MODERN DISTRIBUTION GRID (DSPx)

Volume II: Advanced Technology Maturity Assessment

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DISCLAIMER

COVER PHOTO CREDITS

Top: The Ántukš-Tińqapapt or "sun trap" solar array recently installed by the Confederated Tribes of the Umatilla Indian Reservation in Oregon. Courtesy of the U.S. Department of Energy.

Middle: NREL-owned electric vehicles below solar canopy at the Vehicle Testing & Integration Facility. Courtesy of the U.S. Department of Energy.

Bottom Left: Smart Meters in Washington, DC. Photo by Patricia D'Costa. Courtesy of ICF.

Bottom Right: Lotus Energy designed a solar plus storage system. Photo by Christine Bennett. Courtesy of the U.S. Department of Energy.

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GLOSSARY

Advanced Metering Infrastructure (AMI) typically refers to the full measurement and collection system that includes meters at the customer site, communication networks between the customer and a service provider, such as an electric, gas, or water utility, and data reception and management systems that make the information available to the service provider.[1] It is also referred to as a smart meter system. AMI communications networks may also provide connectivity to other types of end devices such as distributed energy resources (DER).

Customer Information System (CIS) is the repository of customer data required for billing and collection purposes. CIS is used to produce bills from rate or pricing information and usage determinants from meter data collection systems and/or manual processes.[2]

Customer Relationship Management (CRM) is a system that provides tools for documenting and tracking all customer interactions. CRM also provides analytical tools to track and adjust marketing campaigns, forecast participation rates, and move customers from potential participants to fully engaged customers.[3]

Conservation Voltage Reduction (CVR) is an operating strategy of the equipment and control system used for VVO that reduces energy and peak demand by managing voltage at the lower part of the required range.[4]

Energy Management System (EMS) is a system to monitor, control, and optimize the performance of the transmission system and in some cases primary distribution substations.[5] The EMS is the transmission system's analog to the DMS.

Fault Location, Isolation, and Service Restoration (FLISR) include the automatic sectionalizing, restoration and reconfiguration of circuits. These applications accomplish distribution automation operations by coordinating operation of field devices, software, and dedicated communications networks to automatically determine the location of a fault, and rapidly reconfigure the flow of electricity so that some or all customers can avoid experiencing outages. FLISR may also be known as Fault Detection, Isolation and Restoration (FDIR).

Global Positioning System (GPS) is a system of satellites and receivers that determines the position (latitude, longitude, and altitude) of a receiver on Earth.[6] GPS is also used as a source of precision time signals for device synchronization.

Internet Protocol (IP) Packet Communication uses IP digital protocol to handle data in variable length packets that are routed digitally to their destinations asynchronously rather than making a fixed circuit connection or relying on fixed time intervals.[7]

Microwave Radio communications are high-frequency radio systems that may be point-to-point or point-to-multipoint systems. They are widely used for substation and SCADA communications.[8]

Reclosers are electro-mechanical devices that can react to a short circuit by interrupting electrical flow and automatically reconnecting it a short time later. Reclosers function as circuit breakers on the feeder circuit and are located throughout the distribution system to prevent a temporary fault from causing an outage.[9]

Reliability Metrics[10] are used to assess the operational performance of the distribution system in terms of reliability and resilience. Some of the more commonly used metrics are:

- SAIDI (System Average Interruption Duration Index) – the total duration of interruptions for the average customer during a given time period. SAIDI is normally calculated on either a monthly or yearly basis; however, it can also be calculated daily, or for any other time period.
- SAIFI (System Average Interruption Frequency Index) – the average number of outages a customer experienced during a year.
- CAIDI (Customer Average Interruption Duration Index) – if a customer experienced an outage during the year, the average length of time the customer was out of power, in hours.
- MAIFI (Momentary Average Interruption Frequency Index) – the average number of outages a customer experienced during the year that are restored within five minutes.

INTRODUCTION

The U.S. Department of Energy is working with state regulators, the utility industry, energy services companies, and technology developers to determine the functional requirements for a modern distribution grid. These functional requirements are needed in order to enhance reliability, operational efficiency, and integrate and utilize distributed energy resources (DER). The objective is to develop a consistent understanding of requirements to inform investments in grid modernization. The requirements include those needed to support grid planning, operations, and markets.

This report is part of a four-volume Modern Distribution Grid Report intended to support discussions on modernizing the electric distribution grid. The Modern Grid Guidebook provides the overall grid architectural approach, and planning process and methods. This Guidebook is based on the learnings from practical applications of the DSPx frameworks and offers an updated multi-step framework to support the development of grid modernization strategic plans and implementation plans. This Guidebook replaces the earlier Volume III.

The updated Volume I and II are addendums to the Guidebook providing more depth and analysis to support the decision process and methods discussed in the Guidebook. This Volume II v2.0 identifies the enabling technologies linked to the functionalities identified in Volume I v2.0 of this Modern Distribution Grid report. As such, this volume, combined with Volume I, enables a detailed assessment of grid modernization from state policy objectives to the related functional requirements and ultimately the technology needed. Accordingly, this volume indicates the supporting technologies that can be used to implement and support this vision of a modern, holistic grid. The technologies are presented within pertinent overarching “technology categories,” and represented by means of a hierarchical taxonomy.

OVERVIEW

This volume provides an overview of key technologies that will be necessary for the operation of the modern distribution grid to ensure reliable, safe operation while enabling customer choice and increasing integration of DER. Regulators and industry can use This volume to identify distinct technology categories, systems, analytics, and tools as they embark on grid modernization and DER integration activities within their jurisdictions.

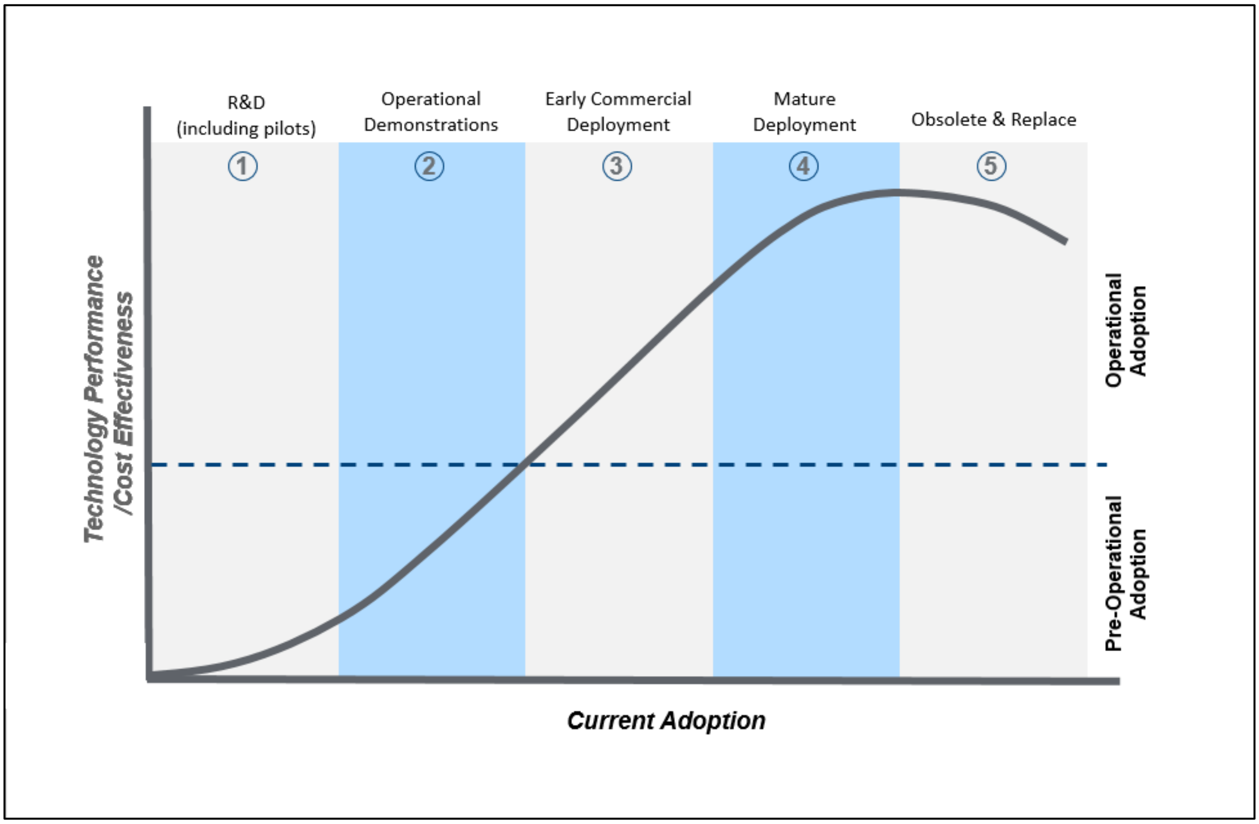
The technology groupings and hierarchical structures identified herein result from research performed by the Core Team, as well as discussions and input from stakeholders in the initiative. In the following sections, technologies are organized into “technology categories” within the three broad functional areas described in Volume I: 1) Distribution System Planning, 2) Distribution Grid Operations, and 3) Distribution Market Operations. These groupings are illustrated in the form of a relational hierarchy. While this structure is used to simplify the presentation in this volume, several of the technologies identified may support multiple functions across the three areas. The one-to-many functional relationships are discussed further in the Guidebook.

