Grid Modernization: Metrics Analysis (GMLC1.1) – Executive Summary

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If you don't collect any metrics, you are flying blind.
If you collect and focus on too many, they may be obstructing your field of view.

Scott M. Graffius

Acknowledgments

The entire Grid Modernization Laboratory Consortium (GMLC) Metrics team expresses its appreciation and gratitude to the U.S. Department of Energy (DOE) for providing the funding for this 3-year long endeavor. In particular, the team appreciates the many hours spent with DOE staff in meetings to clarify the direction of the project. Particular thanks to the project managers Mr. Joseph Paladino and Dr. Guohui Yuan, who challenged the team to think about how this project can be impactful and relevant to the electricity sector. The team also thanks Mr. David Meyer, who in his quiet and well-thought out way provided gentle and yet powerful advice.

We like to thank Mr. Chuck Goldman from Lawrence Berkeley National Laboratory for his vision as a member of the GMLC Laboratory leadership team that created the origin for this Metrics Analysis project. Chuck's steady support and commitment to this Metrics Analysis navigated this project through complex stakeholder communities. He presented the motivation and goals and objectives of the project on several occasions to audiences ranging from NARUC meetings participants and FERC staff to Congressional Committees.

In addition, the project team members interacted with many professionals at federal, state, and municipal agencies; grid operators; representatives of utility organizations and industry associations; as well as practicing engineers from a broad spectrum of disciplines that encompass the metrics scope—(1) reliability, (2) resilience, (3) flexibility, (4) sustainability, (5) affordability, and (6) security.

The team acknowledges the contributions of organizations and individuals for each of the six metric areas:

Reliability

The GMLC Reliability Metrics team is grateful for the strong partnership it has established with the American Public Power Association and the North American Electric Reliability Corporation, and for the timely advice and support provided by Electric Reliability Council of Texas, Idaho Power Company, and Independent System Operator (ISO) New England.

Resilience

The development of metrics to assess the resilience of the electric grid must specifically answer stakeholders' needs and requirements. The work conducted would not have been possible without the support of governmental and industry partners. The methodology presented in this report builds upon previous work funded by the U.S Department of Homeland Security (DHS) and the DOE Office of Electricity. Over the course of the project, several partners have been involved in the project. Their feedback and comments have been paramount to assuring the success of the development of these new metrics. The authors are particularly thankful to Electric Power Research Institute (EPRI), DHS, the City of New Orleans, Entergy, PJM, the Institute of Electrical and Electronics Engineers, the DOE/Office of Energy Policy and Systems Analysis, and the North American Electric Reliability Corporation (NERC) Critical Infrastructure Protection Committee. Finally, the authors recognize the contribution of two of their colleagues, Julia Phillips and Robert Jeffers, who initiated this work.

Flexibility

The GMLC Flexibility Metrics team thanks the California ISO and the Electric Reliability Council of Texas for their advice and data resources.

Sustainability

The GMLC Sustainability Metrics team thanks several partners at the U.S. Energy Information Administration, EPRI, Sustainability Accounting Standards Board, Arizona State University, U.S. Environmental Protection Agency, National Renewable Energy Laboratory, National Regulatory Research Institute, and DOE for their review, advice, data resources, and comments on the greenhouse gas (GHG) portion of the Sustainability Reference Document, Volume 5.

The GMLC Sustainability Metrics team thanks the Energy Information Administration (EIA) and the U.S. Environmental Protection Agency (EPA) for providing data and answering questions regarding their respective GHG data products and surveys, as well as for the thoughtful discussions of federal and voluntary GHG reporting.

Affordability

The GMLC Affordability Metrics team acknowledges the cooperation of the two entities that contributed unpublished data to our affordability use cases: Southern California Edison (SCE) and the Alaska Energy Authority. Lending summarized and anonymized electricity billing data to this effort was essential to testing the metric estimations. We also acknowledge those groups who played a role in helping steer and review this effort periodically during the project, including EPRI, Washington Utility and Transportation Commission, Colorado State Energy Office, Minnesota Public Utility Commission, and Clean Energy States Alliance.

Security

The work conducted during the development of physical security metrics would not have been possible without the support of governmental and industry partners. The methodology presented in the Physical Security Reference Document, Volume 7 builds upon previous work funded by DHS and their support in providing data about the physical security attributes of the electric sector was invaluable. The Security team is also particularly thankful for the feedback and comments from SCE and the Edison Electric Institute during the development of the new physical security metrics.

Acronyms and Abbreviations

ALE	annualized loss expectancy
AMP	Alaska Microgrid Project
ANL	Argonne National Laboratory
APPA	American Public Power Association
CAISO	California Independent System Operator
CBECS	Commercial Buildings Energy & Consumption Survey
CFR	Code of Federal Regulations
DG	distributed generation or generator
DHS	U.S. Department of Homeland Security
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EP	Electric Power
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas, Inc.
FERC	Federal Energy Regulatory Commission
GHG	greenhouse gas
GMLC	Grid Modernization Laboratory Consortium
GMLC1.1	Grid Modernization Laboratory Consortium Project Metrics Analysis
ICE	Interruption Cost Estimate
IEEE	Institute of Electrical and Electronics Engineers
IPC	Idaho Power Company
ISO	Independent System Operator
ISO-NE	New England Independent System Operator
IST	Infrastructure Survey Tool
kV	kilovolt(s)
LBNL	Lawrence Berkeley National Laboratory
LVAT	Laboratory Valuation Analysis Team
MCDA	Multi-criteria decision analysis
MECS	Manufacturing Energy Consumption Survey
MER	Monthly Energy Review
MW	megawatt(s)
MWh	megawatt hour
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory

OMB	Office of Management and Budget
PMI	Protective Measures Index
PV	photovoltaics
RD&D	Research, Development and Demonstration
RDS	Resilient Distribution System
RECS	Residential Energy Consumption Survey
RSTEM	Regional Short-Term Energy Model
RWR	Relative Water Risk
SAIDI	Systems Average Interruption Duration Index
SAIFI	Systems Average Interruption Frequency Index
SCE	Southern California Edison
SNL	Sandia National Laboratories
SRI	solar reflectance index
STEO	Short-Term Energy Outlook
VG	variable generation

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1.0 Introduction

This document summarizes the accomplishments of a three-year project funded by the U.S. Department of Energy (DOE) under its Grid Modernization Initiative, which is working across DOE to create the modern grid of the future. The project, titled "Grid Modernization Laboratory Consortium (GMLC) 1.1: Metrics Analysis"(hereafter GMLC Metrics project) was undertaken by the Grid Modernization Laboratory Consortium (GMLC) Metrics team (hereafter GMLC Metrics team), which consists of national laboratory sub-teams each dedicated to developing one of six volumes in the set of reference documents about new grid metrics.

This first volume describes the importance of metrics for grid modernization and then introduces the six categories of metrics DOE has developed to guide the Grid Modernization Initiative—(1) reliability, (2) resilience, (3) flexibility, (4) sustainability, (5) affordability, and (6) security. It then describes the approach the Grid Metrics team took to working directly with industry stakeholders to develop new grid metrics and demonstrate their use. This report is accompanied by six separate reference documents that provide more detail about the work of the GMLC Metrics sub-teams on each of the six metrics categories and assess the current uses of metrics in these each of the categories to inform grid modernization

2.0 The Importance of Metrics for Grid Modernization

The electric industry and its stakeholders will not be able to manage grid modernization investments effectively if they do not rely on metrics that help them understand how these investments have affected the performance of the grid. The pace of grid modernization will be determined by thousands and thousands of individual decisions (on both sides of the meter) to invest in and adopt new grid technologies and practices. These decisions will be based on firms' and consumers' individual assessments of profitability or preferences. They will be further shaped or influenced by the policies and regulations through which the public interest is conveyed and enforced. How well private and public interests are served by these decisions will be judged and guided, at least in part, by how well new grid technologies and practices perform in the field.

Measurements of performance tailored to capture the aspects of grid modernization that decision-makers seek to influence are essential for assessing progress toward achieving both private and public grid modernization objectives. They are needed to prioritize and select among grid investments, to guide mid-course corrections, and to confirm that objectives have (or have not) been achieved.

Measurements vs. Metrics for Grid Modernization

Measurements are physical properties and characterizations or assessments of a particular aspect of the performance of the grid. Measurements are typically quantitative in nature. (e.g., 120 V, 60 Hz)

Throughout this document, when measurements are used to inform decisions to modernize the grid, they become metrics. That is, metrics are measurements (or combinations of measurements) that are useful in assessing changes (or progress) relative to a reference state that has been influenced or affected by a grid modernization activity. For example, the changes may seek to achieve operational or economic improvements with respect to a particular grid modernization objective, such as reliability or sustainability.

Not all measurements of performance will be useful as metrics. Care must be taken to assure that the measurements selected for use as metrics are well aligned with and directly reflect the aspects of grid performance that are targeted for improvement or that must be taken into account in order to determine the success of an activity.

Selecting which measurements to use as decision-guiding metrics, therefore, requires distinguishing between "means" and "ends." Generally speaking, it is the ends or objectives of grid modernization that should be the focus of such metrics. For example, asset utilization is a measurement that is sometimes used to assess the performance of a grid activity. However, by itself, asset utilization is not a measure of, for example, the profitability of the activity. Other measures must also be used in conjunction with asset utilization to determine profitability. Hence, asset utilization, by itself, is not a metric of profitability.

3.0 DOE's Grid Modernization Metrics Categories

DOE's Grid Modernization Multi-Year Program Plan (DOE 2015a) identifies six aspects of grid performance that together compose—from a national perspective—the foundational objectives of grid modernization. They are defined as follows:

- Reliability – The ability to maintain the delivery of electric services to customers in the face of routine uncertainty in operating conditions.
- Resilience – The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, including the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.
- Flexibility – The ability to respond to future uncertainties that may stress the system in the short term and require the system to adapt over the long term.
- Sustainability – The ability to provide electric services to customers that minimize negative impacts on the health of humans and the natural environment.
- Affordability – The ability to provide electric services at a cost that does not exceed customers' willingness or ability to pay for them.
- Security – The ability to reduce the risk to critical infrastructure by physical means or defense cyber measures to intrusions, attacks, or the effects of natural or man-made disasters.

Grid Metrics for Reliability vs. Resilience

Grid metrics for reliability and resilience are closely related. Some metrics overlap or are identical for assessing both reliability and resilience impacts; others are unique and specific to either reliability or resilience. Understanding these similarities and differences helps to explain why and in which circumstances either or both are important for assessing and informing grid modernization decisions.

Electric system reliability metrics,[1] on the one hand, are generally more focused and limited in scope than electric system resilience metrics, in part, because they were originally developed to assess routine interruptions of electric service to customers. Indeed, an important advancement in the specification of these metrics has been the development of systematic means for distinguishing between routine and nonroutine interruptions of service. Typically, the metrics represent aggregations of events affecting the performance of the power system over multiple events, such as over the course of 1 year.

Electric system resilience metrics, on the other hand, are focused exclusively on describing the impacts of an individual nonroutine event, such as a catastrophic hurricane. Such events always cause either longer-lasting or wider-spread impacts than those associated with routine events. They also typically have impacts that extend beyond the electric power system (for example, other infrastructures). Accordingly, metrics for measuring the impacts of resilience events are necessarily broader and more open-ended than those appropriate for measuring the impacts of routine, reliability events.

The important point is that each set of metrics is useful for assessing and informing decisions to address potentially very different threats to the electric power system. That said, it is also important to recognize that decisions to improve reliability may also improve resilience and vice versa.

