the location until after the transformer fails, thereby avoiding the possibility that personnel could be hurt by an explosive failure. It is worth noting that utility line work is one of the 10 most dangerous jobs in America—between 30 and 50 workers in every 100,000 are killed on the job every year (Mauldin 2015) and 2.1 injuries and illnesses occurred per 100 full-time workers in 2014 (BLS 2015). Therefore, any measures that can reduce crews' exposure to hazards (including windshield time) could protect their safety and well-being, and enable them to use their time more productively.

Equipment commissioning example – ATC has used PMUs to ensure correct phasing of new 345 kV transmission line facilities before interconnecting them to its transmission system. ATC did this by enabling the PMU functionality on relays on both sides of the equipment interface to check phasing without crews being onsite to perform the work. ATC found that this reduced equipment commissioning costs, lowered crew travel and field time, and improved personnel safety.

Power System Stabilizer commissioning example – Manitoba Hydro, a member of MISO, has been able to use PMU data to achieve more efficient commissioning of PSSs on its power system. The PMU data provided instant feedback of power system measurements for small variations in the PSS design parameters, which were originally designed using only models based on off-line testing. Manitoba Hydro achieved both a cost reduction and confidence in the PSS final settings because onsite testing and tuning with PMU monitoring allowed staff to see the PSS performance immediately after every test (Silverstein 2015).

3.2.3 Energy and fuel savings

Real-time synchrophasor measurements can supply data points to online models to better predict transmission thermal and capacity limits. This can optimize the line loading capabilities and increase alternative energy penetration. In addition, better efficiency in power plant dispatch and transmission flows may lead to associated fuel and O&M

savings (Silverstein et al. 2015). The savings can be calculated by determining the run-time and fuel costs of using higher cost generation rather than using less costly forms of generation that would otherwise be employed if synchrophasor technology enabled less congestion. Shorter run times and ramp rates may also enable an incremental reduction in generator O&M. The equation below estimates the increased fuel savings associated with better congestion management.

Reduced O&M and fuel = MW capacity increased * time * ($/MWh (O&M and fuel) of higher cost generation - $/MWh (O&M and fuel) lower cost generation.

3.2.4 Capital deferral and avoidance savings

In the Western United States, BPA has calculated that it could use PMU-based, automated voltage management schemes that would enable another 100 MW of power to flow through the California-Oregon Intertie without any physical grid alterations or additional capital investment. This scheme is still in the monitoring and testing phase and has not been formally proposed for adoption. The capital savings are estimated to be worth $35–$75 million over 40 years (WECC ca 2012).

Because synchrophasor technology enables more precise voltage management and resolution, it may enable grid planners to deploy voltage management and protection system devices more precisely and effectively; in some cases, that may mean that less equipment needs to be installed, or that needed equipment can be sized more precisely, with possible cost savings.

It may be difficult to put actual numbers on the capital cost savings associated with synchrophasor technology projects, because there are few known examples to date where real capital investments have been avoided. But similar challenges occurred in estimating the impacts of distributed generation and demand response deployments, before those technologies reached such a scale that it was obvious when they displaced generation or utility-owned transmission and distribution equipment. When PMU project planners can identify potential capital assets that could be avoided, the value for those assets would be calculated as described below.

For a capital asset deferred or eliminated by synchrophasor technology, the value of capital investment deferral is equivalent to the difference between the present value of the current planned investment stream for the capital asset, and the present value of the deferred investment stream. The net present value would be calculated using a discount rate equal to the owner’s weighted average cost of capital. To determine the stream, the study period and the investment streams for both scenarios need to be determined. The project lifetime is not that important because only the difference in the present value of the capital investment streams in the current scenario compared with the deferred scenario matters. Any other costs that would change with the two scenarios need to be included. Such costs could include any additional O&M costs that would be needed to maintain the new capital acquisition. The key requirements are to determine the number of years of delay, the amount of capital investment deferred, and other operating costs that would be avoided.

Synchrophasor technology might defer at least two types of capital assets: transmission wire assets because of increased efficiency and throughput, and substation equipment because PMUs and applications may enable better substation maintenance and therefore delay replacement of substation equipment. Each asset's deferred value would be calculated the same way.