The following information is provided for each technology category: a) definition of the identified technologies, b) assessment of the current state of the respective technology's adoption on the U.S. distribution grid, and c) identification of technology gaps associated with supporting the functionalities covered in Volume I. A discussion of the capital budgeting and expenditures required to acquire or develop these planning technologies is not within the scope of this report.

TECHNOLOGY ADOPTION ASSESSMENT

Each of the following chapters includes an assessment of each identified technology's position on the utility industry technology adoption cycle. In several instances, there are technologies that are widely used in other industries, but are at an earlier stage of adoption in the electric industry. Figure 1 shows the typical progression of the technology adoption cycle from research and development (R&D) through mature deployment and eventual obsolescence. The modern grid technologies identified in this volume are used to plan and operate critical electric delivery services with reliability and safety as key performance metrics. This drives a technology adoption cycle that is, of necessity, fairly conservative, meaning the technology must be demonstrated or proven to be reliable. This is similar to other industry sectors with critical infrastructure and services that demand very high levels of operational performance, such as the airline industry.

Figure 1: Technology Adoption Cycle



The technology adoption cycle X-axis, "**Current Adoption**," identifies the stage of adoption for a specific technology. The horizontal dashed line represents the crossover point from stages that are **Pre-Operational** (i.e., under test and/or evaluation) to those designated as **Operational** (i.e., proven and in production use). This happens as a technology is recognized as "proven" through referenceable implementations of comparable operational use and scale. The transition is evaluated as having occurred when two conditions are met:

1) More than three reference operational production implementations of similar scale and scope exist; and

2) Sufficient market choice exists. This occurs when more than two vendors offer commercially available products that meet most of the requirements.

Placement along the **Current Adoption** axis also normalizes the time horizons of different technologies. For example, communication technologies generally have much shorter lifecycles than electric power technologies, but both follow the same cycle of adoption from R&D through mature deployment and obsolescence. Hence, to compare technologies with different life cycle lengths, the axis is normalized to total life.

R&D (including Pilots): This is the initial stage during which technology concepts are developed into initial working products. Features, functions, and implementations change rapidly as initial lab testing and limited field pilots identify deficiencies, weaknesses, additional functional requirements, and other related applied R&D activities.

Operational Demonstrations: This stage occurs when technical feasibility has been established and the actual or projected cost will provide an economic, policy, or regulatory benefit. At this stage, the pace of product change slows down. Demonstrations of product suitability begin as potential implementers conduct final testing prior to purchase and operational deployment. The operational demonstrations stage exposes the technology to the rigors of production deployment, allowing parties to assess operational viability, technical reliability, and the value provided.

Early Commercial Deployment: This stage represents the initial operational deployment of commercially available technology. For any technology category, this will often represent fewer than five operational deployments and fewer than three vendors offering commercially available technology products.

Mature Deployment: This stage is reached when multiple vendors start supplying their respective commercially available technology products and support to multiple customers. Planning for technology replacement cycles begins as the prospect of obsolescence and entrance of new technologies into R&D and pilots brings the likelihood of replacement into typical planning horizons.

Obsolete and Replace: This stage may occur as a specific event when a manufacturer announces the end of life of a product and eventually end of support or cessation of service for a service provider. In other cases, it is an attrition that takes place over time as the number of vendors dwindles, production of critical parts or software support diminishes, and eventually new or replacement products and spare parts are no longer available.

1. DISTRIBUTION SYSTEM PLANNING

The information in this section focuses on the software modules of distribution grid analysis tools and is based on a structure drawn from a Grid Modernization Lab Consortium report authored by staff at PNNL and NREL entitled, “Summary of Electric Distribution System Analyses with a Focus on DERs,” published on April 2017.[11]

1.1 FUNCTIONALITY TO TECHNOLOGY MAP

Distribution system planning technologies are mapped to the primary Volume I functionalities supported, as shown below in Figure 2. This mapping was developed based on inputs, reviews, and discussions with industry experts during DSPx Phases 1 and 2. A discussion of the individual technologies and their respective maturities follows.

Note that not all of the technologies identified below are required to conduct a distribution system planning analysis. These analyses vary based on the electrical topography of a region and reliability and service requirements among other reasons.

Figure 2: Distribution System Planning

<table>
<tr><th colspan="3">Distribution Planning</th></tr>
<tr><th>Functionality</th><th colspan="2">Technologies</th></tr>
<tr><td>Short and Long-term Demand and DER Forecasting</td><td colspan="2">Demand Forecast Models
Load Profile Models
DER Forecasting (Customer DER Adoption Models, Customer-EV Adoption Models)
Scenario Analysis Tools</td></tr>
<tr><td rowspan="3">Short-Term Distribution Planning
Long-Term Distribution Planning
Hosting Capacity
EV Readiness</td><td>Power Flow Analysis</td><td>Peak Capacity Analysis
Voltage Drop Analysis
Ampacity Analysis
Contingency & Restoration Analysis
Balanced and Unbalanced Power Flow Analysis
Time Series Power Flow Analysis
Load Profile Analysis
Volt-var Analysis</td></tr>
<tr><td>Fault Analysis</td><td>Fault Current Analysis
Arc Flash Hazard Analysis
Protection Coordination Analysis
Fault Probability Analysis</td></tr>
<tr><td>Power Quality Analysis</td><td>Voltage Sag/Swell Analysis
Harmonics Analysis</td></tr>
<tr><td>Planning Analytics</td><td colspan="2">DER Impact Evaluation Tool
Stochastic Analysis Tools</td></tr>
<tr><td>Reliability & Resilience Planning</td><td colspan="2">Reliability Study Tool
Value of Lost Load (VoLL) Models
Resilience Study Models
Resilience Benefit-Cost Models</td></tr>
<tr><td>Interconnection Process</td><td colspan="2">Process Management Software & Portals</td></tr>
<tr><td>Locational Value Analysis</td><td colspan="2">Cost Estimating Tools</td></tr>
<tr><td>Integrated Resource, Transmission & Distribution Planning</td><td colspan="2">Planning Integration & Analysis Platform</td></tr>
<tr><td>Planning Information Sharing</td><td colspan="2">Web Portals
Geospatial Maps</td></tr>
</table>

1.2 DISTRIBUTION PLANNING TECHNOLOGIES

1.2.1 Forecasting Tools & Power Flow Analysis

1.2.1.1 TECHNOLOGY CATEGORY DESCRIPTION

Forecasting Tools

The development of load, DER and electrification forecasts is the foundation of distribution system planning and forms the basis for the identification of system needs, based on demographics, customer usage trends, and civic planning. A comprehensive load forecasting process often involves complicated data requirements, reliable software packages, advanced statistical methods, and solid documentation to explain the potential future energy use of customers. Load forecasting for the high DER distribution grid must consider the impact of DER output on customer electricity demand, geographic diversity, data quality, forecast horizons, forecast origin, and customer segmentation.

Forecasting the pace and scale of DER adoption/development requires estimates of DER type, quantity, location, timing, and other attributes. Several factors impact DER forecasting, including historical adoption rates, economic return for the customer, available DER incentives and procurement programs, the typical size of DER generation facilities, the influence of weather, regulatory mandates, and DER capital cost trends. Increased adoption of DER introduces new challenges for maintaining forecasting accuracy due to uncertainties associated with the variability of DER output, its evolving correlation with net load, and the impact of geographic diversity on aggregate DER output. DER have locational-specific impacts determined in part by how penetration rates evolve in each part of the distribution system. Multiple forecasts or scenarios may be employed to assess a range of potential changes in DER adoption.

The results of the load and DER forecasting functions are integrated in an analysis of the impact of DER on customer electricity net demand. These DER forecasting functions are supported by analytical tools and methods that make use of software tools that draw on the data from various external inputs, and by established tools that use econometric and predictive models.

Power Flow Analysis

Power flow analysis is a core component of distribution system planning that analyzes how system characteristics change in response to different operating scenarios. Power flow analysis includes steady state snapshot and time-series simulations. The output of power flow analysis is a power flow study that calculates voltages, currents, real and reactive power flows, and losses in the distribution feeder. This analysis is used to identify potential constraints on the system and scope the need for system upgrades based on violations of planning criteria, such as voltages outside acceptable limits or the overloading of equipment.