4.0 The Objectives for and Approach Taken by the Grid Metrics Team

DOE charged the Grid Metrics team to "move the ball forward." DOE emphasized that the GMLC Metrics project only had an initial 3-year term. Within this period of performance, DOE expected the team to prove that specialized expertise drawn from across the national laboratory system could confirm the importance and value of new metrics for grid modernization.

DOE made clear that the principal gauge of the usefulness of the team's efforts would be stakeholder engagement. DOE reasoned that meaningful engagement with stakeholders, as illustrated by their working in partnership with the national labs, would be the most transparent means by which they could assess the success of the labs' efforts to improve the practice and use of new grid metrics.

DOE also expected the national labs to show how, in a short period of time, they could not only assemble this expertise, but also engage as a team and effectively and efficiently achieve ends greater than each could achieve individually. Specifically, DOE sought to establish a national body of expertise on the six foundational objectives for its Grid Modernization Initiative that could be tasked to support future DOE grid modernization activities.

The Grid Metrics team addressed DOE's guidance using a structured and coordinated phased approach.

During the first phase of the project, the national lab leadership tasked each national lab to put forward candidates who have expertise in metrics related to the six foundational grid modernization objectives. National lab leadership worked with the project team leadership to identify sub-teams composed of experts for each objective, plus a seventh sub-team to work on cross-cutting issues. Early face-to-face meetings involving all team members were held at which members presented the expertise they each brought to the project and discussed approaches for addressing DOE's guidance.

During the second project phase, the six sub-teams conducted a thorough literature review of existing metrics related to each foundational grid modernization objective. A focus of the literature reviews was identification of key gaps among existing metrics. Gaps were identified with respect to the need for new metrics, or new applications of existing metrics—all from the standpoint of the importance of addressing these gaps to pursue effectively one or more of the foundational grid objectives. A critical element of this second phase was extensive outreach—coordinated by the seventh sub-team—to a broad array of industry stakeholders to inform them about the project and to solicit their input about gaps and approaches for addressing them.

During the third phase, which was initiated in conjunction with the second phase, the sub-teams identified and secured agreements to partner with one or more industry stakeholder to develop, demonstrate, or apply the metrics that had been identified. The activities conducted in support of and through these partnerships constituted the core activity of the Grid Metrics project.

The fourth phase of the project was to socialize the findings from the stakeholder partnerships in support of broader adoption of the metrics by industry. These activities will continue past the formal end of the initial 3-year term of the Grid Metrics project.

5.0 Project Accomplishments

The motivation for the activities of each sub-team and a summary of their major accomplishments follows. It should be noted that the GMLC1.1 metric areas span a wide range of technical and scientific maturities. Some metric areas are very mature, and sometimes have benefited from past DOE research and investment (i.e., reliability). Other metric areas, such as flexibility, are less mature because they have only gained prominence recently. As a consequence, the impacts of the GMLC Metrics project ranged from incremental contributions and advancements that build upon prior contributions sourced by other DOE projects, to more original and distinct advancements, because relatively little prior work has been completed.

This document summarizes the accomplishments of the GMLC Metrics research conducted in each metric area. Each metric-specific summary begins by defining the scope of the metric development, and then describes the motivation for the research that was conducted, references the current state of the art, and identifies remaining needs related to metrics addressed by the project. Finally, the summaries describe the nature of the research contributions; that is, whether the contributions were incremental to an ongoing body of research or whether they stand alone as new or unique contributions to the field.

5.1 Reliability

Lab Team: Joe Eto and Kristina Hamachi-LaCommare, Lawrence Berkeley National Laboratory (LBNL); and Meng Yue, Brookhaven National Laboratory (BNL)

Reliability

The ability to maintain the delivery of electric power to customers in the face of routine uncertainty in operating conditions.

For utility distribution systems, measuring reliability focuses on interruption in the delivery of electricity in sufficient quantities and of sufficient quality to meet electricity users' needs for (or applications of) electricity.

For the bulk power system, measuring reliability focuses separately on both the operational (current or near-term conditions) and planning (longer-term) time horizons.

5.1.1 Scope of Metrics Development

The GMLC Metrics team focused on three areas for the reliability metrics development:

1. Distribution reliability: developed new metrics for distribution reliability, which account for the economic cost of power interruptions to customers, and implemented the metrics in partnership with the American Public Power Association (APPA).
2. Interconnection-wide transmission reliability: participated in the development and implementation of improvements of interconnection-wide metrics for bulk power system reliability, which will be reported annually in the North American Electric Reliability Corporation (NERC) State of Reliability report.

3. Metrics for probabilistic transmission planning: conducted a demonstration of the use of metrics for probabilistic transmission planning and reviewed them with the Electricity Reliability Council of Texas (ERCOT), Independent System Operator (ISO) New England (ISO-NE), and Idaho Power Company (IPC).

5.1.2 Motivation

The reliability of the electric power system has long been a focus of study. Many highly mature metrics are in widespread use for this area. The purposes they serve remain important today, but there also are rapidly growing needs for new, complementary reliability metrics, such as the three described below, on which the GMLC Metrics team focused.

First, household, firm/industrial, and society's dependence on electricity have grown and expectations for reliability have increased. Our understanding of the economic consequences that arise when electric service is interrupted has also increased. It is appropriate to take explicit account of these economic consequences when making decisions to maintain or improve reliability. Newly developed tools, such as LBNL Interruption Cost Estimate (ICE) Calculator, are available to support incorporation of this information into reliability decision-making. Yet traditional reliability metrics, such as the Systems Average Interruption Duration Index (SAIDI) and Systems Average Interruption Frequency Index (SAIFI), cannot—in their current form—be used in conjunction with these tools.

Second, restructuring of the electricity industry has led to distinct federal and state regulatory regimes for overseeing reliability. The federal regime focuses on oversight of the operation of the bulk electric power system (generally, above 100 kilovolts [kV]). The state regime focuses on oversight of the operation of local distribution systems (generally, less than 100 kV). Current system-wide reliability metrics, such as SAIDI and SAIFI, do not identify whether the cause of power interruptions originates from the bulk electric power system or from within the local distribution system. Hence, they cannot be used with precision to inform the decisions that federal and state regulators must make in overseeing the reliability of the portions of the electric power system they regulate. NERC has begun to develop a new system-wide measure of the reliability of the bulk power system called the Severity Risk Index (SRI), which it publishes annually in the State of Reliability report. In its current form, however, the SRI does not account for two important aspects of the manner by which the bulk power systems of the United States are operated: (1) there are three interconnections; each is operated (and hence performs) independently of the other two, yet there is only a single SRI calculated for the entire United States; and (2) the SRI is composed of a combination of three static measures of reliability and does not account for the dynamic interactions among these measures, which makes some combinations much more challenging for achieving reliability than others.

Third, uncertainty about the future generation mix and composition of loads has grown. The growth in renewable sources of generation whose output varies and hence cannot be dispatched in the traditional sense, in particular, introduces specific new types of uncertainties into utility planning and operations. Current planning techniques are challenged to take these uncertainties into account and lead to misleading conclusions. Probabilistic planning techniques can treat these new types of uncertainty explicitly and consistently in reliability planning and thereby improve these decision-making processes. Currently, their application is nascent, and formal metrics to assess their performance have not been adopted by the transmission planning community.

5.1.3 Outcomes/Impacts

5.1.3.1 New Distribution Reliability Metrics Developed with APPA

The APPA eReliability Tracker is an online tool available to APPA's members for recording and analyzing utility reliability information.[1] A principal use case is automated development of standard distribution reliability metrics, such as SAIDI and SAIFI, based on information entered by a participating utility. Information is typically entered at the circuit-level (as opposed to the whole utility), which facilitates the automated generation of circuit-level reliability reports, such as lists of the worst (or best) performing circuits. These reports are used by utilities to help prioritize reliability-enhancing investments of improvements in practices.

The ICE Calculator is a publicly available, online tool that allows users to estimate the economic costs borne by customers because of interruptions of their electric service.[2] The analytic engine underlying the ICE Calculator is a series of econometrically estimated equations that relate the economic cost to features of the customer experiencing the interruptions (e.g., whether they are a residential, small commercial or industrial, or large commercial or industrial customer) and of the interruption (e.g., how long the interruption lasts). The equations were developed through analyses conducted on a pool of all available past utility-sponsored customer surveys of the value of lost load.[3]

The GMLC Metrics team provided the underlying equations in the ICE Calculator to APPA, which then programmed them into the eReliability Tracker. APPA then developed automated reports about the economic costs to customers of power interruptions as a standard offering of eReliability Tracker. The team participated in reviews of developmental versions of these reports and made suggestions for improvement to the information (e.g., metrics) presented.

At the time of this writing (Winter 2018-19), APPA reports that approximately 250 utilities are routinely receiving these reports.[4] The team continued work with APPA in 2019 to review how utilities used the reports and suggested enhancements to further extend and ease their membership's use of the tool.

This effort did not explore the causes of power interruptions. However, as a result of GMLC-supported engagement with APPA, in 2019, LBNL and APPA entered a Cooperative Research and Development Agreement to explore the interruption cause data using the eReliability Tracker web portal.

[1] https://www.publicpower.org/reliability-tracking

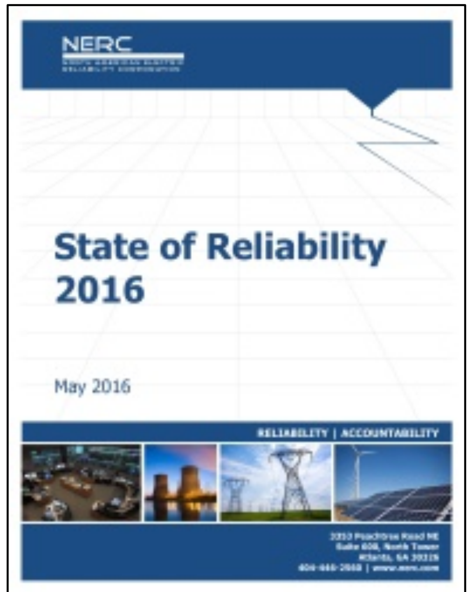
[2] https://icecalculator.com/home

[3] Sullivan MJ, J Schellenberg, and M Blundell. 2015. *Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States.* Lawrence Berkeley National Laboratory, Berkeley, CA. January. LBNL-6941E. http://emp.lbl.gov/sites/all/files/lbnl-6941e.pdf

[4] Personal communication. Alex Hoffman, APPA, 8 November 2018.

5.1.3.2 Improved Bulk Power System Reliability Metrics Developed by NERC

NERC, through its Performance Analysis Subcommittee, has for many years compiled and published leading and lagging metrics for aspects of bulk power system reliability in its annual State of Reliability report.[1] The report features an overall metric of the reliability of the bulk power system, called the SRI (Severity Risk Index).[2] The SRI is calculated for each day of the year. It enables a ranking of the overall reliability of the bulk power system on daily basis. The Grid Metrics team was invited to join the NERC Performance Analysis Subcommittee to participate in ongoing refinements of the SRI and the preparation of the State of Reliability report. For Winter 2018-2019, the team was involved in two enhancements of the SRI.



First, rather than calculate a single, daily SRI for the United States as a whole, the Performance Analysis Subcommittee worked toward calculating a separate daily SRI for each of the three U.S. interconnections. The motivation for this effort is the recognition that each interconnection operates independently of the other on an essentially stand-alone basis. The reliability of each interconnection does not affect the reliability of its neighboring interconnections.