The capital costs for transmission costs will include the cost of lines and substations and the type of lines assumed. Black & Veatch recently updated costs for transmission lines for the Western Electricity Coordinating Council (WECC), estimating the cost of a single circuit 230 kV line cost at approximately $960,000/mile (2014$), including transmission and substation equipment costs). The study considered costs for 230 kV, 345 kV, and 500 kV AC single and double circuit and a 600 kV high-voltage direct current line. Substation costs range from $1.7 million for 230 kV to $2.6 million for a 500 kV substation (2014$) (WECC 2014). A 2011 BPA O&M study indicated that O&M costs ranged from $0.28/MWh to $0.59/MWh (in 2010$) (BPA 2011). Projected capital costs would be the length of transmission line deferred multiplied by the cost per mile of the line deferred. Capital investment in real terms would be the same in both the current and deferred plans until the deferred plan was discounted to present value. Savings would be calculated as follows:

> Estimated capital deferred = (miles of line * $/mile of transmission lines) + associated equipment costs, or other transmission capital assets deferred
>
> Savings = Present Value of capital plan without the synchrophasor project – Present Value of the capital deferred by synchrophasor technology + Present value of Current Plan O&M – Present Value of Deferred Plan O&M.

3.2.5 Other cost savings

Other cost savings do not fit easily into the above categories. The strongest example is for synchrophasor-based model validation. Many transmission owners and RCs are using PMU data for routine model validation in lieu of older methods that require hiring consultants to conduct physical tests while a power plant is taken off-line. Several users of PMU-based power plant model validation have estimated that this saves between $100,000 and $700,000 relative to the physical plant test process, while producing more accurate models. Cost savings include not having to hire a consultant to conduct the physical plant tests and revise the generator model and the labor time required to accompany and oversee the consultant during the physical test. These savings are accompanied by the net revenues retained because the generator does not have to be taken off-line for the physical testing period, but remains in operation during ongoing PMU data-based model validation (Silverstein et al. 2015; 146 FERC ¶61, 21).

3.2.6 Standards compliance

The Energy Policy Act of 2005 (Public Law 109-58) created a new regime of mandatory electric reliability standards to be developed and enforced by NERC with oversight by FERC. Although none of the current reliability standards explicitly require the use of synchrophasor technology, several of these standards can be met effectively using PMUs. Table 3-5 identifies the NERC reliability standards that could be effectively met by the routine use of synchrophasor technology in well-accepted, mature applications. Many of the synchrophasor tools available for these uses can be semi-automated, enabling significant staff time and labor savings while improving the quality of standards compliance.

Table 3-5 – NERC reliability standards that can be met using synchrophasor technology for compliance[14]

Standard Number	Title	Status
BAL-003-1	Frequency Response and Frequency Bias Setting	Subject to Enforcement
FAC-001-2	Facility Interconnection Requirements	Subject to Enforcement
IRO-003-2	Reliability Coordination – Wide-Area View	Subject to Enforcement
MOD-026-1	Verification of Models and Data for Generator Excitation Control System or Plant Volt/Var (volt-ampere reactive) Control Functions	Subject to Enforcement
MOD-027-1	Verification of Models and Data for Turbine/Governor and Load Control or Active Power/Frequency Control Functions	Subject to Enforcement
MOD-033-1	Steady-State and Dynamic System Model Validation	Subject to Enforcement
PRC-002-2	Disturbance Monitoring and Reporting Requirements	Approved, pending enforcement

3.3 Efficiency and throughput benefits

Table 3-6 summarizes the benefits and calculation methods for the efficiency and throughput benefits discussed in this section. Most of these benefits make sense in principle, but we do not calculate them here because they involve relatively small amounts of energy and would require significant extrapolation beyond currently available facts.

Table 3-6 – Efficiency and throughput benefits calculations summary table

Benefit	Benefit metric	Calculation method
Enhanced energy flows	Bottleneck facilities relieved	Itemize the bottleneck facilities or lines that can be managed more effectively with synchrophasor technology
	MWh of incremental flows from bottlenecks reduced	Add up MWh
Better reactive power management	NQ	NQ
Line loss reduction	NQ	NQ

3.3.1 Enhanced energy flows

Enhanced energy flows are addressed above in the cost savings discussion of congestion management.

[14] Information provided by Ryan Quint, NERC, September 2015.