1.2.1.2 TECHNOLOGY DESCRIPTIONS

Demand Forecast Models

Load forecasting for the distribution grid involves the development of granular time and circuit level demand forecasts. Forecasting models are advancing toward the use of 8760 hourly forecasts over multi-year time periods. This requires the use of complex computer model that integrates mathematical models, statistical analyses such as linear regressions, and artificial intelligence techniques such as neural networks and fuzzy logic. The data inputs to a load forecasting tool include weather, geographic, economic, demographic, and DER and DR data. The load forecast tool must be capable of providing load profiles across circuits, banks, and sub-sections of the circuit, with the necessary temporal and spatial granularity in order to consider the impacts from various scenarios over the planning horizon.[12]

Load Profile Models

Load profile software modules evaluate actual customer consumption curves from interval metering or typical customer load curves developed from historical data. A load profile study tool allows the user to define the time period for which loading patterns are to be analyzed. This tool allows the user to determine peak and off-peak load days, feeder loading patterns, transformer loading, and line losses. The tool can also be used to estimate future electricity generation requirements.[13]

DER Forecasting

DER forecasting for the distribution system is evolving to better forecast adoption of various DER (including electric vehicles (EVs)) based on customer decision making and develop more granular forecasts in relation to circuit and operational characteristics. One set of DER forecasting tools involves customer adoption models that combine technology diffusion and economic models for long-term planning. Inputs include market information (e.g., fuel prices, existing electricity tariff), customer load information (e.g., hourly end-use loads), DER technology information (e.g., capital costs, operating and maintenance costs, performance data), as well as other customer decision factors.[14]

Another set of software solutions is used for near-term operational forecasts. This tool assesses the "hidden load" challenge faced today, which hinders operational ability to distinguish between supply resources (such as distributed generation and storage) and gross demand to accurately forecast impacts under various operating conditions, such as routine switching or outage restoration.[15,16]

Scenario Analysis Tools

Multi-scenario planning requires the use of models to integrate the attributes of each scenario into the planning analysis. One method and related tools involve Monte-Carlo simulation of individual scenarios and the related range of probabilities associated with key attributes that are inputs to the power flow analysis. In a multi-scenario analysis, these individual scenario analyses need to be considered collectively and a tool to facilitate this complex analysis is needed.

Peak Capacity Analysis

Peak capacity planning study tools examine load growth in relation to existing grid capacity over a planning horizon. This is done to determine whether there is a need to upgrade transformers or other grid equipment to meet load growth and keep the system operating reliably and safely. Multiple snapshot power flow analyses (often one for each year) are run to see how the system performs and what needs to be upgraded or changed. The analysis can also consider commissioning and decommissioning dates for network components. Absolute or relative load changes can be assigned to individual loads, groups/types of loads, or loads in graphically selected areas. Commissioning and decommissioning data for grid assets can be entered, which allows for taking new elements, including loads, transformers and lines, into service and existing ones out of service at future points in time. The analytical result is an entire load flow calculation with an evaluation of minimum and maximum values (e.g., voltages or loading levels). Finally, the analysis can provide diagrams with information on power requirements and overloaded lines, as well as additional information if limits have been violated during the calculation.

Voltage Drop Analysis

A voltage drop calculation tool helps investigate the possibilities of voltage limit violation and plan the operations of regulators and capacitors. A voltage drop calculation is one of the basic power flow functions in distribution grid software tools. Industry standards such as ANSI C84.1 provide guidelines for acceptable voltage ranges. To the extent that voltage violations are identified during the study, these can be mitigated by leveraging the ability of tap changers, regulators, and capacitors to regulate feeder voltages within the defined ranges. A voltage drop study may be performed as part of an integrated power flow study.

Ampacity Analysis

Ampacity is the maximum current that a conductor can carry continuously under the conditions of use without exceeding its temperature rating. Ampacity studies are used to calculate the minimum conductor size and cable configuration required based on the design requirements and expected load. Because the ampacity of a conductor is affected by ambient temperature, ampacity ratings under different temperatures are usually calculated. Key inputs to a calculation include conductor temperature, ambient temperature, conductor resistance, thermal resistance, and related loss factors.[17,18]

Contingency and Restoration Analysis

The contingency and restoration module of a distribution grid software tool allows the simulation of multiple “what-if” scenarios in a batch Monte-Carlo type analysis. These “what-if” cases represent the loss and/or disconnection of a device. Several contingencies can be concurrently defined to represent network operation under a variety of scenarios, such as the modification of loads and DER generation, the connection and disconnection of line sections, and the addition or removal of induction and synchronous motors.

Balanced and Unbalanced Power Flow Analysis

The load flow or power flow calculation analysis tool is a module within a commercial distribution planning software solution for the analysis and optimization of existing networks for network planning. Various solution algorithms (e.g., Newton-Raphson, Gauss-Seidel, and current iteration) are available for calculating the distribution of currents, voltages, and loads in the network, even under difficult circumstances (such as when several in-feeds, transformer taps, and poor supply voltages are involved). Balanced network models can be easily transformed into unbalanced network models by changing model parameters.[1]

Time Series Power Flow Analysis[2]

A time series power flow analysis tool is used for multiple steady-state load flow calculations with user-defined time step sizes between each power flow, with simulation periods ranging from seconds to hours or years. It analyzes the impacts of variations in solar irradiance or wind on power system controls, such as regulators, load tap changers, and switched capacitors. A time series power flow tool can help verify the sequence and performance of automatic switching, voltage control, and protection system operations. It may include the effects of end-use load components turning on or off, which can create short-term overloads or voltage disturbances. In conjunction with other tools, the time series power flow analysis may enable the study of grid interactions with markets (e.g., DR and transactive energy) and communication systems in the future. In addition, a time series power flow analysis can be used in power quality studies.

Volt-var Study Analysis

Volt-var optimization analysis focuses on system design considering voltage and reactive power compensation controls in order to optimize system losses and demand reduction. The analysis takes into account system criteria such as power factor, reactive power, and voltage limits, as well as varying loading conditions and the operation of system assets such as voltage regulators and load tap changers (LTC).

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[1] In a symmetric three-phase power supply system, three conductors each carry an alternating current of the same frequency and voltage amplitude relative to a common reference but with a phase difference of one third the period. The common reference is usually connected to ground and often to a current-carrying conductor called the neutral. Due to the phase difference, the voltage on any conductor reaches its peak at one third of a cycle after one of the other conductors and one third of a cycle before the remaining conductor. This phase delay gives constant power transfer to a balanced linear load. It also makes it possible to produce a rotating magnetic field in an electric motor and generate other phase arrangements using transformer.

[2] Formally known as a Quasi-Static Time Series Analysis (QSTS)

DER Impact Evaluation Tool

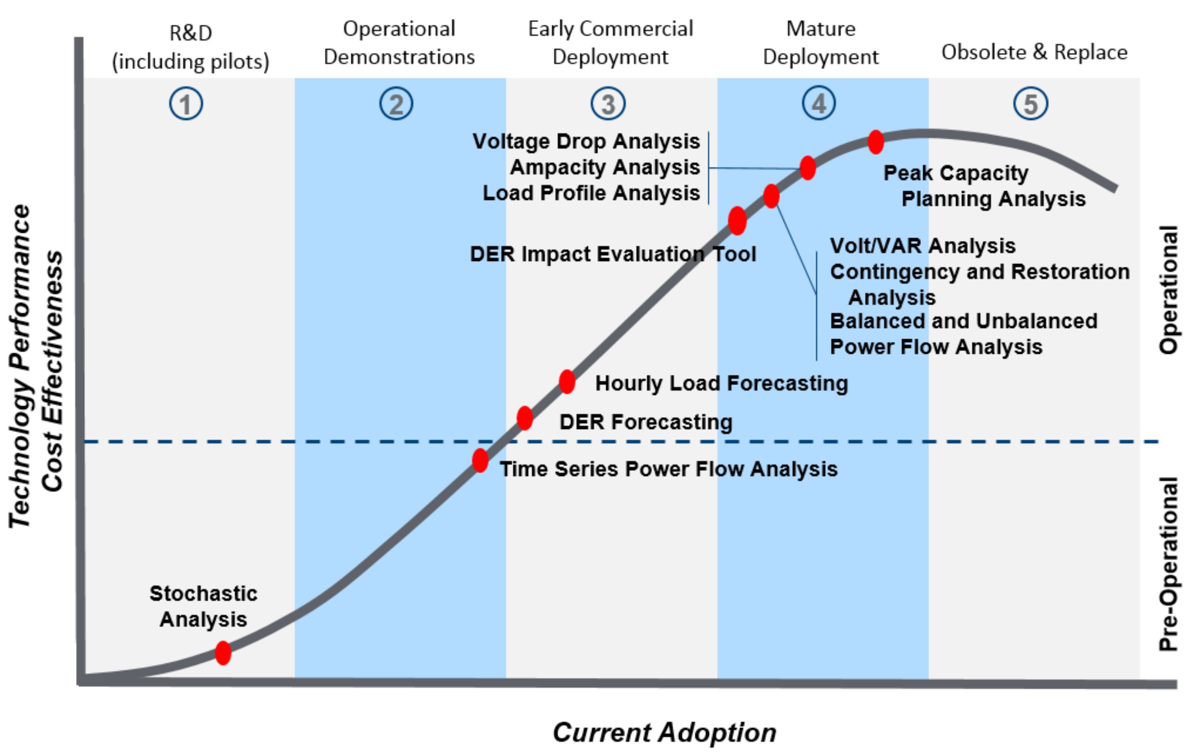
The DER impact evaluation tool enables DER interconnection studies and hosting capacity analysis. Relying on a simplified or detailed model of the DER installation, the module allows the creation of various study cases by combining grid loading conditions (e.g., peak and minimum load) with minimum and maximum DER contributions (e.g., 0% and 100%), all defined as simulation parameters. Controlled load flow analyses are then executed on each scenario to assess the impacts on the distribution system in terms of steady-state voltage, transient voltage variations (flicker), thermal overloads, and reverse power flow to assess protection issues. The studies performed by such a tool can also ensure that the hosting capacity limits of grid infrastructure are not exceeded due to the integration of DER.