As part of this effort, the Performance Analysis Subcommittee also evaluated options for improving the loss-of-load element that is a key input to the calculation of the SRI. The information provided by the Institute of Electrical and Electronics Engineers (IEEE) Distribution Reliability Working Group, while the best available, was long recognized as being neither a precise nor a comprehensive measure of the loss of load due to causes originating from the bulk power system. First, the definition of loss of supply does not describe losses that are due solely to causes originating from the bulk power system; it also includes losses originating from sub-transmission systems (which are outside the jurisdiction of the NERC/Federal Energy Regulation Committee [FERC]). Second, because the information developed by IEEE is provided voluntarily by some but not all utilities, the information may not be representative of an entire interconnection. This fact contributed to the reason why an interconnection-specific SRI could not be calculated for the 2018 State of Reliability. It was found that there was no information about loss of load from utilities within one interconnection, and efforts to go back to utilities in this interconnection to collect the needed information occurred too late in the process to be included in the 2018 State of Reliability report. It was included in the 2019 State of the Reliability report.

Going forward, the GMLC Metrics team is also in discussions with leading academics to explore potential enhancements to the SRI to account for the dynamic relationships among generation availability, transmission availability, and loss of load. Currently, these three elements of the SRI are calculated independently from one another and then combined using static weights that are invariant across all the days of the year. The team seeks to develop a systematic means of

[1] https://www.nerc.com/pa/RAPA/PA/Pages/default.aspx

[2] https://www.nerc.com/comm/PC/Performance%20Analysis%20Subcommittee%20PAS%202013/SRI%20Enhancement%20Whitepaper.pdf

replacing these weights dynamically by explicitly considering time-varying, inter-dependencies among the three underlying elements (and potentially other elements, as well).

5.1.3.3 Metrics for Probabilistic Transmission Planning Demonstrated for ERCOT, ISO-NE, and IPC

The GMLC Metrics team performed a scoping study of transmission system reliability metrics that reviewed existing transmission planning activities, major challenges, and reliability metrics used by ERCOT, ISO-NE, and IPC.[1] The scoping study also included a discussion of ongoing or planned activities related to these utilities' probabilistic planning applications and metrics. In their current planning activities, almost all the metrics they use are deterministic. The sole exceptions are those used in resource adequacy studies, e.g., loss-of-load expectation.

The scoping study showed that, although these utilities are facing different types of challenges, all of them recognized the uncertainties they encounter in daily operations were growing and can no longer be ignored. In particular, uncertainties that affected specific planning metrics, but were currently unaccounted for, were identified and discussed.

One example is the metrics used for transmission contingency analysis. Currently, the analysis of these contingencies is binary: a reliability criterion either is or is not exceeded. This form of analysis does not consider the relative frequencies of the individual contingencies. Nor does the pass/fail nature of the evaluation consider the relative severity of the potential impacts of various contingencies with respect to one another. Yet understanding the frequency and severity of various contingencies is essential for assessing the risks that contingencies pose to the system and, hence, the priorities to assign to potential remedies. The scoping study showed that deterministic metrics such as loss-of-load and voltage violations can be enhanced by associating each with a probabilistic distribution. The probabilistic distribution is determined by the distributions of frequencies and durations of the individual contingencies of grid components such as generators and transmission circuits, as well as renewable generation that are used in the deterministic calculations.

In the scoping study, the sources and modeling of uncertainties for various planning studies, the existence and availability of data sources needed for calculating the probabilistic metrics, and the availability of the tools that can be used for the calculation were identified. A brief discussion of development of the aforementioned probabilistic enhancement to existing deterministic metrics was also provided.[2]

5.1.3.4 Summary of Accomplishments

Accomplishments related to reliability metrics development are as follows:

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[1] Yue M. 2018. A Scoping Study on Transmission System Reliability Metrics Performed for GMLC Project 1.1 Foundational Metrics. Brookhaven National Laboratory. May.

[2] Note that the perspective taken by the scoping study is that transmission planning authorities would use both deterministic and probabilistic reliability metrics simultaneously, not one or the other. Using both metrics takes advantage of the strengths of both types of metrics. Also note that the focus of this study was on transmission planning. These methods could also be extended to operational planning, but pursuit of this was beyond the scope of this initial scoping study.

- For the distribution system reliability metrics, the contribution was incremental to an ongoing lab/industry engagement, which had initiated the integration of the LBNL ICE Calculator methodology into the APPA web portal.
- For the bulk power reliability metrics engagement with NERC, the project advanced the discussion at academic and practical levels regarding how generation and transmission availability and loss-of-load data could be used to derive insights that may lead to future use of these data for predictive analytics related to loss-of-load probabilities. These discussions are aimed at bringing new predictive analytics to the field and to NERC's report on the State of Reliability.
- The project showed that the value of deterministic metrics currently used for transmission planning activities would be enhanced by incorporating information about probabilistic distributions for, as an example, (1) loss of load and (2) voltage violation thresholds. These enhancements would more accurately represent real-world conditions, not only of the performance of renewable resources, but also by implication of the overall performance of the integrated transmission system.

5.2 Resilience

Lab Team: James Kavicky and Frederic Petit, Argonne National Laboratory (ANL); and Vanessa Vargas, Sandia National Laboratories (SNL).

> **Resilience**
>
> The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, including the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.

5.2.1 Scope of Metrics Development

The GMLC Metrics team developed two analysis approaches for resilience in the electricity sector. Each approach embodies resilience metrics and a methodology with an associated process to quantify resilience. The two approaches can be used independently or in conjunction with one another to measure and assess the resilience of electric power systems.

5.2.2 Motivation

Historically, U.S. government policy toward critical infrastructure security focused on physical protection. However, after the terrorist attacks of September 11, 2001, the devastation from Hurricane Katrina in 2005, and a series of other disasters in the early 2000s, the infrastructure security community in the United States and around the world recognized that it was simply not possible to prevent all threats to all assets at all times. Consequently, assuring critical infrastructure resilience emerged in the United States and across the globe as a complementary goal to prevention-focused activities. Whereas critical infrastructure security policies historically emphasized prevention of terrorism, accidents, and other disruptions, critical infrastructure resilience activities emphasize the infrastructure's ability to continue to provide goods and services even in the event of disruptions. Together, critical infrastructure security and resilience strategies provide a more comprehensive set of activities for assuring that critical infrastructure systems are prepared to operate in an uncertain, multi-hazard environment.

Today, resilience is at the forefront of several efforts by local, state, and federal governments and agencies. However, no consensus exists at present about how to define or quantify resilience. This issue was highlighted in the National Academy of Sciences' report about disaster resilience: "without some numerical basis for assessing resilience, it would be impossible to monitor changes or show that community resilience has improved. At present, no consistent basis for such measurement exists…" (NRC 2012). Currently, resilience metrics development is a very active area of research.

5.2.3 Outcomes/Impacts

The Grid Metrics team pursued two main categories of metrics that can be used independently or in conjunction with one another to quantify the resilience of grid infrastructures.

The first category is called multi-criteria decision analysis (MCDA). MCDA-based metrics generally try to answer the question: "What is the current state of resilience of the electric system, and what are the options for enhancing its resilience over time?" MCDA-metrics provide a baseline understanding of the system's current resilience and facilitate consideration of resilience-enhancement options. Thus, they typically include categories of system properties that are generally accepted as being beneficial to resilience. Examples of these categories might include elements of robustness, resourcefulness, adaptiveness, or recoverability. Application of these metrics typically requires that analysts follow a process of reviewing their system and determining the degree to which the properties are present within the system. These determinations are usually made by collecting survey responses, developing a set of weighting values that represent the relative importance of the survey responses, and performing a series of calculations that result in numerical scores for the resilience attributes. The baseline can then be used to conduct "what if" analysis to understand the impacts of targeted investments or actions to improve the resilience posture of one or more of the attributes. Figure 5.1 illustrates the major category groupings that are used to develop a resilience index using MCDA.

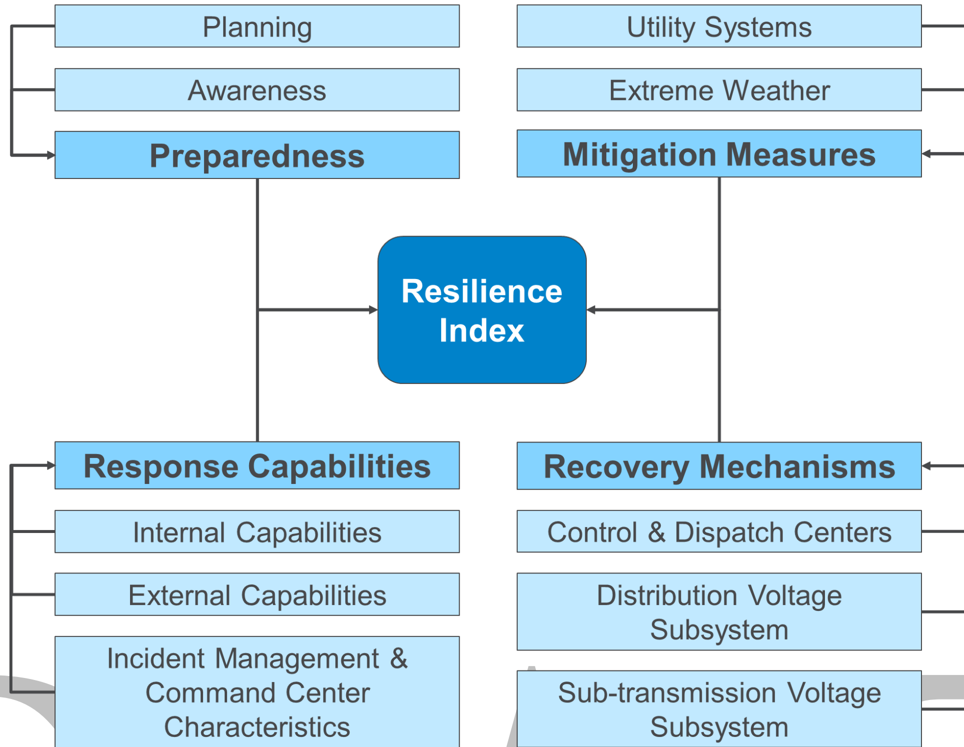


Figure 5.1. Major Level 1 (bold font) and Level 2 Category Groupings Constituting the Resilience Index

The second category is called performance-based. Performance-based metrics generally try to answer the question: "How would an investment affect the resilience of my system?" Performance-based metrics are used to describe quantitatively how the grid has been affected or compromised in the event of a specified disruption (such as a natural disaster). The required data can be gathered from historical events, subject matter estimates, or computational infrastructure models. Because the metrics can often be used to measure the potential benefits and costs associated with proposed resilience enhancements and investments, performance-based methods are often ideal for cost-benefit and planning analyses. Table 5.1 provides examples of resilience consequence categories and metrics that might be developed using the performance-based approach.

Table 5.1. Examples of Consequence Categories for Consideration in Grid Resilience Metric Development

Consequence Category	Resilience Metric
Direct	
Electrical Service	Cumulative customer-hours of outages Cumulative customer energy demand not served Average number (or percentage) of customers experiencing an outage during a specified time period
Critical Electrical Service	Cumulative critical customer-hours of outages Critical customer energy demand not served Average number (or percentage) of critical loads that experience an outage

Consequence Category	Resilience Metric
Restoration	Time to recovery Cost of recovery
Monetary	Loss of utility revenue Cost of grid damages (e.g., repair or replace lines, transformers) Cost of recovery Avoided outage cost
Indirect	
Community Function	Critical services without power (e.g., hospitals, fire stations, police stations) Critical services without power for more than *N* hours (e.g., *N* > hours of backup fuel requirement)
Monetary	Loss of assets and perishables Business interruption costs Impact on Gross Municipal Product or Gross Regional Product
Other critical assets	Key production facilities without power Key military facilities without power

Combining these two approaches allows for a more comprehensive analysis of the resilience of the grid and the potential consequences resulting from disruptions of electricity supply, thereby representing both electric grid and community resilience benefits. The MCDA approach can be used first to provide a high-level characterization of a grid's resilience and allow for comparing different resilience-enhancement options. The performance-based approach can then be used by incorporating the outputs of the MCDA approach to deepen the resilience assessment of a grid by integrating economic and regional considerations. See Figure 5.2.