3.3.2 Better voltage and reactive power management

Because synchrophasor technology enables more precise grid monitoring, including voltage stability monitoring and management (NASPI Oct 2014; Parashar et al. 2013; Malik et al. 2014; Glavic et al. 2012), it should enable grid operators to manage grid voltage much more effectively. Southern California Edison (SCE) has a PMU monitoring voltage at a substation that is integral to wind energy transport, and is using that PMU in a closed loop control for a local series capacitor to assure voltage support for the line (Johnson et al. 2008). While these are very real benefits, it is difficult to determine how to quantify them.

3.3.3 Line loss reduction

In principle, if the grid is operated more efficiently with better voltage management, transmission-level line losses should be marginally smaller. In fact, it is difficult to determine how to estimate all the pieces of a line loss calculation.

3.4 Environmental benefits

Table 3-7 summarizes the benefits and calculation methods for the environmental benefits discussed in this section. The specific environmental benefits and their calculation methods are discussed below. Most of these discussions offer one or more examples of representative synchrophasor uses and estimated benefit components for each benefit calculation.

Table 3-7 – Environmental benefits calculations summary table

Benefit	Benefit metric	Calculation method
Increased delivery and use of renewable generation	Incremental renewable MWh	Incremental renewable generation enabled by synchrophasor voltage management and grid throughput
	Net decrease in fossil generation	Incremental renewable generation MWh * net fossil MWh displaced by renewable generation
	Net decrease in fossil fuel consumed	Incremental renewable generation MWh enabled by synchrophasors * net fossil MWh displaced by renewables * heat rate of marginal fossil generators during displacement hours
Decrease in net carbon emissions	Incremental tonnes pollutants avoided from fossil generation	Net decrease in fossil generation * tonnes pollutants/MWh for the marginal fossil generators

3.4.1 Increased delivery and use of renewable generation

Increasing the amount of low-polluting renewable generation within the nation's energy mix has become an important goal for grid planners and operators. Higher levels of renewable generation are desired or mandated under the U.S. Environmental Protection Agency's (EPA's) Clean Power Plan (40 CFR Part 60), by renewable portfolio standards, or by goals adopted by over half the states in the nation (Heeter et al. 2014), by federal agency electrical consumption requirements. In addition renewable generation is sought by retail customers as a way to demonstrate their environmental commitment, and by retail electric providers as a way to stabilize the fuel costs of their energy portfolio.

Furthermore, the economics of wind and solar generation now appear to be competitive with fossil generation (Wiser and Bollinger 2015). As such, several of the Smart Grid Investment Grant and Smart Grid Demonstration Projects explicitly designed their synchrophasor projects to facilitate renewables integration (DOE ca 2014).

Many transmission owners and RCs are using their synchrophasor systems to manage high levels of renewable generation more effectively. Synchrophasor technology enhances renewables integration efforts by:

- using PMUs at the point of renewable generator interconnection to improve power plant models and gain insight into generator operations;
- using PMU data to provide high-resolution, real-time information and visualization of conditions on the grid, for better wide-area monitoring and situational awareness;
- using PMU data in voltage stability management, oscillation monitoring, and state estimation tools to monitor and manage voltage and other renewables-to-grid interactions effectively, including setting integrated alarms and alerts to improve operators' recognition and response to evolving grid events;
- using PMU data with congestion management and dynamic line loading tools to modify transmission line and asset throughput consistent with real operating conditions rather than conservative nomograms and limits (DOE 2012);
- using PMU data to detect and monitor subsynchronous resonance,[15] which may occur when a wind power plant become electrically connected close to series-compensated transmission lines (Saylors 2013; Bongiorno et al. 2013);
- using PMU data to trigger automatic operation of transmission assets for voltage management, to increase throughput of a line carrying renewables from generation source to load (Johnson et al. 2008);
- using PMU data to verify and validate the performance of control devices, such as SVCs (static var compensators), following grid events; and
- using PMU data for faster, more insightful analysis of grid conditions and forensic analysis of grid disturbances.

3.4.2 Incremental renewable generation

Estimating the incremental renewable generation enabled by synchrophasor technology use is challenging because most examples of synchrophasor usage to date reflect single episodes; e.g., using PMU data to identify and mitigate local oscillations caused by a wind plant, that forced grid operators to curtail the plant until a mis-operating wind generator control card could be fixed (Chen 2014; Wan 2013).[16]

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[15] Subsynchronous resonance is a phenomenon of grid voltage and current oscillations below 60 Hz frequency that can stress generator turbine shafts (NERC 2011).