Stochastic Analysis Tool

Stochastic analysis tools are distribution grid software tools that model the impact of random variations of load, DER changes, and changes to the distribution system on system operation. The model operates on a defined set of input variables (e.g., the number, size ranges, and locations of solar photovoltaic (PV) systems) and then performs a large number of simulations. Each Monte-Carlo simulation uses a random selection of different variable choices in accordance with statistical rules for these choices.[19]

1.2.1.3 ADOPTION MATURITY ANALYSIS

Figure 3: Forecasting Tools & Power Flow Analysis



Forecasting Tools

The application of demand forecasting techniques and DER operational forecasts to high DER penetration systems is inherently different from traditional top-down forecasting models. For high DER distribution systems, the need for granular circuit-level accuracy becomes very important, as does alignment of traditional top-down forecasts with bottom-up customer adoption models. Granular, location-based, circuit-level accuracy is a function of the grid's distribution system design; system and locational information; modeling capabilities; and internal roadmaps for forecasting, including improved tools, methodologies, and data resources. Given the varying availability of data among different distribution systems creates challenges for technology vendors to develop cost-effective technical solutions. Detailed load forecasting tools for distribution grid planning is in the early commercial adoption stage.

Likewise, customer adoption models for DER have largely been custom developed and not fully commercialized. The several tools used to-date have largely been developed by consulting firms and not as commercial tools. As such, these tools have been deployed in limited use and, thus, are in a state of operational demonstrations.[20] DER operational forecasting tools (not identified in the figure) to support intraday, day-ahead and several months ahead are an emerging area for R&D.

Power Flow Analysis

There are a variety of power flow analyses (listed below) used by planners and can be considered to be in a state of mature deployment:

- Peak capacity planning study,
- Voltage drop study,
- Ampacity study,
- Contingency and restoration study,
- Reliability study,
- Load profile study, and
- Volt-var study.

There are two types of power flow analysis; steady-state and stochastic. A steady-state power flow study is a central component of distribution system planning. The increasing penetration of DER and its impact on load curves will challenge the ability of traditional system analyses to accurately identify system needs. In particular, as DER with time-varying power outputs are integrated, time-series simulations for load profile studies are preferable and will become a key part of a distribution system power flow analysis. In turn, this will increase the volume of data that grid planners need to analyze. Intermittent DER will also require stochastic power flow analyses, which require an accurate network model (including interconnected DER). DER impact evaluation tools are considered to be in the operational demonstration stage and stochastic analysis is in the R&D stage.

While most distribution system analysis tools have software modules with the capability to conduct basic distribution engineering studies and time-series simulations with the integration of DER, notable gaps exist in the ability to conduct advanced engineering optimization studies and to reconcile these with hosting capacity analyses in an automated fashion. A significant challenge is the ability of a single solution or tool to address the full range of issues (e.g., voltage, thermal and protection issues) that arise from DER interconnection due to the highly location-specific value of DER. The lack of software tools with the ability to perform this function is a key barrier.

In addition, most distribution systems do not presently have phase models nor separate telemetry for all three conductors of a three-phase circuit. The ability of a software tool to work in both modes, where phasing is unknown on a segment or feeder but known in the broader sense, or when telemetry is present only on one of three phases of a transformer or segment, is presently quite limited. These tools will also require detailed, accurate network models to reflect the system at the appropriate point in time. Optimizations could be required at a more local, granular level or a system-wide level. The software tool should be capable of simultaneously processing both system-level and local level optimizations.

Additional discussion of technology needs and related research and development for distribution market operations is discussed in Chapter 5.

1.2.2 Fault and Power Quality Analysis

1.2.2.1 TECHNOLOGY CATEGORY DESCRIPTION

A power fault is any abnormal flow of current. A fault analysis evaluates fault current conditions and the ability of the system to quickly isolate faults and power system failures. Fault analyses can help design the settings and locations of protective devices, based on the calculated fault current. Power system failures occur due to lightning or switching surges, insulation contamination, or other mechanical or environmental causes. Protective equipment is installed in the system to quickly eliminate faults that cause abnormally large current flows, such as a short circuit.

The tools that support fault analysis include software modules for arc flash hazard analysis, protection coordination study, and fault probability analysis.

Power quality is defined as maintaining voltage, frequency, and waveform to defined standards.[21] Power quality analysis evaluates the operating conditions that can cause power quality disturbances, finds the equipment affected by disturbances and supports the identification of strategies to eliminate the causes while mitigating the impact of disturbances. Electrical disturbances caused by low power quality can result in economic losses and potential damage to end-use equipment such as sensitive industrial equipment[22] while also decreasing the power delivery efficiency of the distribution system. Due to the increased penetration of DER and other intermittent sources of power generation on the distribution grid, there is potential for harmonic content and injections to increase. This potential could be reduced via interconnection standards and advanced controls, i.e., letting inverters act as active filters.

Historically, power quality studies have been performed by dedicated equipment and on an ad-hoc basis. Concerns for the hosting of DER and distribution grid planning are driving further evaluation and development in this area. Power quality analyses are enabled by software tools for both voltage sag and swell studies and harmonic studies.

1.2.2.2 TECHNOLOGY DESCRIPTIONS

Fault Current Analysis

Fault current analysis is probably one of the most crucial calculations of the electrical design process. This analysis identifies the maximum available fault current at different points in the electrical system. The fault current found is then used to design and specify electrical components that can withstand the tremendous forces of faults without harming occupants and without damaging equipment. This information is also used to inform relay protection designs and settings.

Arc Flash Hazard Analysis Tool

The arc flash hazard analysis tool allows users to evaluate the risk of arc flash hazards on any part of a network. It calculates the short-circuit fault current using a short-circuit calculation algorithm, finds the clearing time from a library of device-specific time-current curves and calculates the resulting incident energy and risk level. These tools can also be run to allow the analysis for every bus in the network in one single simulation.

Protection Coordination Study Tool

A protection coordination study determines the optimum characteristics, ratings, and locations of power system protective devices. The associated software tool draws on a library of protective decisions, which stores several thousand device characteristics, time-current curve plots, and device settings reports. The tool may offer a screen editor that allows the user to build a line diagram with the desired circuit devices, by choosing them from the device library. The program is capable of generating all the necessary study benchmarks, such as cable and conductor damage curves, motor starting curves, transformer withstand curves, inrush, and thermal points. It also offers comprehensive graphical and tabular means for verifying the curve clearances at any fault current or system voltage level.

Fault Probability Analysis

Fault analysis in the context of the planning process involves determining the probable location of future fault events and momentary outages in the distribution grid. The associated software tool takes into account the actual switching configuration of the network, as well as the load flow. The grid planner can place possible line faults and vary their location on a line in order to ascertain their impact to the grid. A number of fault and conductor interruption types (single and three-phase) can be simulated on lines.

Voltage Sag and Swell Study Tool

Software tools used for this purpose assess the voltage stability of a network using the Power-Voltage (P-V) study[3] technique. This is achieved by scaling up all the loads by bus, area, and zone or globally in user-defined steps for a given network, base case, and all defined contingencies. The steady-state P-V approach dictates that for each load increase, pertinent generators within the system should be re-dispatched to match this load increase. Voltage calculations result from several studies, such as power flow and fault analyses. In most cases, post-processing of voltage data is needed for accurate voltage sag and swell studies, based on the duration of over-voltage and under-voltage conditions.

Harmonics Study Tool

A harmonics study analyzes the disruptions to a current or voltage waveform. This software tool features analyses such as frequency scan, voltage and current distortion calculations, capacitor rating, and filter sizing analysis, and K-Factor[4] calculations. The module allows the user to model non-linear loads and other sources of harmonic currents such as converters and arc furnaces while also being able to detect resonant frequencies due to due to capacitor banks.

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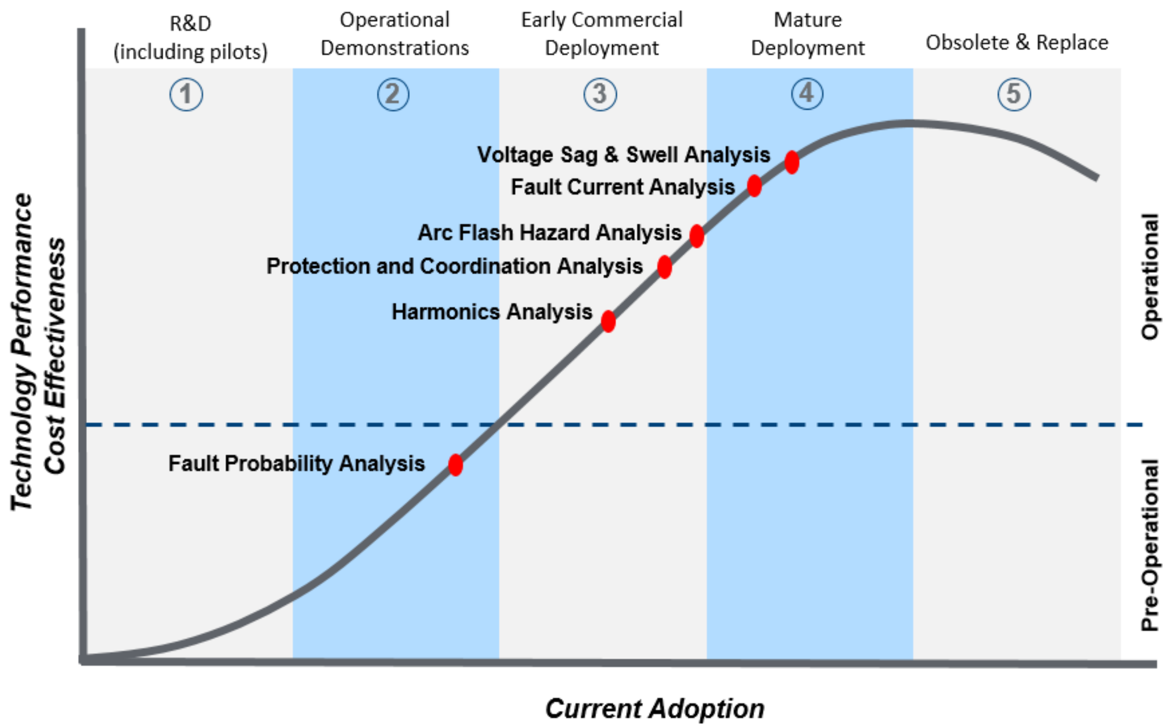
[3] When considering voltage stability, the relationship between transmitted Power (P) and receiving end Voltage (V) is of interest. The voltage stability analysis process involves the transfer of power, P from one region of a system to another, and monitoring the effects to the system voltages, V. This type of analysis is commonly referred to as a P-V study.