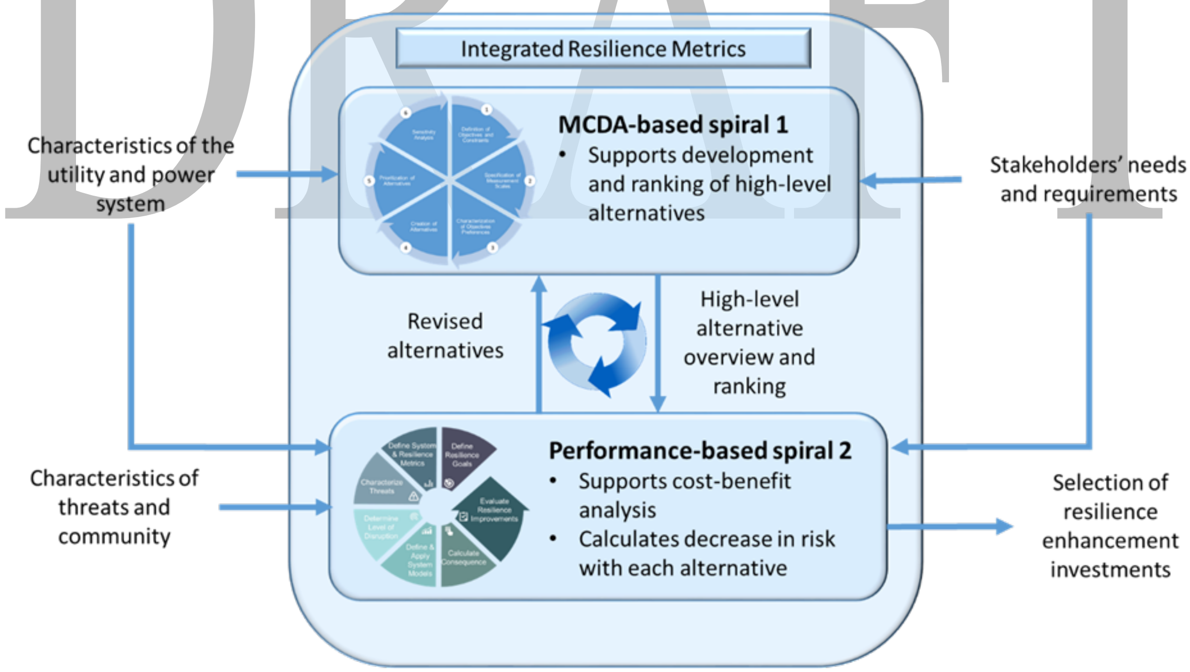


Figure 5.2. Integration of Resilience Metric Approaches

At the time this report was prepared (Winter 2019), the team was in discussions with a variety of stakeholders to conduct an integrated demonstration of the two complementary approaches.

5.2.3.1 Summary of Accomplishments

The ANL/SNL team developed a process by combining two complementary approaches to estimate potential consequences using a combined resilience measure composed of a set of previously existing independent metrics. The innovation of this project was to develop an integrated approach of a rapidly deployable process (ANL) to identify resilience gaps or areas of improvements, followed by a more comprehensive simulation activity (SNL) to identify and select potential resilience-enhancement investments to address those gaps.

5.3 Flexibility

Lab Team: Thomas Edmunds, Pedro Sotorrio, Lawrence Livermore National Laboratory (LLNL); Andrew Mills, LBNL; Thomas Jenkin and Paul Denholm, National Renewable Energy Laboratory (NREL)

> **Flexibility**
>
> The ability to respond to future uncertainties that may stress the system in the short term and require the system to adapt over the long term.
>
> These two temporal dimensions translate to different flexibility perspectives: (1) an operational viewpoint that relies on the agility of a static electrical network to adjust to known or unforeseen changes, for instance in load conditions or responding to sharp ramps due to error in renewable generation forecasts; and (2) a planning viewpoint that relies on changing the electrical network to respond to new regulatory and policy changes as well as to technological breakthroughs (ideally, without incurring stranded assets). The GMLC Metrics project focused on the operational viewpoint.

5.3.1 Scope of Metrics Development

The GMLC Metrics team focused on bulk power flexibility characterization because the bulk power system interconnects more variable production renewable energy generation technologies, and variability in these resources is currently managed at the bulk power level. The team recognized that additional sources of variability, such as distributed energy resources and the growing fleet of electric vehicles, affect the operation of the bulk power system. However, consultations with grid operators suggested that currently the biggest need for addressing flexibility characteristics stems from the variability of the solar and wind generation technologies. Therefore, the team focused on that cause.

The GMLC Metrics team worked with data from the California Independent System Operator (CAISO) and ERCOT to develop and demonstrate both new lagging and new leading metrics that measure the flexibility of the bulk power system in accommodating high penetrations of variable sources of renewable electricity.

Flexibility characteristics and attributes related to distribution systems planning and operations were not addressed. This omission was primarily driven by stakeholders’ interest in first exploring the bulk power-related flexibility concerns.

5.3.2 Motivation

Increased variability and uncertainty resulting from growing shares of variable renewable generation, such as wind and solar power, are increasing the need for flexibility in grid planning and operations. In the past, static measures of (and metrics for) generation resource adequacy were generally sufficient to assure reliability. Going forward, power systems that have larger shares of wind and solar generation will also require supplementary sources of flexible generation (and load) to accommodate continuously varying and sometimes large swings in the output from wind and solar generation.1 The goal of these flexible sources is to balance load and generation by assuring the “net load” or difference between total system load and the output from wind and solar generation is always met.

Static measures of generation adequacy are not capable of capturing the requirements for these flexible sources of generation. For example, in the past, a traditional loss-of-load probability analysis could be used to develop a simple metric like a planning reserve margin that would be sufficient to assure reliability. Such a planning reserve margin, alone, is not sufficient to assure adequate reliability because of the increased variability and uncertainty associated with operating a power system with significant penetration of wind and solar generation. As a result, there is growing recognition that traditional assessments of reliability need to be augmented with additional measures that adequately capture these issues related to flexibility.

5.3.3 Outcomes/Impacts

The GMLC Metrics team developed both new lagging and leading metrics to measure aspects of operating power systems that have high penetrations of wind and solar generation.

The team developed new lagging metrics using historical data provided by CAISO and ERCOT and also developed new leading metrics for flexibility using production cost simulations of the California grid. CAISO and ERCOT were selected because both grid operators have considerable experience operating power systems that have high penetrations of wind and solar generation, and hence have a wealth of operating data from which new lagging flexibility metrics could be demonstrated.

The lagging metrics focus on three aspects of the flexibility required for reliable operation of a power system reliably that has high penetrations of wind and solar generation: (1) minimizing over-generation by traditional generation sources when the output from wind and solar is high; (2) ramping traditional generation quickly and for extended periods during the late afternoon when solar generation decreases and system load increases; and (3) dealing with the inherent uncertainty involved in forecasting the output from wind and solar generation.

The team identified measures that express the relevant dimension of each aspect of flexibility and then posited indicators or metrics of inflexibility for each dimension. See Table 5.2.

[1] See, for example: Edmunds T, O Alzaabi, and A Mills. 2017. *Flexibility Metrics to Support Grid Planning and Operations*. LLNL-CONF-738350, Siebel Energy Institute Future Markets Workshop, Washington, D.C., July 26, 2017, which was prepared as part of this GMLC Metrics project.

Table 5.2. Taxonomy of Lagging Flexibility Metrics

Dimension of Flexibility	Flexibility Demand	Indicator of Inflexibility
Over-generation	Ratio of peak to minimum	Renewable curtailment, negative prices
Ramping	Ramp rates of net demand	Price spikes, out-of-market actions
Uncertainty	Net demand forecast errors	Real-time price premium, cost of forecast errors

Over-generation is a particular concern for flexibility during periods when net demand is at a minimum. As a last resort, grid operators will actually curtail the output from wind or solar generation when market-based options for balancing load and generation have been exhausted. Figure 5.3 shows the times of day and year and the amounts of curtailed renewable energy for CAISO over a 5-year period. The figure indicates that curtailments have been increasing over time, particularly around the noon hour when solar generation is at a maximum.

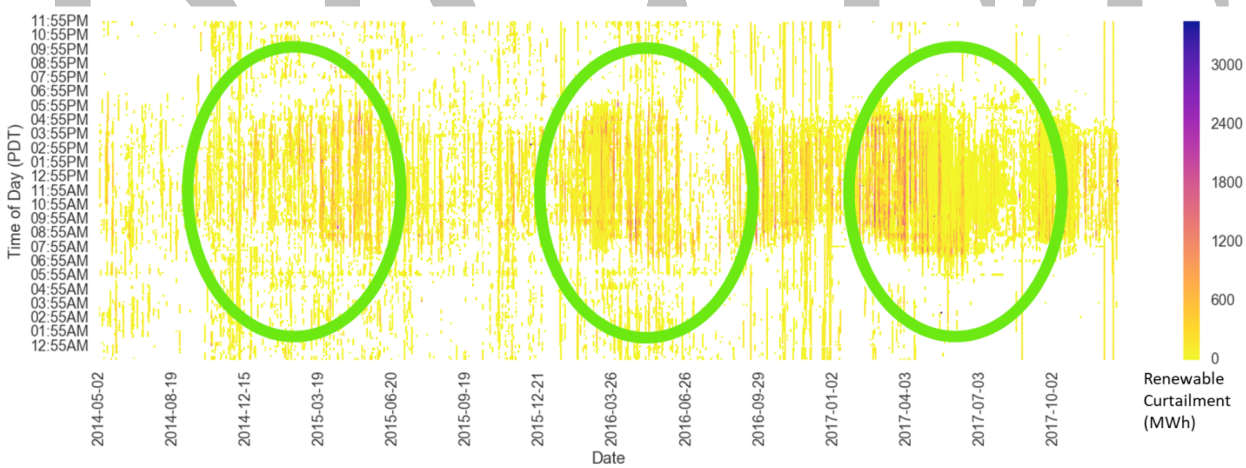


Figure 5.3. CAISO Renewable Curtailment (MWh)

The team also developed new <u>leading</u> metrics of flexibility and demonstrated them using production cost simulations of the California grid.[1] 4 shows an example of the application of a production cost model to evaluating system flexibility using three different flexibility metrics—*renewable curtailment, operational savings,* and *renewable economic carrying capacity*. The example is drawn from a study of the California grid under increased penetration of solar photovoltaics (PV) (Denholm et al. 2016). Four flexibility strategies were analyzed and compared relative to the base case: (1) added 1,290 megawatts (MW) of new storage, roughly following the California storage mandate; (2) changed the instantaneous variable generation (VG) penetration limit from 60 percent to 80 percent; (3) removed a 25 percent local-generation

[1] A production cost model simulates a least-cost unit commitment and dispatch over a period of time to establish which resources—generators, storage, or demand response—are required to be online to meet the electricity demand and supply reserves for operational reliability, and to satisfy other system constraints.

requirement; and (4) allowed curtailed VG to provide upward regulation, contingency, and flexibility reserves.