[16] Events 3, 4, and 5 in NASPI Control Room Solutions Task Team Video Library (NASPI, March 2014)

While the use of PMUs for model validation and plant-to-grid interaction mitigation is growing rapidly, few public documents offer specific data on the amount of renewable generation affected by the use of synchrophasor technology. Without documented experience, it is difficult to construct a counter-factual for, “how much more wind and solar energy could be generated and delivered if we use synchrophasor technology for monitoring and grid management?”

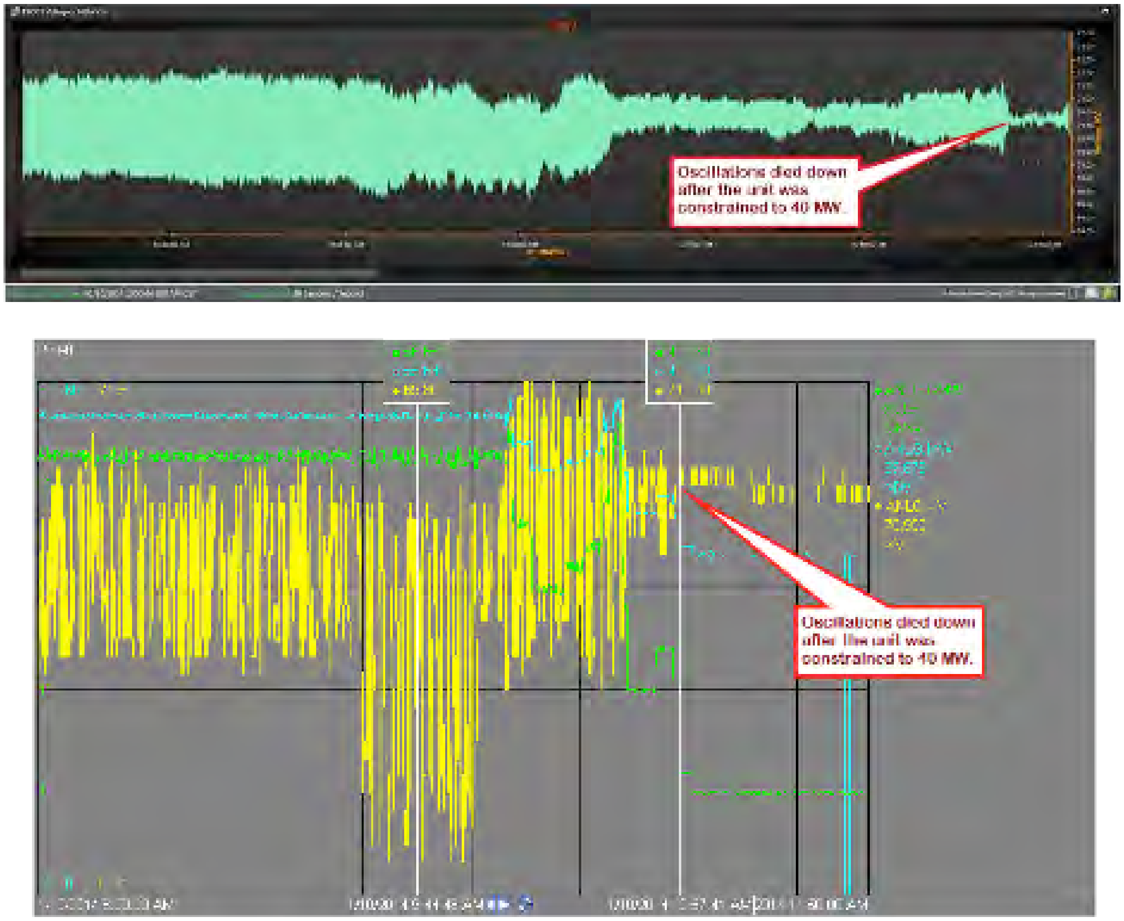
<u>ERCOT example</u> -- Because synchrophasor data can be used in many ways to facilitate renewable energy production and delivery, it would be challenging (and likely inappropriate) to attribute specific renewable energy increments to one synchrophasor application versus another. In such a case, it might be easier to identify a percentage of total renewable generation to the increment enabled by synchrophasor technology. Within ERCOT, for instance, where wind generation now produces over 10% of the electricity used within the interconnection, one might hypothesize that the last 5% of the wind generation in ERCOT is enabled because operators are able to use the region’s PMU network and synchrophasor tools for grid monitoring and reliable operation. Using this approach, the analyst might calculate the value of synchrophasor technology for renewable generation within ERCOT as:

> Renewable generation enabled = 2014 wind generation = 36,142 thousand MWh (ERCOT 2015) * 5% = 1,807 thousand MWh in 2014

<u>SCE Rector SVC example</u> -- More detailed calculations might be feasible in the context of narrow, specific synchrophasor uses and analyses. One such example is the case of SCE’s Rector Substation, where SCE is using PMUs to control the Rector Static Var Compensator on a 230 kV transmission line to provide voltage support for wind and hydropower deliveries that would otherwise be curtailed (Johnson et al. 2008). In this case, it should be possible to estimate based on modeling and pre-SVC experience how much throughput on the line would have been limited in the absent absence of the PMU-controlled SVC, and therefore how much renewable generation (and throughput broadly) would have been foregone without the SVC.

<u>An ERCOT event example</u> -- a wind plant in ERCOT was generating about 56 MW when the oscillations were identified at 8:30 a.m. on January 10, 2014 (although they began at 6:15 p.m. on January 9); ERCOT curtailed the wind output to 45, then 40 MW at 10:57 a.m. (CCET 2015, p. 110). If one determined the time when the wind farm oscillator corrected the turbine control cards, which stopped the oscillations, and restored output back to 50 MW, one could hypothesize the amount of wind generation foregone in this event, and could even suppose that without the ability to track oscillatory behavior, the wind plant might have been shut down completely and its entire generation foregone for that time period.

Figure 3.2 – ERCOT – reductions in wind generator-caused oscillations after constraining the generator to 40 MW



Source: "Technology Solutions for Wind Generation in ERCOT, Final Technical Report," February 23, 2015, Center for the Commercialization of Electric Technologies, p9.

3.4.3 Fossil fuel offset by synchrophasor technology

If we assume that every incremental megawatt-hour of wind generation produced within ERCOT offset an equal amount of fossil generation, then it would be easy to calculate the fossil generation avoided.[17] However, it may not be appropriate to assume that incremental renewable generation displaces an equivalent amount of fossil generation, because increased wind generation requires some increased fossil generation to provide ancillary services for wind integration. Thus a fossil generation displacement estimate should be reduced by the amount of fossil generation used for integration. Because wind integration costs are usually presented in terms of dollars per megawatt-hour rather than megawatt-hours or megawatts (Milligan et al. 2013), it may be necessary to hypothesize

[17] A one-for-one displacement between renewables and fossil energy is not a given; for instance, the GE wind integration study performed for PJM on the feasibility of meeting a 30% wind penetration target indicated that on average for all scenarios, the wind generation displacement affected 18% of coal and 35% of combined-cycle generating technology generation (GE Energy Management 2013).

this figure based on modeled results; e.g., assume that the emissions offset by incremental renewable generation comes from a 50% reduction in offset megawatt-hours of fossil energy.

The best way to estimate how much renewable generation displaces fossil generation is to look at forward-looking renewable integration studies and scenarios of the type conducted by the National Renewable Energy Laboratory (NREL).[18] Such studies have shown that fossil displacement by renewables can vary between regions. A 2013 study of 30% renewables penetration in WECC found that, "Adding 4 MWh of renewable generation displaces 1 MWh of coal and 3 MWh of gas generation" (NREL 2013) while a 2014 study for Minnesota found that a 40% in-state renewables requirement would be balanced by a decrease in coal and gas-fired combined cycle generation and a decrease in imports from out-of-state (GE Energy Consulting 2014). Therefore, if fossil generation displacement is an important goal and metric for a specific synchrophasor project, the analyst should look for a renewables integration study that is geographically relevant to the synchrophasor project footprint, to find approximate renewables-to-fossil generation displacement figures.

3.4.4 Emissions offset by synchrophasor technology

A recent NREL renewable integration study estimated that under 33% wind and solar generation scenarios, net carbon emissions were reduced by a third (NREL 2013). Because we are assuming that the increase in renewable generation that can be attributed to synchrophasor technology is fairly small, it stands to reason that the amount of emissions reduced principally by synchrophasor-enabled renewables would be small, but perhaps not trivial.

The EIA's eGRID survey monitors power plant emissions. EIA indicates that "annual total output emission rates for greenhouse gases [GHGs] can be used as default factors for estimating GHG emissions from electricity use when developing a carbon footprint or emission inventory" (EIA 2014). eGRID offers annual total output emission rates and annual non-baseload output emission rates (lb/MWh) for carbon dioxide (CO_2), methane and nitrous oxide in 26 sub-regions covering the United States; the non-baseload output emission rates might be more appropriate to use to estimate GHG emission reductions for incremental wind generation.