[4] K-factor is a weighting of the harmonic load currents according to their effects on transformer heating, as derived from ANSI/IEEE C57.110.,A K-factor of 1.0 indicates a linear load (no harmonics), The higher the K-factor, the greater the harmonic heating effects.

1.2.2.3 ADOPTION MATURITY ANALYSIS

Figure 4: Fault and & Power Quality Analysis



Fault current analysis is supported by existing commercial planning software. Software modules can be used for arc flash hazard studies and protection coordination studies. Arc flash hazard studies are needed to define the danger to people working on or near live equipment. Arc flash models, based on Institute of Electrical and Electronics Engineers (IEEE) 1584 standard, are used to estimate the incident heat energies to which a person near an arc fault is exposed. Protection coordination studies are necessary to determine the optimum characteristics, ratings, and locations of power system protective devices. Based on the feeder topology and manufacturer's data of the protective devices, such as time current curve settings, the optimal relay and recloser settings that provide the best protection for the system are determined. Results include settings and ratings of each protective device. These features of the software tools are in the mature stage of adoption.

Detecting temporary and high impedance faults and failures, including voltage dips, sags, and distortions, quickly and accurately will help distribution companies increase the reliability of their systems at lower costs. Very few existing distribution software tools can be used for the purposes of planning, analyzing and identifying potential fault locations. New tools are being developed to address the following scenarios:

- Location of "nagging" temporary faults causing momentary outages;
- Detection of high impedance faults; and

- Reduced patrol time to locate faults on inaccessible facilities (including rural and underground).

Some newer fault analysis tools (e.g., fault probability) are capable of improved system analysis and are in operational demonstrations. These fault analysis tools must also be capable of interfacing with existing software systems, and the available communications infrastructure. The routine use of fault analysis tools on every circuit, which will be needed due to the great proliferation of DER, is not yet common and will be impeded by the lack of accurate model network model data.

Several distribution grid software tools are capable of voltage sag and swell studies. As a result, this module of the tools is in mature deployment. However, poor quality and availability of network model data from Geographic Information Systems (GIS) or other systems may pose challenges to the effective support for routine voltage sag and swell studies.

Distribution system harmonics studies are seldom performed and are usually in response to customer complaints. DER integration may increase harmonics on a distribution feeder necessitating increased adoption of software modules that can perform harmonics studies. Software modules for harmonic studies are currently in a state of early commercial deployment.

1.2.3 Resilience and Reliability Analysis

1.2.3.1 TECHNOLOGY CATEGORY DESCRIPTION

Reliability Study Tool

This software tool is designed to assess the reliability of electric distribution networks. The tool computes a set of predictive reliability indices, such as SAIFI, SAIDI, and CAIDI for the overall system and their corresponding protection zones. It also computes customer point indices, such as the frequency of interruption and duration for each customer. The tool can also calibrate a predictive model based on historical data. This functionality can be useful in adjusting the failure rates and repair time for the overhead lines and cables, in order to match the simulated model with historical indices. A future-focused reliability study tool should include modules to plan and optimize the placement of new distribution automation (DA) devices to maximize their reliability benefit. Additionally, it should support a risk-based reliability planning module that compares the benefits of different reliability improvement programs (e.g., tree trimming, cable replacement, DA, inspection/maintenance) on an individual feeder basis and produces a plan on how to spend reliability improvement budgets to maximize impact.

Value of Lost Load Calculator (VoLL) Models

Value of Lost Load (VoLL) represents a customer's cost associated with an interruption of electricity supply. It is generally measured in dollars per unit of power (e.g., $/kWh). Calculation tools, such as LBNL's Interruption Cost Estimate (ICE) Calculator is a tool designed for electric reliability planners at utilities, government organizations or other entities that are interested in estimating interruption costs and/or the benefits associated with reliability improvements.[23]

Resilience Study Tool

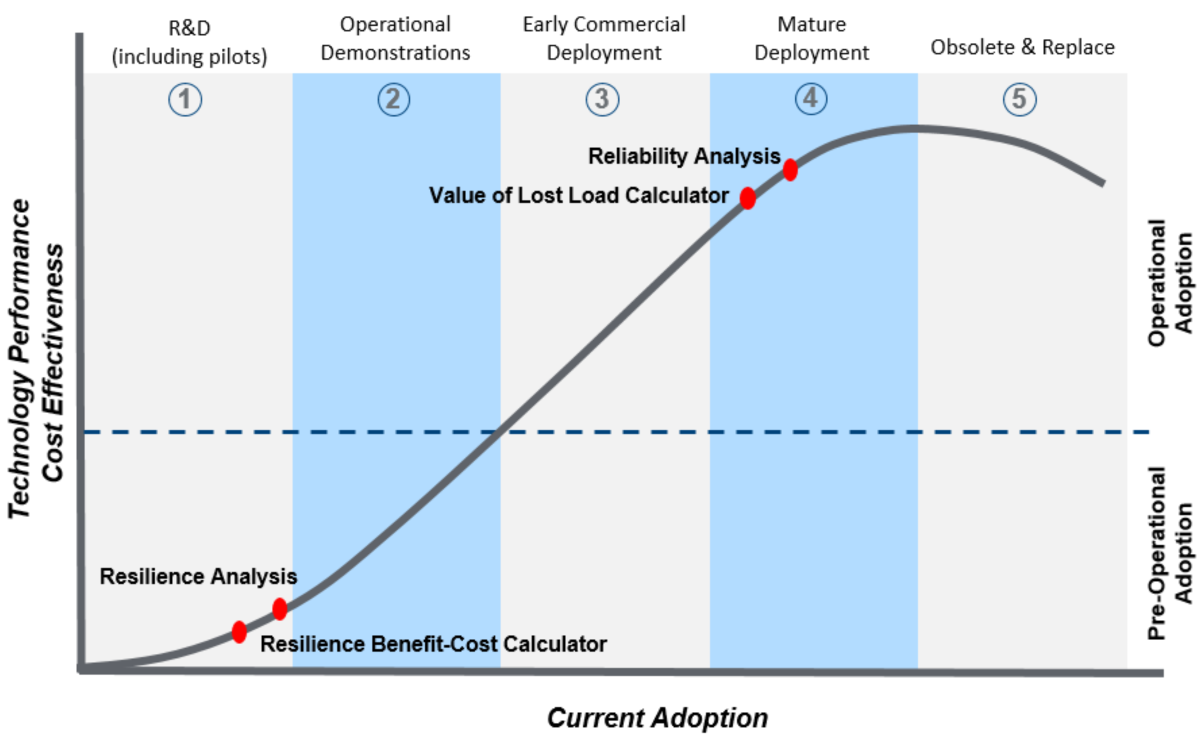
Resilience study tool would enable specific major event scenarios to be studied for heterogeneous distribution planning areas. This analysis may need to consider asset condition, locational characteristics, and other relevant considerations to assess initial outage impacts. Additionally, such a tool would enable an assessment of the restoration of a distribution planning area after a major event given certain damage scenarios.

Resilience Benefit-Cost Tool

Resilience Benefit-Cost tool would enable the estimated value of long duration power outages to society associated with major power events not captured in reliability calculations. The tool is intended to enable policy, utility, and other planners to estimate the impact of major events and assess incremental resiliency improvements.

1.2.3.2 ADOPTION MATURITY ANALYSIS

Figure 5: Resilience and Reliability Analysis



Reliability study analysis tools are mature, as are Value of Lost Load calculators, particularly LBNL's ICE calculator that is widely used.

Resilience study tools are not yet commercially available. Techniques to analyze distribution resilience under different major event or threat scenarios are currently in the R&D stage. These scenarios will help inform the development of resilience planning criteria and associated metrics. Additionally, VoLL research and customer surveys have been conducted in an effort to understand customers' and societal economic impact from multi-day outages, catastrophic loss of life, and damage to critical facilities and property. While tools such as ICE are effective at short-duration outages, new Resilience Benefit-Cost tools are needed to address uniquely different major long-duration events with a variety of potential impacts.

Additional discussion of technology needs and related research and development for distribution market operations is discussed in Chapter 5.