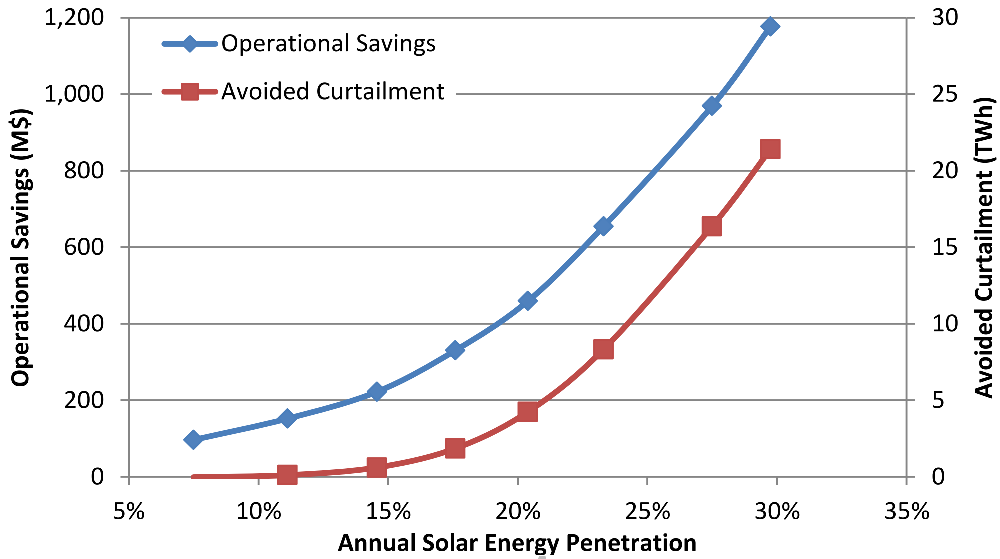


Figure 5.4. Operational Savings and Curtailment Reduction Associated with Added Flexibility

Figure 5.4 shows the leading flexibility metrics *operational savings* and *avoided renewable curtailments* as a function of PV penetration relative to the "business-as-usual" scenario that represents traditional operating practices prior to 2016, including multiple restrictions on the flexibility of thermal power plants, interaction with neighboring regions, and provision of reserve services from VG. The increased operational flexibility case represents changes that are under way and will likely be implemented by 2020 (CPUC 2015). These changes include allowing greater use of VG for provision of reserves and reliability services, as well as the addition of more than 1,000 MW of new storage capacity in response to the California storage mandate (Eichman et al. 2015).

5.3.3.1 Summary of Accomplishments

The accomplishment of the GMLC flexibility metrics team includes the verification of lagging flexibility metrics (Table 5.2) for their use as indicators to represent historical trends of flexibility (i.e., has the system become more or less flexible) with respect to over-generation, ramping, and uncertainties in the resource forecast. With these insights, they proposed to use them as leading flexibility metrics as well to estimate the outcome of operational interventions or technology deployments.

5.4 Sustainability

Lab Team: Garvin Heath, Annika Eberle, Jordan Macknick, and Maninder Thind, NREL

Sustainability
The ability to provide electric services to customers while minimizing negative effects on humans and the natural environment.
Note that sustainability is sometimes defined as including three pillars: (1) environmental, (2) social, and (3) economic. The Grid Metrics team focused only on the environmental pillar.

5.4.1 Scope of Metrics Development

The GMLC Metrics team focused on two areas:

1. Greenhouse gas (GHG) emissions from U.S. electricity generation: The GMLC Metrics team reviewed and compared the major sources of information about GHG emissions from U.S. electricity production, identified a data gap common to all of them that is anticipated to grow through grid modernization activities (specifically, a lack of consistent and complete information about emissions from smaller generation sources), and then worked with the U.S. Energy Information Administration (EIA) to close this gap.
2. Water dependency of U.S. generation capacity: The GMLC Metrics team assessed current metrics for U.S. power plant-driven water stressors and began developing a new metric to address a gap in the current metrics; it involves relating water demand to water availability.

The entire scope related to the sustainability of the economy and to social systems was beyond the scope of the current project. Furthermore, there is a rich body of research and literature about ecological sustainability, for which this project only addresses two very specific areas that are of high value and concern for grid expansions activities.

5.4.2 Motivation

5.4.2.1 Metrics for Greenhouse Gas Emissions Associated with Electricity Generation

Some sources of electricity produce GHG emissions and some do not. Grid modernization, among other things, enables all types of resources to be used to generate electricity. Understanding how GHG emissions change over time requires good data about the types and quantities of electricity generation sources.

The U.S. Environmental Protection Agency (EPA) and the EIA are the two primary federal agencies that report GHG emissions from the electric power sector. Between them, they produce at least eight data products, which report estimates for aspects of GHG emissions from this sector. Because these products were initially created for distinct purposes, it was not known (prior to this GMLC Metrics project) whether they fully captured GHG emissions from all generation sources of electricity, particularly, smaller generators that are expected to be used as distributed energy resources. In short, prior to this project, there was no information about whether a data gap existed, how big it might be, or, most importantly, if there was a gap, what would be the best way to address it.

5.4.2.2 Metrics for Water Stress Associated with Electricity Generation

Water-related metrics describe the water dependence of the generation of electricity. Traditionally, they are defined as some measure of consumptive usages or water withdrawals and they are compared with available water resources to express some measure of scarcity. However, water-related metrics are often aggregated over a period of a year and a large region and, thus, lack the necessary temporal and spatial resolution to better understand when and where water scarcity occurs. For instance, existing water intensity metrics do not consider the total magnitude of the water use or the timing of energy activities. Furthermore, water scarcity definitions are inconsistent and do not factor into the actual effect of energy activities. Finally, total water use estimates fail to consider regional availability of water. A recent EPRI report states specifically that "additional metrics are needed" to fully understand the "location-based water scarcity," "water risk position," and "regional ecological impacts" of the energy sector (EPRI 2016a).

5.4.3 Outcomes/Impacts

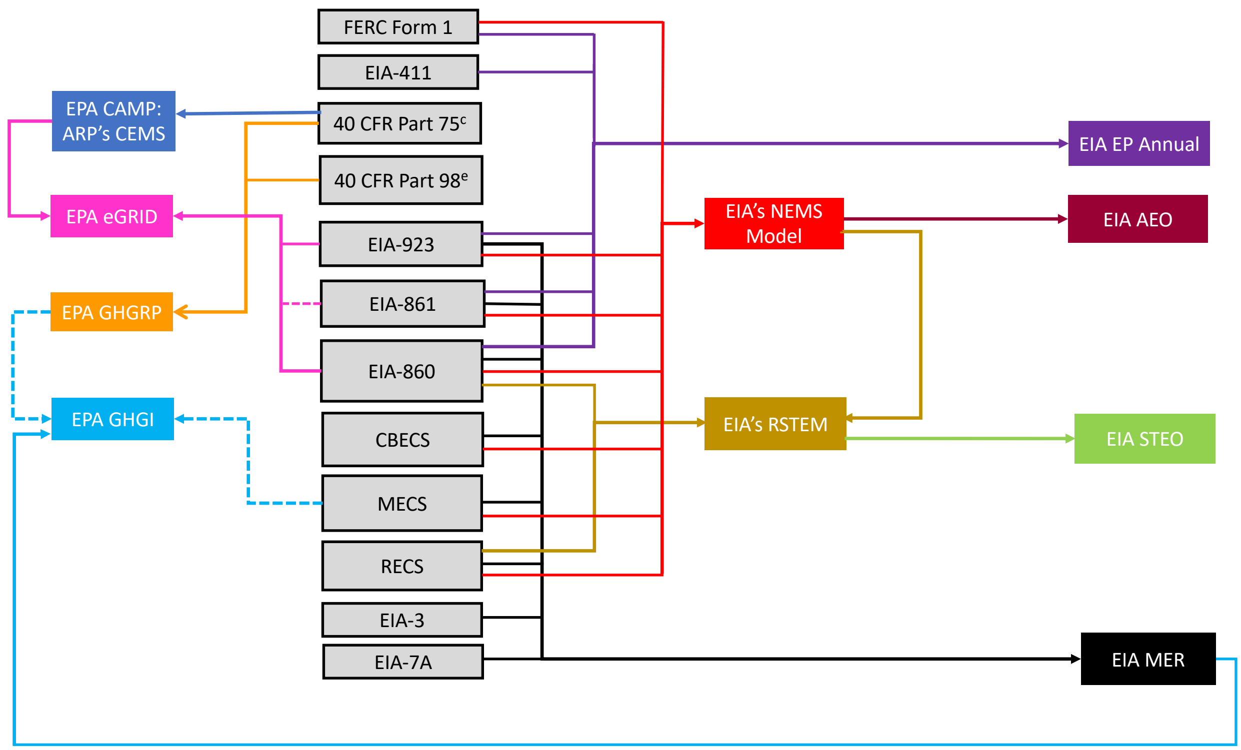
5.4.3.1 Metrics for Greenhouse Gas Emissions Associated with Electricity Generation

The GMLC Metrics team performed a detailed review of the eight data products that are produced by EIA and EPA about aspects of GHG emissions from the electric power sector. They found that none of the data products are able to fully capture the electric sector portion of GHG emissions from several energy sources that are projected to grow in the future: biopower, energy storage, combined heat and power, and small-scale (<1 MW), fossil-fueled distributed generation. Although these data gaps do not affect the data products' abilities to accurately track electric sector GHG emissions today, depending on how much these generation sources grow, the data products' abilities to accurately track future GHG emissions could decrease.

The team next identified the EIA survey forms that underlie the eight federal GHG data products (Figure 5.5) and completed a detailed review of six survey forms that had the greatest number of connections to data on these small, but growing generation sources: EIA-860, EIA-861, EIA-923, Commercial Buildings Energy & Consumption Survey (CBECS), Manufacturing Energy Consumption Survey (MECS), and Residential Energy Consumption Survey (RECS). The team focused on MECS, CBECS, and EIA-861 because internal combustion engines form the largest proportion of non-net metered distributed generators (DGs), and the majority of the internal combustion engines are found in the industrial and commercial sectors.

The team found that the MECS, CBECS, RECS, and EIA-861 could be augmented because they already track generation for generators of all sizes. Augmentation would require a modification of existing questions for these surveys to determine the portion of fuel consumption and generation that occurs at facilities below 1 MW of capacity. For example, MECS already collects data about onsite electricity generation for combined heat and power, solar, wind, hydro, and geothermal power, but it fails to differentiate these data by nameplate capacity, which would be necessary to monitor the growth of small-scale DG sources (those <1 MW vs. those >1 MW). Thus, the inclusion of additional survey language would be necessary to enable this distinction. Furthermore, additional language would be necessary to differentiate onsite electricity generation sources by their type and fuel for fuel cells-based generators, microturbines, or diesel or gasoline generator sets, instead of lumping them together into one "Other" category.

The team reviewed its findings with EIA survey managers and provided information about proposed language changes to individual surveys to provide more clarity for <1 MW generators. After reviewing the team's findings, the EIA survey teams for CBECS, MECS, and EIA-861 expressed interest in making changes to their surveys, and the team worked with the survey managers to develop changes to their survey questions. As part of each survey's three-year information-collection extension request, these changes were submitted for review by the Office of Management and Budget (OMB). OMB approved EIA's request to add a question about <1 MW sources to MECS and CBECS for the 2018 survey. These changes will allow future surveys to monitor how many establishments use DG and, thus, help anticipate and assess when more detailed data collection might be warranted.