Emissions offset calculation example -- Using the eGRID 2010 CO_2 emissions figures to calculate the emissions impact of a 5% incremental increase in wind generation due to synchrophasor use within ERCOT in 2014, and assuming that the incremental wind production offsets 50% fossil generation within ERCOT:

> Emissions offset = 1,807 thousand MWh incremental wind generation * eGRID 2010 annual non-baseload CO_2 emissions of 1,181.7 lb/MWh * 50%
>
> = 1,068 million lbs CO_2 carbon emissions avoided in 2010.

[18] Recent NREL transmission integration analyses are posted at http://www.nrel.gov/electricity/transmission/publications.html .

The EPA's Clean Power Plan calculates CO_2 emission performance rates by state for coal and natural gas combined cycle (NGCC) power plants, and aggregates them up to regional baselines for the years 2020 and later (EPA 2015). This document provides pound per megawatt-hour estimates for the CO_2 emissions attributable to fossil steam and NGCC generation; those numbers could be used as the basis for emissions offset per megawatt-hour of future renewable generation attributable to synchrophasor technology use.

Section 4 – Aggregating project benefits

4.1 Factors affecting project benefits

Several factors combine to make it difficult to determine how the magnitude of transmission-level reliability and cost savings from synchrophasor technology use will change over time. The factors include the following:

- Synchrophasor impacts are likely to increase over the short term as current systems move from the pilot stage into accepted usage and more planners and system operators act upon the insights and recommendations derived from synchrophasor analysis.
- Impacts may increase because new synchrophasor applications and uses are maturing, extending synchrophasor usage into new functionalities and activities. Improvements will occur as synchrophasor data quality improves, more data are shared between transmission owners and RCs, as baselining and pattern recognition from historic data enable creation of sophisticated operator decision support tools, and as synchrophasor technology is extended to distribution-level monitoring and management.
- The operational impacts of new technology and tools may flatten out over time as the incremental benefits diminish. For example, as engineers use PMU-based model validation techniques to improve generator and system models, the reliability benefit and cost savings per model improved could be significant for the first few years. But once these techniques are automated and all the models have been improved, the incremental benefit from ongoing model validation will be low relative to the new, higher baseline created by the better models and better methods. Similarly, once oscillation detection using PMUs becomes routine, oscillation detection, mitigation, and management should become significantly better, and a few years later the large, early-year benefits from synchrophasor usage will seem exaggerated relative to the improved baseline.
- The magnitude of transmission-level reliability and cost savings from synchrophasor technology may erode over time if the amount of energy managed at the bulk power system level diminishes due to increasing energy efficiency, distributed generation, and storage at the distribution level.

Thus the assumptions and rationale for the estimated benefits need to be clearly stated. The time span of the benefits will directly relate to the assumptions used.

4.2 Project asset lifetime and the benefits time horizon

While it is common to assess project benefits for many transmission capital investments over a multi-decade project life (Carter et al. 2010), the asset life of a synchrophasor technology investment is not entirely clear. A synchrophasor system includes PMUs (which may have a 20- to 30-year life), impacts on transmission assets with 40-year lives, communications networks (which may require technology refreshment within 5 to 10 years), and analytical applications (that may be updated every 6 months or replaced within 5 years).

However, it is not necessary that the non-monetary benefits of a synchrophasor project be estimated over a time horizon that matches the lifetime of the underlying assets – particularly since project investment may occur in phases. It may be appropriate to avoid the question of overall project lifetime and simply set a fixed time horizon (such as 20 years out) for benefits assessment. This would recognize that there is great uncertainty about technology uses and impacts in the more distant period. As a practical matter, because the value of discounted future dollars diminishes at moderate discount rates as the dollars recede farther into the future, there may be little monetary difference between the total benefits realized over a twenty-year versus twenty-five year time horizon.

Whatever time horizon is used for benefits assessment, the assumptions should be clearly stated.

4.3 Discounting benefits

For financial benefits such as the customer value of outages, cost savings, value of increased megawatt-hours due to increased grid throughput and efficiency, and the value of increased environmental benefits, the last step in calculating the total benefit value is to discount the string of annual monetary benefit values back to the present. An appropriate real discount rate, such as the weighted average cost of capital faced by the investor installing the PMUs or synchrophasor system, should be used (CPUC no date). In addition, a range of discount rates may be used to indicate uncertainty in the appropriate discount rate.