2. DISTRIBUTION GRID OPERATIONS

Grid modernization is changing distribution grid operations from a model that was largely passive, relying on robust design margins to accommodate normal operational variations, to a new model that accommodates DER, multi-way power flows, and active management of the distribution grid to achieve reliability and greater efficiency. Operating the grid under the new paradigm will require a wide variety of new analytics and simulation solutions and will rely on robust and secure communications to bring situational awareness of the distribution grid much closer to real time.

2.1 FUNCTIONALITY TO TECHNOLOGY MAP

These technologies are mapped to the primary Volume I functionalities supported as shown below in Figure 6. This mapping was developed based on inputs, reviews, and discussions with industry experts during DSPx Phases 1 and 2. A discussion of the individual technologies and their respective maturities follows.

Figure 6: Distribution Grid Operations

Distribution Grid Operations	
Functionality	**Technologies**
Observability (Monitoring & Sensing)	Advanced Metering Production Metering Grid Asset Monitoring Environmental Sensing Electrical Parameter/Event Sensors (Line Sensors, LIDAR Sensor, Satellite/Arial Imaging & Sensing)
Operational Forecasting	*See Planning*
Reliability Management	Outage Management System (OMS) Fault Location, Isolation & Restoration (FLISR)
Distribution System Representation (Network & State Information)	Geographic Information System (GIS) Electric Network Connectivity Model State Estimator
Grid Optimization	Distribution Management System Asset Management System Control Center Modernization Operational Analytics Volt-var Optimization (VVO)
Distribution Grid Control	Distribution Supervisory Control & Data Acquisition (SCADA) Advanced Protection Advanced Switches, Circuit Switchers & Reclosers Grid Energy Storage Power Flow Controllers D-STATCOM
Integrated Operational Engineering & System Operations	Network Operational Scheduling Systems Contingency Analysis & Restoration Analysis *(see Planning)*
Threat Assessment & Remediation	
Operational Information Management	Field Data Management Meter Data Management System (MDMS) Data Historian Data Warehouse/Data Lake Data & Analytics Platform Operational Service Bus
Power Quality Management	Integrated Volt-var Control Power Electronics-Var Compensator Advanced Inverters

Distribution Grid Operations	
Functionality	**Technologies**
Operational Telecommunications	Wide Area Network Field Area Network Neighborhood Area Network Communications Network Management System
DER Operational Control	Distributed Energy Resource Management Systems (DERMS) DER Portfolio Optimization EV Charging Infrastructure
Distribution to Customer/Aggregator Coordination	
Microgrid Management	Microgrid Interface
Workforce Management	Advanced Safety Tools Digital Workforce Tools Workforce Management System
Distribution to Transmission Coordination	Operational Data Exchange Operator-to-Operator Communication Interface
Customer Information	Customer Meter Data Access Portal (Green Button) Customer Information Portal
Physical Security	Intrusion & Threat Detection Systems
Cybersecurity	Cybersecurity Techniques & Tools

2.2 DISTRIBUTION GRID OPERATIONS TECHNOLOGIES

2.2.1 Sensing and Measurement

2.2.1.1 TECHNOLOGY CATEGORY DESCRIPTION

Sensing allows for observation of the distribution grid and DER, as well as environmental factors that influence DER performance and grid operations and sensing for cyber and physical security. Sufficient sensing and data collection can help to assemble an adequate view of the grid state. Measurement refers to the ability to record and monitor grid parameters such as three-phase voltage, current, phase angle, and power factor, as well as DER output and performance. [24, 25, 26, 27] Sensing and measurement data is also utilized in distribution and system planning. The underlying technology components within sensing and measurement are:

- Smart Metering,
- Advanced Meter,
- Production Metering,
- Grid Asset Monitoring,
- Environmental Sensors,
- Line Sensors and Imaging.

2.2.1.2 TECHNOLOGY DESCRIPTIONS

Metering

Smart Metering

Smart meters are digital, solid-state meters that are used to measure a customer's consumption during configured time intervals through a periodic polling mechanism. Smart metering can measure customer energy use or production, service voltage, outage events, and certain condition notifications, such as tampering and overheating. Additionally, smart meters have an embedded two-way communications module to allow remote meter reading as well as limited computing, software, and security elements. Smart meters may also have an optional service disconnect switch that can be remotely operated.

Advanced Metering

Advanced meters are the next generation of smart meters and represent a significant advancement in terms of supporting grid operations. Advanced customer metering has significantly greater computing and analytics capability embedded to augment the greater power characteristics measurement capability, such as real and reactive power measurement and power quality (harmonic distortion) measurement.[28] Advanced meters may also incorporate peer-to-peer communication capability, which enables one meter to talk to another and to other devices on the same network, such as a fault current indicator and advanced switches. These advanced meters can, therefore, be used as grid sensors and computing platforms to support more complex field automation and DER integration.

Production Metering

Production meters provide the telemetry, software, and tools necessary for the metering and monitoring of DER assets that supply power to the grid.

Grid Asset Monitoring

Grid asset monitoring technologies are sensing systems that monitor parameters related to the health and maintenance of grid equipment and can record and communicate those values to other systems. These devices may also automatically generate alarm signals if the equipment characteristics reach critical or dangerous levels.[29]

Environmental Sensors[30]

Environmental sensors are devices that provide real-time data on a variety of environmental factors ranging from solar irradiance, temperature, humidity, wind, geomagnetic disturbances and earthquakes to the presence of chemicals such as methane and hydrogen. Sensors may also monitor coronal discharge and capture thermal images from infrared cameras trained on substation transformers. Sensors also provide physical and cybersecurity situational awareness via measuring and monitoring parameters, including cell phone signals, presence of drones, sensor network cyber intrusion attempts, and physical intrusion detection. This information can then be fed back into the operations systems over the appropriate communications channels.[31]

Thermal Sensors

Temperature or thermal sensors can take temperature values directly from built-in device temperature monitors or use voltage and current profiles built up from near real-time meter data to estimate circuit hot spots.[32]

Weather Sensors

Weather sensors are deployed at substations according to local geography and microclimates. These sensors supplement commercial weather telemetry available from commercial sources.

Solar Irradiance Sensors

These sensors measure solar irradiance at the installation location. As the variability in output from solar PV installations is largely driven by local climatic conditions, such sensors can help develop knowledge of location-specific solar variance, which in turn can help maintain safe and reliable grid operations.[33]

Line Sensors & Imaging

Event sensors are devices that sense and measure values or variations in feeder circuit electrical parameters such as voltage and current. Such sensors provide visibility into grid operating conditions. When coupled with analytical tools, the sensors also provide observability into both normal operations, and disturbances such as faults and power quality issues.[34]

Line Sensors

Line sensors can be used on the distribution grid to measure voltage, load current, fault current, power factor, phase angles, harmonics, sags, and surges, among other metrics.

LIDAR Sensor

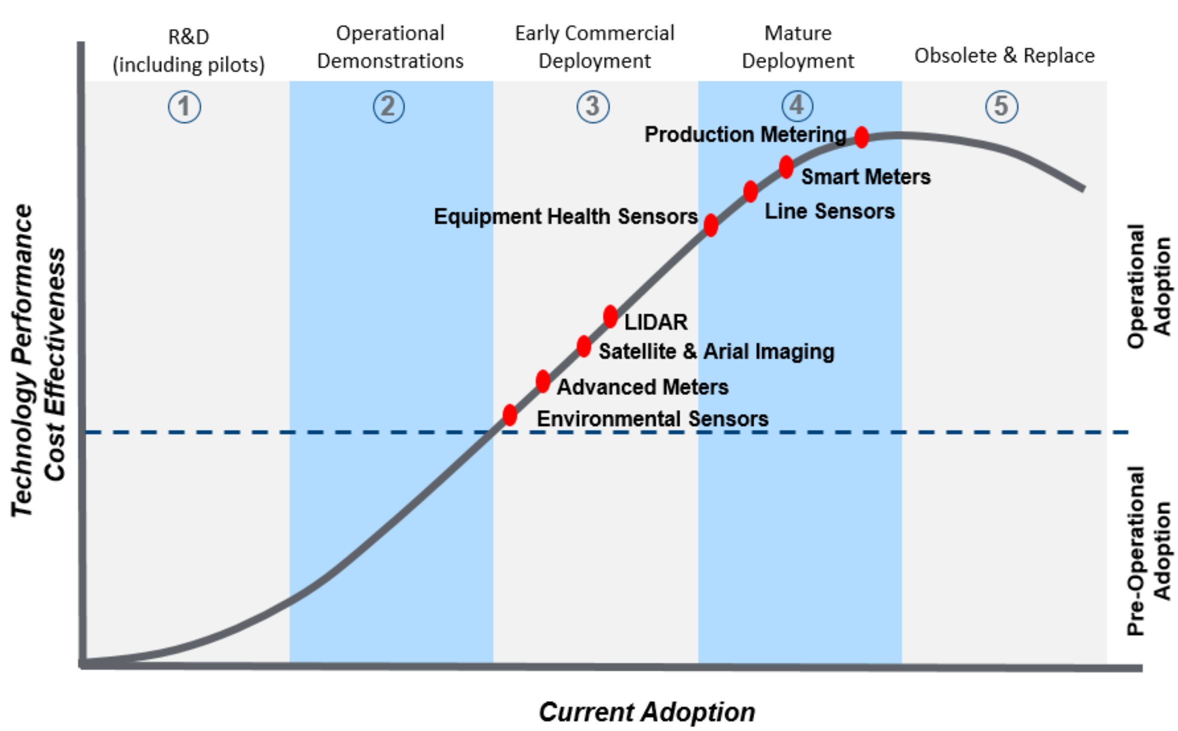
Light detection and ranging (LIDAR) sensors record 3D data to translate into utility maps showing grid assets and system topology. LIDAR can support vegetation management and asset condition monitoring.