Abbreviations: Environmental Protection Agency (EPA); Energy Information Administration (EIA); Federal Energy Regulatory Commission (FERC); Code of Federal Regulations (CFR); Commercial Buildings Energy & Consumption Survey (CBECS), Manufacturing Energy Consumption Survey (MECS) and Residential Energy Consumption Survey (RECS); Clean Air Markets Program (CAMP); Emissions & Generation Resource Integrated Database (eGRID); Greenhouse Gas Reporting Program (GHGRP); Greenhouse Gas Inventory (GHGI); Regional Short-Term Energy Model (RSTEM); National Energy Modeling System (NEMS); Electric Power Annual (EP Annual); Annual Energy Outlook (AEO); Short-Term Energy Outlook (STEO); and Monthly Energy Review (MER).

Figure 5.5. Mapping Underlying Data Sources (grey boxes) to the Eight Federal GHG Emission Data Products (boxes on the far left and right)

5.4.3.2 Metrics for Water Stress Associated with Electricity Generation

The GMLC Metrics team conducted a literature review and identified 154 water evaluation metrics. The team used the review to describe the multitude of approaches used to evaluate water availability, water stress, and water scarcity,[1] and evaluate the strengths, weaknesses, and gaps of each approach. The results of the review are shown in Figure 5.6.

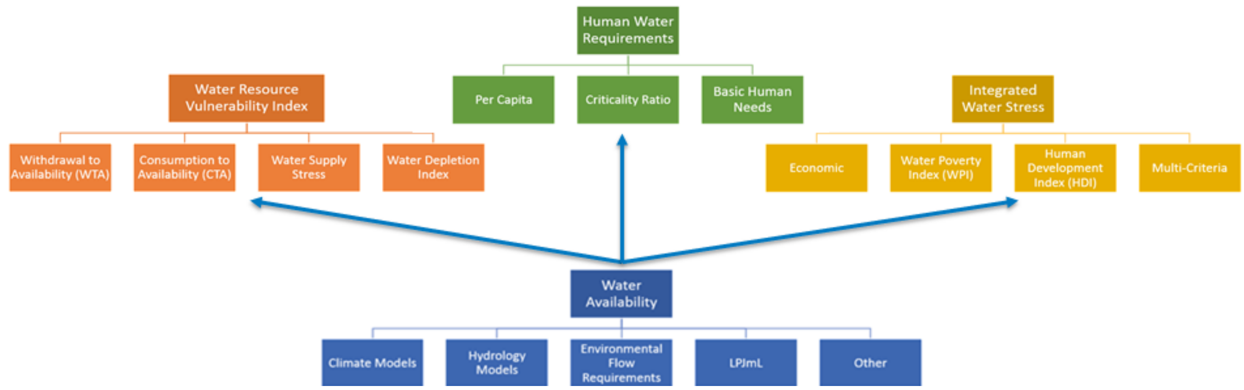


Figure 5.6. Landscape of Existing Water Stress and Scarcity Metrics

By conducting the literature review, the team identified a need for new metrics that would improve upon three separate existing metrics, for which data are often available. Those reflect better the risk profile of the electricity generation process at the location of the generation plant at the precise time when the metrics are needed to act upon. The following three metrics were identified to be augmented by considering how they interact:

- Water intensity: Currently defined as water withdrawal or water consumption per unit of energy activity on an average or annualized basis. We propose it should include reference to the total water use and total energy activity.
- Water scarcity and availability: Currently, there are no standard definitions of these terms, which are used inconsistently across the literature. We propose standardizing the types of water scarcity and clearly defining thresholds.
- Total water use: Currently defined as an annual value of water withdrawal or water consumption. We propose to refer to water use in the context of water scarcity and availability.

The team posited that a new metric is needed to quantify the use (both withdrawal and consumption) of water in the context of local and regional water availability across time. Such a metric is needed to express the risk or level of uncertainty that water may or may not be available for current and future generation plants.

[1] Water availability is defined as specific relation to water accessibility, obtainability, and overall source abundance available for use or consumption. Such sources include surface runoff, baseflow, and aquifer storage. Water stress is defined as the specific relationship to water strain caused by over withdrawal or unsustainable use practices caused by anthropogenic sources, such as overpopulation, agriculture, industrial intensities, or energy generation. Water scarcity pertains to the specific relationship to water shortages caused by general lack of water supply from natural causes, such as low precipitation, climate, or seasonal fluctuations.

The team's effort built upon recent, ongoing DOE and EPRI research to develop this new metric, tentatively titled Relative Water Risk (RWR).[1] The RWR is intended to be used when assessing the investment risk of proposed infrastructure deployments.

5.4.3.3 Summary of Accomplishments

Accomplishments related to sustainability metrics development are as follows:

- The sustainability metrics team identified a gap in the GHG reporting in the United States and proposed actionable recommendations for how to remedy the gap. The recommendations were submitted to EIA and are being evaluated by OMB.
- The team identified a gap in the metrics for adequately addressing the risk profile of thermal generation that requires water for cooling purposes. The team proposed a new metric to account for the risk or level of uncertainty that water may not be available for current or future thermal generation plants: the RWR (Relative Water Risk) metric.

5.5 Affordability

Lab Team: Dave Anderson, Sumitrra Ganguli, Alan Cooke, Madison Moore, PNNL

Affordability

The ability to provide electric services at a cost that does not exceed customers' willingness or ability to pay for these services.

5.5.1 Scope of Metrics Development

The GMLC Metrics team focused on affordability metrics that measure the impacts of electricity costs on residential customers' ability to pay for them (cost burden). The team developed new metrics expressing various aspects of cost burden for residential customers and discussed potential new metrics for businesses (commercial and industrial customers).

The team created a public-facing website for the residential sector that compiles publicly available data and displays affordability metrics at the state and county levels and demonstrated the use of the metrics and website for three remote village utilities in Alaska and a major electricity utility in California, Southern California Edison (SCE).

[1] See for example:

- U.S. Department of Energy-Office of Climate, Environment, and Energy Efficiency. 2017. *Quadrennial Energy Review 1.2: Environment Baseline Vol. 4: Energy-Water Nexus*. Washington, D.C.
- Electric Power Research Institute, Inc. 2016. Metrics to Benchmark Sustainability Performance for the Electric Power Industry. EPRI Technical Report: 3002007228, Palo Alto, California.
- Macknick J, E Zhou, M O'Connell, G Brinkman, A Miara, E Ibanez, M Hummon. 2016. *Water and Climate Impacts on Power System Operations: The Importance of Cooling Systems and Demand Response Measures*. NREL/TP-6A20-66714, National Renewable Energy Laboratory, Golden, Colorado.
- McCall J, J Macknick, D Hillman. 2016. *Water-Related Power Plant Curtailments: An Overview of Incidents and Contributing Factors*. NREL/TP-6A20-67084, National Renewable Energy Laboratory, Golden, Colorado..
- Tidwell VC, M Bailey, KM Zemlick, BD Moreland. 2016. *Water supply as a constraint on transmission expansion planning in the Western interconnection.* Environmental Research Letters 11 (12), 124001.

5.5.2 Motivation

Cost-effectiveness is the most well-known perspective from which the affordability of grid modernization activities is assessed. However, cost-effectiveness does not address an important, related, yet often incompletely considered aspect of affordability: namely, the cost burdens on customers that result from utility recovery of the costs of grid investments through electricity bills. The cost-burden connotes the notion that while grid technology investments may prove to be cost-effective in the aggregate, they also necessarily lead to obligations for customers to pay for them; these obligations may or may not be affordable (i.e., they may exceed the customer's willingness or ability to pay).

Cost burden is typically expressed as the proportion of income or revenue required to acquire a desired level of electricity service. For instance, for residential customers it could be the monthly electricity bill divided by household income. Customer cost burden can be tracked over time or compared across specific geographic areas of interest (service territory, state, balancing area, interconnect, etc.).

Customer cost-burden metrics are gaining in importance to individual utilities from the social responsibility perspective. Affordability metrics derived from customer cost burden may become a differentiator for utility service providers, in the context of socially responsible electricity delivery.

5.5.3 Outcomes/Impacts

The GMLC Metrics team focused initially on the residential sector. The team identified and then based its work on eight affordability metrics. The definitions are listed in Volume 6—the Affordability Reference Document. The affordability metrics proposed are as follows:

- household electricity burden
- household electricity affordability gap
- household electricity affordability gap index
- household electricity affordability headcount index
- annual average customer cost
- average customer cost index
- commercial electricity marginal revenue product
- industrial marginal revenue product.

The team developed a geographic dashboard tool to display the metrics spatially. The tool displays each metric for all 50 states in one view and all counties within the states in another view (see Figure 5.7). From this global view, the user can drill down to increasing levels of granularity.

The affordability headcount gap is a principal metric that is displayed on the dashboard. The affordability headcount gap is a measure of the percentage of households within a state or county that faces monthly electricity costs that exceed a threshold percentage of their monthly income. The threshold is based on rules of thumb from the housing affordability literature, which suggest that total housing costs should not exceed 30 percent of household income to be affordable, and utility costs should not exceed 20 percent of total housing costs to be affordable. Therefore, 20 percent of 30 percent equals the 6 percent figure deemed to be the affordable burden for household utility costs. Thus, if electricity costs represent half the energy costs of the household, the affordable electricity burden would be 3 percent. The actual electricity percentage would vary by utility but would be expected to range between 2 and 6 percent. Expressed in this fashion, it is a measure of the percent of households for whom electricity is not affordable.

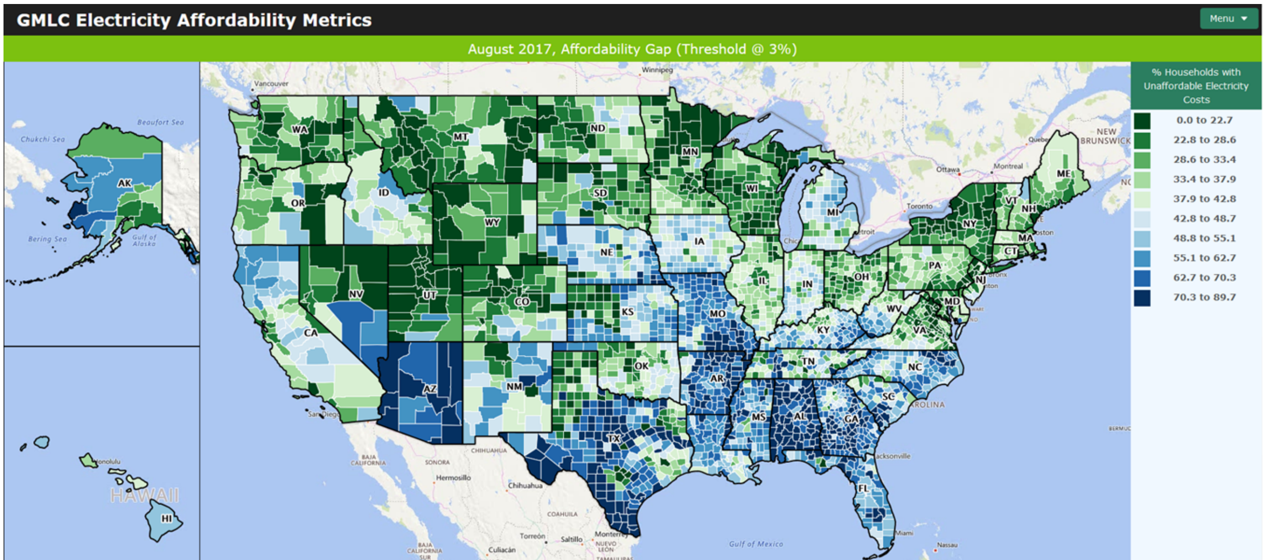


Figure 5.7. County View of the Affordability Dashboard Tool

The team conducted two case studies with industry partners to demonstrate the usefulness of the tool and affordability metrics it displays.