Non-monetary benefits such as customer outage minutes or the number of outage events can be aggregated by simple summation over time, or could be discounted back to a present value if that is the company’s practice.

GLOSSARY, DEFINITIONS, AND ACRONYMS

AC – Alternating Current

BES – Bulk Electric System

CCET – Center for Commercialization of Electric Technology

CCVT – Coupling Capacitor Voltage Transformer

CEC – California Energy Commission

CT – current transformer

DC – direct current

EIA – Energy Information Agency

eGRID – U.S. Environmental Protection Agency survey that monitors power plant emissions.

ERCOT – Electric Reliability Council of Texas

GPS – Global Positioning System, a satellite-based system for providing position and time. The accuracy of GPS-based clocks can be better than 1 microsecond.

Hz – hertz

ICE – Interruption Cost Estimate

IED – Intelligent Electronic Device, a general term indicating a multi-purpose electronic device typically associated with substation control and protection.

IPMU – Integrated Phasor Measurement Unit, any device that is integrated with phasor measurement function, including relays, meters, and fault recorders where phasor measurement is an added function to the primary functions of a device.

kV – kilovolt(s)

LBNL Lawrence Berkeley National Laboratory

LMP – Location Marginal Price

MWh – megawatt-hour(s)

NERC – North American Electric Reliability Corporation

NQ – not quantifiable

NREL – National Renewable Energy Laboratory

O&M – operation and maintenance

OE – Office of Electricity Delivery and Energy Reliability

PDC – Phasor Data Concentrator. A logical unit that collects phasor data and discrete event data from PMUs and possibly from other PDCs, and transmits data to other applications. PDCs may buffer data for a short time period; PDCs often feed data directly into a data storage ("historian") unit.

Phasor – A complex equivalent of a simple cosine wave quantity such that the complex modulus is the cosine wave amplitude and the complex angle (in polar form) is the cosine wave phase angle.

PJM – PJM Interconnection

PMU – phasor measurement units

POW – point on wave. Applies or relates to instantaneous signal wave-forms, rather than to some average or simplified characterization of them.

PMU – phasor measurement unit, a device that samples analog voltage and current data in synchronism with a universal time source such as a GPS clock, external GPS receiver, or network-distributed time source. The samples are used to compute the corresponding phasors.

PSS – Power System Stabilizer

PT – potential or voltage transformer

Relay – An electromechanical or electronic device applied to the purpose of power apparatus protection. A relay typically monitors voltages and currents associated with a certain power system device and may trip appropriate breakers when a potentially damaging condition is detected.

RC – reliability coordinator

Sampling rate – The number of samples (measurements) per second taken by an analog to digital converter system.

SCADA – supervisory control and data acquisition

SOL – system operating limit

SPS – system protection scheme

SPS – samples per second.

SSM – synchronized system measurements. This extends the concept and technology of synchronized phasor measurements to include devices such as advanced point-on-wave recorders or control system monitors. Many of these are operational in the Western Electricity Coordinating Council wide-area measurement system.

Synchronism – The state where connected alternating-current systems, machines, or a combination thereof operate at the same frequency and where the phase angle displacements between voltages in them are constant, or vary about a steady and stable average value.

Synchrophasor – A phasor calculated with respect to a nominal frequency reference phasor that is synchronized to an absolute time reference.

TCP/IP – TCP/IP is a low-level protocol for use mainly on Ethernet or related networks. Most of the higher-level protocols use TCP/IP to transport the data. TCP/IP provides a highly reliable connection over unreliable networks, using checksums, congestion control, and automatic resending of bad or missing data. TCP/IP requires time to handshake new connections and will block if missing data are being resent.

TVE –total vector error, the magnitude of error between the theoretical phasor value of the signal being measured and the phasor estimate, as defined in 5.2

TOP – transmission operator

UTC – Coordinated Universal Time (initials order based on French). UTC represents the time-of-day at the Earth's prime meridian (0° longitude).

WAMS – Wide- area measurement system. A WAMS generally features one or more PMU networks as a “backbone,” but may also include local recorders, legacy equipment, or advanced technologies that are GPS synchronized to the PMU networks while recording non-phasor data.

WECC – Western Electricity Coordinating Council

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