Satellite/Aerial Imaging

High-resolution digital imagery and measurement are taken by satellites, helicopters, airplanes, or drones to use for primary mapping, track weather events, and monitor infrastructure.

2.2.1.3 ADOPTION MATURITY ANALYSIS

Figure 7: Sensing and Measurement



The development of advanced meters for customer metering that can also fulfill requirements of a grid sensor is in early commercial deployment. The adoption of production meters (mature technology) for DER is in the early commercial deployment stage given the limited use since it is typically only installed above a certain size threshold.

The development of equipment health sensors is in early commercial deployment largely in substation applications, such as transformer dissolved gas monitoring. Increasingly these sensors are being incorporated into the equipment and not a retrofit device.

Environmental sensors have primarily been deployed on transmission systems; their adoption on the distribution grid remains low. As a result, they are in the operational demonstrations stage. Exposure to extreme weather-related events along with a large-scale proliferation of intermittent DER may drive the need for cost-effective installation of environmental sensors.[35,36]

Line, voltage and current sensors and technologies for monitoring grid parameters have been deployed by a number of utilities over the years and are approaching mature deployment.

LIDAR and aerial/satellite imaging technology is mature, but the adoption by utilities is at an early stage of commercial adoption growing over the past decade.

2.2.2 Operational Analytics

2.2.2.1 TECHNOLOGY CATEGORY DESCRIPTION

The analog-to-digital transformation of the distribution grid enables improved awareness of the current grid configuration, asset information and condition, power flows, and events. This may include visibility into all steady-state grid conditions, such as criteria violations, equipment failures, customer outages, and cybersecurity. DER situational awareness is also required to operate a grid with high DER and optimize DER services to achieve maximum system benefits. As such, operational analytics transform historical and real-time data for the electrical grid into actionable insights for improving operational reliability and efficiencies. This section focuses on the data aggregation and analysis tools that are used to provide clarity and context for operational decision making and support for business processes.[37]

2.2.2.2 TECHNOLOGY DESCRIPTIONS

Outage Management System (OMS)

An OMS integrates meter-level outage information and real-time information (such as interactive voice response) on customer outages. Analysis of that data identifies interrupted equipment and circuits, enabling work crews to be dispatched to the location of the fault and decreasing the time to repair and the duration of the outage. It also provides suggested switching plans to accelerate outage restoration.

OMS can monitor equipment status to optimize outage prediction and enhance situational awareness by integrating real-time data from customers with telemetered analog data from the distribution system. [38, 39]

Geographic Information Systems (GIS)

A GIS is used to capture, store, manipulate, analyze, and manage all types of geospatially referenced data. GIS tools enable users to create queries, analyze spatial information, edit data and maps, and present the results. Relevant geodata types might include land-based data, streets, ownership/real estate, vegetation, network topology, GPS location data for grid devices and components, and census data.[40]

Electrical Network Connectivity Model

An electrical network connectivity model is a data set, in spatial context that contains geospatial grid asset details (physical data), configuration information, customer and DER connectivity details, and electrical network information (connectivity data) to accurately depict the current state of the distribution system. This model is often visually represented in a GIS and used in power flow studies. Distribution operations employ two versions of the model: as-built and as-operated. The as-built model reflects original design and implementation, while the as-operated model reflects the actual real-time model for daily operations.[41] This data is also used in the planning activities described in Section 2.1. Connectivity model data can be volatile on both short and long time scales through outage remediation (short) and maintenance and construction (long).

Distribution network connectivity software models provide a web-based, geospatial visualization of the electric distribution network and assets providing a single view of data and analysis for all users of the software system. The models are capable of dynamic updates and automated integration with GIS systems, power engineering, and planning modeling tools. An operating system such as a Distribution Management System (DMS) unifies data from DMS, SCADA, and OMS to maintain a real-time “as-operated” distribution network connectivity model.[42]

Distribution Management System (DMS)

A DMS is an operational system capable of collecting, organizing, displaying, and analyzing real-time or near real-time electric distribution system information. A DMS can also allow operators to plan and execute complex distribution system operations to increase system efficiency, optimize power flows, and prevent overloads. A DMS can interface with other operations applications, such as GIS, OMS, and customer information system (CIS) to create an integrated view of distribution operations.

Distribution State Estimation

State estimation is the prediction of all voltages and currents in the system, from a limited set of actual measurements. It must account for missing or bad data, load variations, and local control operations such as capacitor switching, voltage regulator operation, and automatic switch operation. State estimation is a key enabler for a number of applications on the distribution system, including reactive power management, outage management, loss reduction, DR, adaptable over-current protection, condition-based maintenance, and integration with transmission system operations.[43, 44]

The technologies and tools used for distribution state estimation include customer side smart meters, grid meters, and pseudo-measurements. Customer smart meters and grid meters are installed to enable the measurement of power consumption, voltage, and reactive power at frequent intervals, at the customer site, and on the distribution grid respectively. In unobservable areas or without any measuring points, the estimation depends on the existing knowledge of the grid and pseudo-measurements, such as historical data, load templates, nominal voltage value, and average power factor.[45]

Volt-var Optimization (VVO)

A VVO application includes analytics models to determine which grid devices to adjust and by how much for optimal performance. The software system, in a centralized or decentralized arrangement, sends control setting adjustments to devices, such as LTCs, voltage regulators, capacitor banks, power flow controllers, and smart inverters.

Advanced Distribution Management Systems (ADMS)

ADMS are software platforms that integrate numerous operational systems, provide automated outage restoration, and optimize distribution grid performance. ADMS components and functions can include DMS; demand response management system (DRMS); automated fault location, isolation, and service restoration (FLISR); conservation voltage reduction (CVR); and VVO.[46]

DER Optimization

As DER penetration increases, combining traditional energy assets and DER may require optimization to achieve system reliability, resilience and/or efficiency goals in a more efficient way. DER optimization tools must be capable of analyzing different types of DER in combination with physical grid assets in order to manage distribution operations through dynamic optimizations. This results in the utilization of these resources to achieve desired performance as non-wires alternatives in terms of response time, duration, and load profile impacts.

Customer Information Portals

Online portals provide customers (or their designated provider) access to their usage data and market participants with information related to distribution operational markets for grid services. Customer data access portals support access to market data from the front-end (e.g., web-based displays) or from the back-end (e.g., electronic data interchange) for downloading large quantities of data while being safeguarded by strong privacy protections and cybersecurity measures.

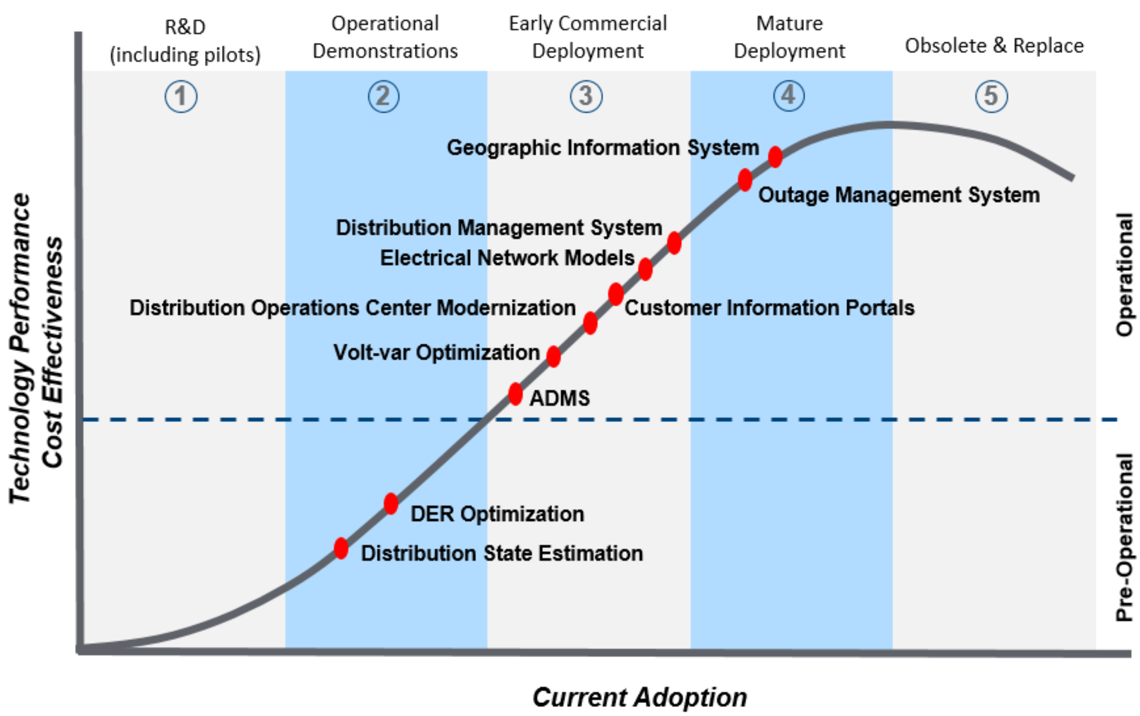
Standards-based approaches have been developed to support customer information access such as Green Button Connect (GBC).