The first case study was conducted in partnership with the Alaska Microgrid Project (AMP), a sister GMLC project. The AMP designed renewable-based microgrids for three remote Alaskan villages— Chefornak, Kokhanok, and Shungnak—as a means of mitigating the extreme costs associated with transporting petroleum-based fuel to their remote locations for power generation. There is clear linkage with the affordability metric, because the purpose of the AMP is to demonstrate that renewable resource solutions can reduce fuel costs, and therefore customer costs to villagers throughout Alaska.

The team found that, based on increasing average cost burdens, electricity affordability has declined through 2015 for Chefornak because electricity costs have increased faster than incomes. The team found that electricity has become slightly more affordable for Kokhanok because of a slight drop in electricity costs, paired with stable incomes. Finally, the team found that electricity affordability has improved for Shungnak because average electricity costs have declined slightly, while incomes have remained relatively stable.

The second case study was conducted in partnership with SCE using summarized billing data they provided for 2015–2017. This case study compared baseline metrics derived from public data sources to the same metrics derived from the utility's proprietary customer billing data. The interest of both parties is to identify and test whether the residential sector metrics developed in this work using public data sources would produce metric values similar to estimates derived using the unpublished, utility-supplied data.

Results were developed at the utility level, the county level, and the census tract level for several metrics for the years 2015, 2016, and 2017. A comparison of published data from EIA's Form-861 and SCE's unpublished data showed good agreement for utility level metrics, such as the number of customers and the usage of electricity. Results analyzed at the county level also indicated that the public data do a reasonable job in comparison to the unpublished data for estimating customer average cost burdens for the core counties of the SCE service area (Los Angeles, Ventura, San Bernardino, Riverside, Orange) and are less effective for the edges of the service area where SCE may not dominate the market. Census tract-level results were not as encouraging when estimating example metrics other than simply comparing the number of customers and electricity sales. In Volume 6, the Affordability Reference Document, a complete examination of the trends in metrics across the limited 3-year period is provided. In general, spatial comparisons between metrics using the SCE data and fully public data were best for 2015 and became progressively less encouraging for 2016 and 2017.

This effort has also resulted in the development of entirely new metrics that address electricity affordability in the commercial and industrial sectors. Unlike residential electricity customer affordability, electricity affordability affects the profit function of a business. Commercial and industrial customers use electricity as an input to the production of goods and services. Volume 6 offers a novel approach to analyzing electricity affordability for businesses.

Electricity costs affect business profitability. We related the profitability of a business to the affordability of its electricity cost by stating that if a business is operating profitably, then electricity costs are found to be affordable. If increased electricity costs would flip a business from reaping profits to incurring losses, then electricity costs would be found to be unaffordable, without additional adjustments in the production function of the business to offset the effects of the electricity costs. Thus, metrics have been developed to attribute the effect of electricity costs on profits. The marginal revenue product of electricity measures the benefits (or losses) attributable to acquiring more electricity in the operation of the firm and, in aggregate, entire industries.

Examples of the marginal revenue product of electricity have been developed for the automotive industry (industrial customers) and the food services industry (commercial customers). State-level results for these industries and plant- or firm-level results within states are presented as examples of the metrics. In nearly all cases, electricity is within the affordable threshold using this metric.

5.5.3.1 Summary of Accomplishments

The following eight new metrics were proposed by the team and express the cost burden of customers of electric services.

- household electricity burden
- household electricity affordability gap
- household electricity affordability gap index
- household electricity affordability headcount index
- annual average customer cost
- average customer cost index
- commercial electricity marginal revenue product industrial marginal revenue product.

5.6 Security

Lab Team: Steve Folga, Jessica Trail, Debra Fredrick, Shabbir Shamsuddin, ANL

> **Security**
> Presidential Policy Directive 21 defines "security" as "reducing the risk to critical infrastructure by physical means or defense cyber measures to intrusions, attacks, or the effects of natural or man-made disasters." This project focused on metrics for physical security.

5.6.1 Scope of Metrics Development

The GMLC Metrics team adapted a U.S. Department of Homeland Security (DHS)-developed physical security metric, along with the underlying survey instrument and software system used to calculate and display the metric for application by electric utilities to assess their security postures. The system enables utilities to assess their current security posture and evaluate the effectiveness of investments to change or modify aspects of their current posture.

The entire area of cybersecurity was beyond the scope of this project effort. It was decided early on that other DOE and DHS programs that have much larger budgets are better suited to addressing the metrics development of cybersecurity for the U.S. electric infrastructure.

5.6.2 Motivation

Physical security planning in the electricity sector does not yet possess a long-accepted canon of techniques for measurement and does not yet have established metrics. In other industries, the security community uses metrics, such as Annualized Loss Expectancy (ALE), as a means of justifying budgets for security-related expenditures or actions.[1]

Application of the ALE approach in the electricity sector is difficult because the ALE approach depends on prior quantification of risks (i.e., annualized rates of occurrences); these risks are not yet well-understood and are much less quantifiable with precision for the electric sector. For example, there are no actuary tables derived from decades of data collection that can tell us what adversaries will do, how often they will do it, and how much it will cost the electric sector to respond when they do it.

The absence of widely understood and accepted metrics for security is an emerging and national concern. The Congressional Research Service recently concluded that the electricity grid's physical safeguards are "a work in progress" and stated that there is currently no comprehensive accounting of changes in physical security throughout the sector.[2] It also concluded that security metrics (for both cyber and physical security) have consistently been a challenge because of evolving threats and vulnerabilities. It emphasized that anecdotal information in the public domain suggests that these threats and vulnerabilities are significant and widespread.

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[1] ALE is the monetary loss that can be expected for an asset due to a risk over a 1-year period, and it is calculated by multiplying the single loss expectancy by the annualized rate of occurrence.

[2] Congressional Research Service (CRS). 2018. *NERC Standards for Bulk Power Physical Security: Is the Grid More Secure?* Accessed Nov. 15, 2018 at https://fas.org/sgp/crs/homesec/R45135.pdf..

5.6.3 Outcome/Impacts

The GMLC Metrics team adapted a physical security metric, developed originally by DHS, for specific application to and use by electric utilities.[1] The purpose of the metric is to enable electric utilities, their regulators, and stakeholders to assess the physical security posture or readiness of the utility.

The metric is called the Protective Measures Index (PMI). It has nine constituents and is developed through a systematic process of assigning values to the constituents. The PMI structure is shown in Figure 5.8.

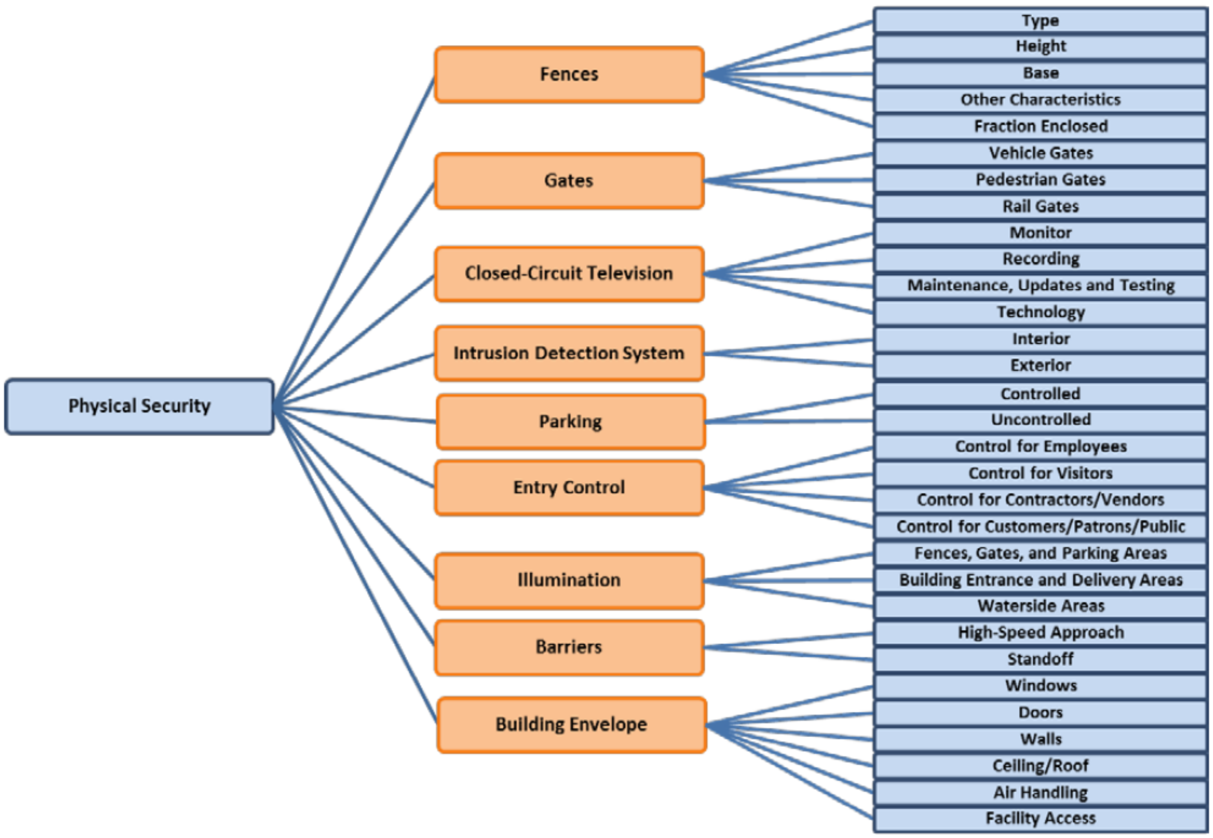

Figure 5.8. Level 1 and 2 Subcomponents for Physical Security (Argonne 2013)

The team developed a customized survey instrument for assigning values to the constituents within the PMI and adapted an existing software tool for calculating and displaying the PMI. The survey instrument guides a utility analyst through a set of questions to assess the various underlying aspects of PMI and assign numerical or qualitative values. The outcome of the survey instrument is a ranking that scores relative values against a default value or peer groups, such as

[1] Physical security is one of six major security-related components addressed by the DHS Enhanced Critical Infrastructure Protection Initiative. The other five components address security force, security management, information sharing, and security activity history/background. (Argonne National Laboratory. 2013. *Protective Measures Index and Vulnerability Index: Indicators of Critical Infrastructure Protection and Vulnerability*. Available at http://www.ipd.anl.gov/anlpubs/2013/11/77931.pdf)

utility organizations of similar size. Figure 5.9 provides an example of the survey output, as displayed by the software tool.

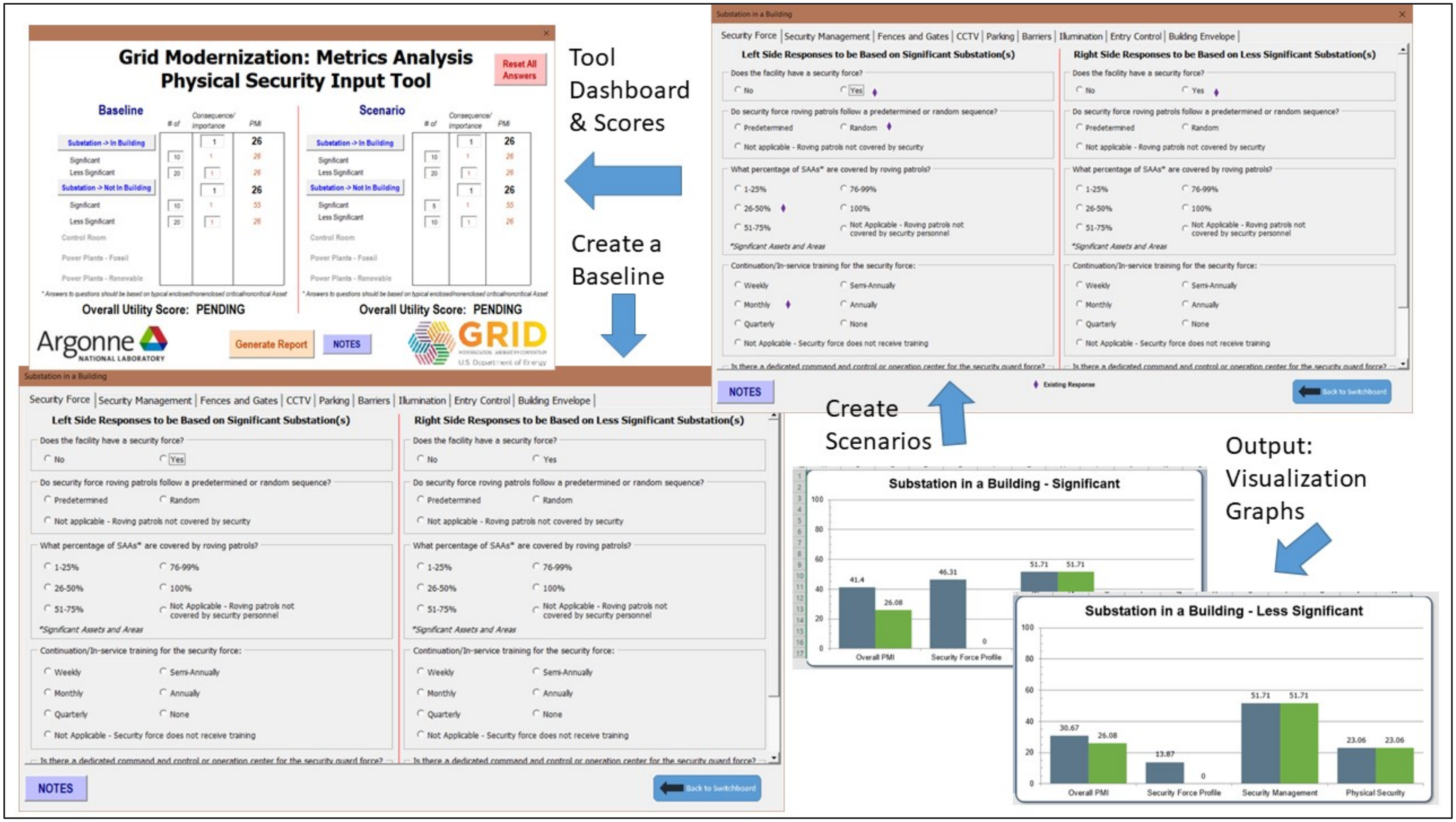

Figure 5.9. Example PMI Dashboard for Consideration as Physical Security Metrics

The team envisioned use of the tool by electric utilities to self-assess their current security posture, identify current strengths and weaknesses, and evaluate how targeted investments could improve the overall PMI value or specific underlying constituents of the PMI.

To this end, the team sought an electric utility partner to demonstrate the approach. At the time this reference document was in preparation (2020), the team was in active discussions with the Electricity Information Sharing and Analysis Center about the demonstration.

5.6.3.1 Summary of Accomplishments

The GMLC security metrics team proposed 1 new metric to represent physical security and 31 sub-metrics. Furthermore, the team developed an automated survey tool to elicit the information for populating the sub-metrics.

5.7 Stakeholder Mapping

Lab Team: Gian Porro and Monisha Shah, NREL

The GMLC Metrics team complemented the stakeholder engagement activities pursued by each of the area-specific metrics teams by systematically categorizing the grid metrics that are currently in use for grid investment and modernization-related decisions made by a wide range of stakeholder groups. The purpose of this task was to document the breadth of metrics areas used in recent grid investment and modernization decision-making.

5.7.1 Motivation

Each of the area-specific metrics teams identified and partnered with key stakeholders who usually represented very specific metric areas. This approach provided deep but narrow insights.

As a complement to these activities, the GMLC Metrics team attempted to document how cross-cutting metrics and information are currently being used in grid investment and modernization decision-making. The team used recent literature that documented the criteria underlying grid investment decisions. The GMLC Metrics team analyzed a set of publicly available documents, and collected, cataloged, and mapped the metrics into the six broad metrics areas discussed in previous metric-specific sections of this document.

5.7.2 Outcomes/Impacts

The Grid Metrics team identified and reviewed 20 examples of grid upgrade and modernization decisions related to investments, or related to market design or policy issues. The examples were drawn from proceedings in seven states and four regional transmission organizations or ISOs. They addressed supply- and demand-side generation, transmission, cost allocation, research development and demonstration, and market monitoring. The examples also varied in terms of the stakeholder perspectives (i.e., ratepayers, load serving entities, grid operators, and public utility commissions) and the range of technology decisions (i.e., distributed energy, nuclear, and smart metering) considered. Table 5.3 illustrates the types of grid investment and modernization decisions, the examples selected to examine how they were made, and the types of analyses or considerations that were involved.

Table 5.3. Review Summary: General Methods

Decision/ Investment Area	Decision/ Investment Sub-Area	Jurisdiction/ Docket or Report	Cost-Benefit Analysis: Project	Cost-Benefit Analysis: Project/ Portfolio	Performance Reporting	Levelized Energy Cost	Cost of New Entry	Cost Allocation Protocol	Proposal Evaluation Critera	Competitive-ness Analysis	Market Power Analysis	Qualitative	Varied by Specific Issue
Generation, Storage, Demand-side	Performance-based ratemaking	IL- ComEd (11-0772)			■								
	Distributed generation	NY - REV (14-M-0101)	■										
		TVA - DG-IV	■										
	Smart metering	IL - Ameeren (12-0244) ComEd (14-0212)	■										
	Energy storage	CA - SCE (16-03-002)	■										
	Resource planning & procurement	CO - PSCO (Related to C17-0316)				■							
	Net metering	NV - NV Energy (17-07026)										■	
	Generation retirement	IL - Nuclear (HR 1146)	■										
		NY - CES	■										
		CA - PG&E (18-01-022)											■
	Capacity	PJM - CONE					■						
Transmission	Portfolio	MISO - MVP	□	■									
	Clean energy zones	TX - CREZ	□	■									
	Economic assessment	CAISO - TEAM	■ Supple-mented with production cost simulation										
Cost Allocation	Multi-state	OR - PacifiCorp (UM 1050)						■					
Research, Development and Demonstration	State program solicitation	CA - EPIC	□						■				
		NJ - Microgrid Feasibility		□					■				
Market Monitoring	Market competition	TX - Market Competition								■			
		TX - TXU (34061)									■		
		ISO-NE - Market Assessment									■		

Notes
■ Primary method applied
□ Secondary focus/application, or subset of a broader set of criteria

Table 5.4 identifies which of the six GMLC metric categories and sub-categories were used primarily or secondarily in informing the decisions made in each example.

Table 5.4. Review Summary: Metrics Sub-Categories Applied to Inform Decisions or Investments

		Generation, Storage, Demand-side										Transmission			Cost Allocation	RD&D		Market Monitoring		
		PBR	DG		SM	ES	IRP	NEM	Generation Retirement			Cap	Port	CEZ	Econ	Multi-state	State program solicitation		Market competition		
Metric Category	**Metric Sub-Category**	**IL**	**NY**	**TVA**	**IL**	**CA**	**CO**	**NV**	**IL**	**NY**	**CA**	**PJM**	**MISO**	**TX**	**CAISO**	**OR**	**CA**	**NJ**	**TX**	**TX**	**ISO NE**
Affordability	Consumption/ Revenue	●			●	●					●	●				●	●		●		
	Investment Costs		●									●		●							
	Integration Costs					●	●		●							●					
	Operations Cost												●	●							
	Operations Cost												●								
	Compliance Costs		●	●						●											
	Program Costs		●		●	●							●			●	●				
	Avoided Costs		●	○	●		●				●		●	●	●		●				
	Value of Reliability		●		○										●						
	Retail Rates		●	●					●										●		
	Benefit-Cost		●							●	●	●	●	●	●						
	Equity				○					●											
	Market Power																			●	●
Reliability	Resource Adequacy	●				●	●		●			●	●	●							
	Dynamic												●								
Sustainability	Environmental		●		○				●	●				●			●				
	Economic Impact				○				●	○	●						●				
	Health				○																
	Equity	●			○																
	Other Societal				○								●	●			●				
Other						○	●											●			

Notes
● Considered in decision
○ Presented or recommended, but not necessarily considered in decision

The following insights were gained by completing this task:

- Whenever cost-benefit analyses were performed, metrics addressed only very specific and narrow feature sets of any technology or policy assessment. While narrowly defined cost-benefits analyses are not inherently insufficient for informed decision-making, sometimes they do not recognize the significant implications of grid operational aspects such as their impacts on bulk power flexibility and resilience.
- New metrics areas such as resilience, security, and flexibility are not applied, especially, not in any quantifiable manner.
- The literature analyzed indicated that metrics in the affordability category were commonly defined as cost-effectiveness of a technology or a project. Affordability was then interpreted as the most cost-effective option, rather than how it affects the ability of the ratepayer to afford the potential effects on his/her bill payments.

The insights gained from this metrics mapping exercise could inform follow-on activities designed to facilitate a broader implementation and institutionalization of the metrics developed by this GMLC project as well as additional metrics-development efforts. The following follow-on actions are proposed for consideration:

- Engage custodians of existing cost-benefit analysis methodologies and performance ratemaking frameworks in targeted discussions about including specific refined metrics in the future. For instance, make more explicit the consideration of specific resource adequacy metrics in net benefit calculations, including at the distribution system level.
- Work with system planners and operators to explore how traditional assessments conducted to understand the reliability implications of bulk power system additions and retirements could be extended and strengthened with the inclusion of flexibility and resilience metrics.
- Partner with community and utility planners to develop and test cost-benefit analysis methodologies specifically designed to assess resilience and security-related investments.
- Work with DOE to develop decision criteria based on some new metrics to assess proposals for further DOE investment in grid modernization research, development, and demonstration (RD&D). This may allow the authors of proposals to better characterize the impacts of the work proposed and the reviewers to review the potential of effects of RD&D.

6.0 What's Next?

The GMLC Grid Metrics project has been highly successful in accomplishing the objectives set forth by DOE. As noted, two classes of activities will proceed after this project. First, efforts will continue to socialize the findings from the project. In most instances, the end-state for these efforts will be formal adoption of the metrics in ongoing grid modernization activities, as evidenced, for example, by their inclusion in industry standards and best practices. In almost all metrics areas, the accomplishments, outcomes, and findings were generated during Years 2 and 3 of the 3-year project. They require more vetting with the broader community beyond individual partners. Second, DOE deploys the experts, as a team, in support of its own future grid modernization activities. An early example of this deployment has been the formation of a Laboratory Valuation Analysis Team (LVAT) to support the Resilient Distribution System (RDS) demonstration activities. The LVAT team has been tasked to produce a consistent valuation of all six RDS demonstration projects using metrics and processes, several of which were developed during this Grid Metrics project.

More cross-cutting applications of metrics are envisioned to be used in the future to inform decision-makers about how to address and consider technology and policy options from a more holistic perspective than is currently being done. The proposed metrics may inform generation, transmission, and distribution planning activities to incorporate a broader scope of outcome and performance metrics that may include flexibility, resilience, sustainability, affordability, and security considerations, in addition to the conventional reliability and least-cost criteria. Finally, the outcome of this project has laid the foundation from a technical and skill development perspective for future grid modernization RD&D efforts.

DRAFT

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