Distribution Operations Center Modernization

Distribution operations center (DOC) modernization involves digitalization of the network and other operational information in addition to a human interface with control systems. This includes capabilities to enhance human interface and decision-making involved with operating more complex, digitized distribution systems and related advanced technologies.

2.2.2.3 ADOPTION MATURITY ANALYSIS

Figure 8: Operational Analytics



Recent market trends indicate a preference for single vendor OMS bundled with DMS, SCADA, and volt-var management, for example. However, discrete ("best of breed") outage management systems have been widely implemented over the past decade through interfaces with customer systems and DMS. OMS are in the mature deployment stage.

Geographic information systems and tools are in mature deployment.[47]

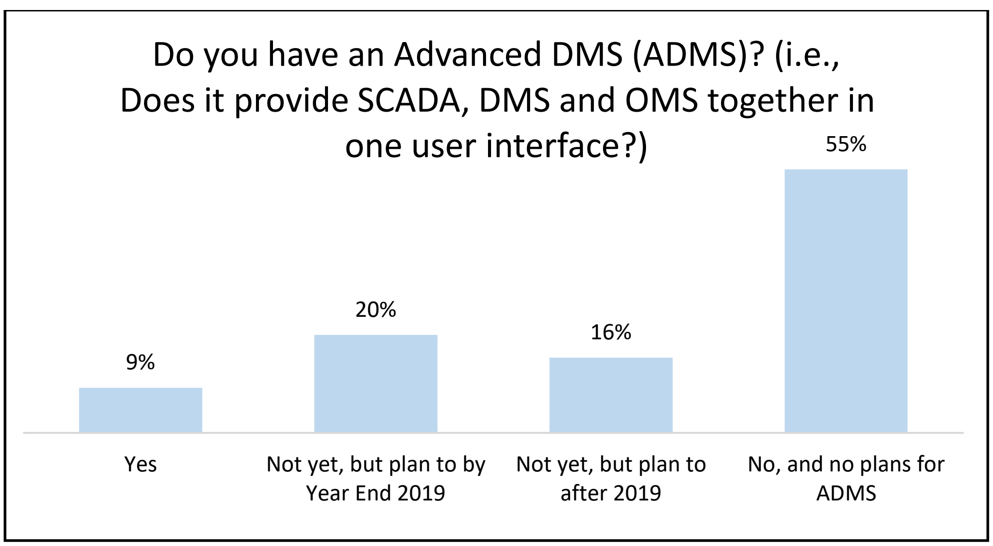
Software-based electrical network connectivity models are in early commercial deployment. However, the key challenge to real-time connectivity models is maintaining the availability of accurate and "clean" data. Typical approaches to GIS/network model data cleanup do not ensure ongoing data integrity because they do not address the underlying volatility of an operational grid. Real-time connectivity models are therefore in operational demonstrations.

Distribution state estimation for real-time use in distribution systems with high levels of DER is in initial operational demonstrations. The unique features of the distribution grid (i.e., a significant number of nodes, radial topology, unbalanced phases, etc.) create challenges that are not faced on transmission systems. Also, problems can arise if inputs to the state estimator consist of a combination of pseudo data and real measurements, which vary temporally and spatially, or if the measured objects delivered from different sources are different from each other in terms of voltage or power. As such, classic state estimation methods for transmission work poorly on distribution feeders.

VVO systems have not been widely deployed, as traditional voltage management techniques can be used to achieve most of the efficiency gains from CVR. Today, the driver for the installation of VVO systems is often the increasing levels of variable DER that impact voltage quality and require more sophisticated approaches to manage.

A number of DMS implementations are underway, each with a unique definition of the functionalities that the new system should enable. Most commercialized advanced DMS contain analytics modules that can model the distribution system components and switching activities and conduct distribution power flow simulations. However, the implementation of a comprehensive DMS requires seamless integration with OMS, GIS, and CIS systems. The term ADMS is often used to include a combination of these systems with a DMS from a single vendor. While the adoption of these new DMS has been increasing, DSCADA systems are often used to manage a growing portfolio of DA functions. These systems are in a stage of early commercial deployment but expected to move into mature deployment over the next five years as identified in the figure below.[48]

Figure 9: ADMS Deployment Survey[49]



DER optimization tools are generally in the R&D stage of adoption maturity. Today, assessment of DER non-wires alternatives portfolios at the distribution level is often performed through spreadsheet-type analysis. Some DER portfolio optimization capability is included in a Distributed Energy Resource Management System (DERMS), but these are typically designed for managing the dispatch function, not for constructing portfolios resulting from sourcing evaluations and distribution planning. It may be possible to extend the DERMS functionality for this purpose in planning, as well as to integrate with market operations and grid operations.

Green Button-compliant customer information portals and DOC modernization utilize mature technology but deployment is not yet widespread in the industry to be considered commercially mature.

Additional discussion of technology needs and related research and development for distribution market operations is discussed in Chapter 5.

2.2.3 Distribution Automation and Controls

2.2.3.1 TECHNOLOGY CATEGORY DESCRIPTION

Power delivery functions can be more efficiently monitored and controlled in real-time with field automation assistance. Distribution field devices such as reclosers, switches, capacitors, and transformers can all be monitored—if not controlled or operated—remotely. DA devices can also remotely measure voltage, current, power factor, and phase balance, as well as identify faults. Taken together, this information provides system operators with the current conditions of the power delivery system. Adjustments to optimize operating efficiencies are more easily made, and increases in power delivery reliability are provided. When system failures occur, automation of the distribution network enables an enhanced ability to pinpoint outage locations and causes and to restore power swiftly, thus minimizing the frequency and duration of unplanned power outages.[50]

2.2.3.2 TECHNOLOGY DESCRIPTIONS

Substation SCADA

SCADA measurement, controls, and computing platforms are widely available in commercial software for transmission and distribution substation applications. The distributed computing capability in a substation provides support for several functions, such as analytics, remote control functions, physical security and cybersecurity, and sensor and data management.

Advanced Protection

Advanced protection relays are digital and software-driven with standards-based communication interfaces. This contrasts with traditional electromechanical relays that are still prevalent in distribution substations. Advanced protection has the capability to remotely change settings (e.g., current, voltage, feeders, and equipment) both periodically and in the future, as needs may dictate, in real-time based on signals from local sensors or a central control system. For example, a change in settings preserves the protective function of the relay while preventing false trips (i.e., disconnects or activations) despite changing conditions that result from the varying output of DER.

Distribution Automation

DA enables the monitoring, coordination, and operation of distribution system components in real-time mode while adjusting to changing loads and failure conditions of the distribution system, usually without interventions. These functions require telemetry, analytics, and control, which in turn require communication and computational resources.

Distribution SCADA

Distribution SCADA (DSCADA) is the extension of SCADA capabilities to distribution substations and basic DA functions, such as capacitor bank control, recloser control, switches, and protection devices. DSCADA installations also support data acquisition from pole-top and line-mounted DA devices. DSCADA platforms are typically—but not always—limited in the extent to which they can perform advanced or complex DA functions such as switching analysis and FLISR. In many installations, the SCADA platforms are used for monitoring and control of field devices, with additional applications implemented to provide coordination and control of automated field devices.

Advanced Switches and Reclosers

Conventional switches have rudimentary capabilities to be opened or closed by manual operation or via remote control, or to automatically open or close under certain conditions including fault conditions, or under de-energized conditions. Advanced switches contain sensors, analytics and control software, microprocessors, and communication interfaces, with the ability to act as a control hub in a distributed control scheme to enhance reliability and DER integration through improving distribution flexibility. This is done through coordination of power measurement, fault identification, and distributed circuit control/reconfiguration coordination. Measurements and event information and actions are transmitted in real-time to other devices on its circuit and adjacent circuits, to the originating substation, and to the operations control center.[51]

Power Flow and Volt-var Control

Advanced electrical devices typically comprised of power electronics, control software, and communication interfaces are used for providing fast-acting real power injection and/or reactive power compensation. The controllable parameters include line reactance, phase angle, and voltage. Power flow controllers can also provide harmonic cancellation and power quality functions. These controllers often include sensing and measurement capability as well.

Distribution-STATCOM

The distribution-static compensator (D-STATCOM) is a fast-response, power electronics-based device that provides flexible voltage and reactive power control at the point of connection for improving the power quality in distribution systems. The D-STATCOM system's control logic monitors distribution system performance (voltage and load current) and adjusts reactive power on a cycle-by-cycle basis if necessary. The D-STATCOM connects in shunt to the distribution three-phase feeder circuit via a coupling transformer. It can exchange reactive power with the distribution system by varying the amplitude and phase angle of an internal voltage source with respect to the line terminal voltage, resulting in controlled current flow through the coupling transformer. [52, 53]

Distribution Power Flow Controllers

Distribution power flow controller (DPFC) controls both real and reactive power flow enabled by power electronics, which is the application of semiconductor switching devices to the conversion and control of electric power. DPFCs typically can operate autonomously or controlled within an integrated volt-var optimization system and may provide voltage regulation, reactive power compensation, harmonic cancellation, and power quality functions, as well as sensing and measurement.

Solid-state Transformer

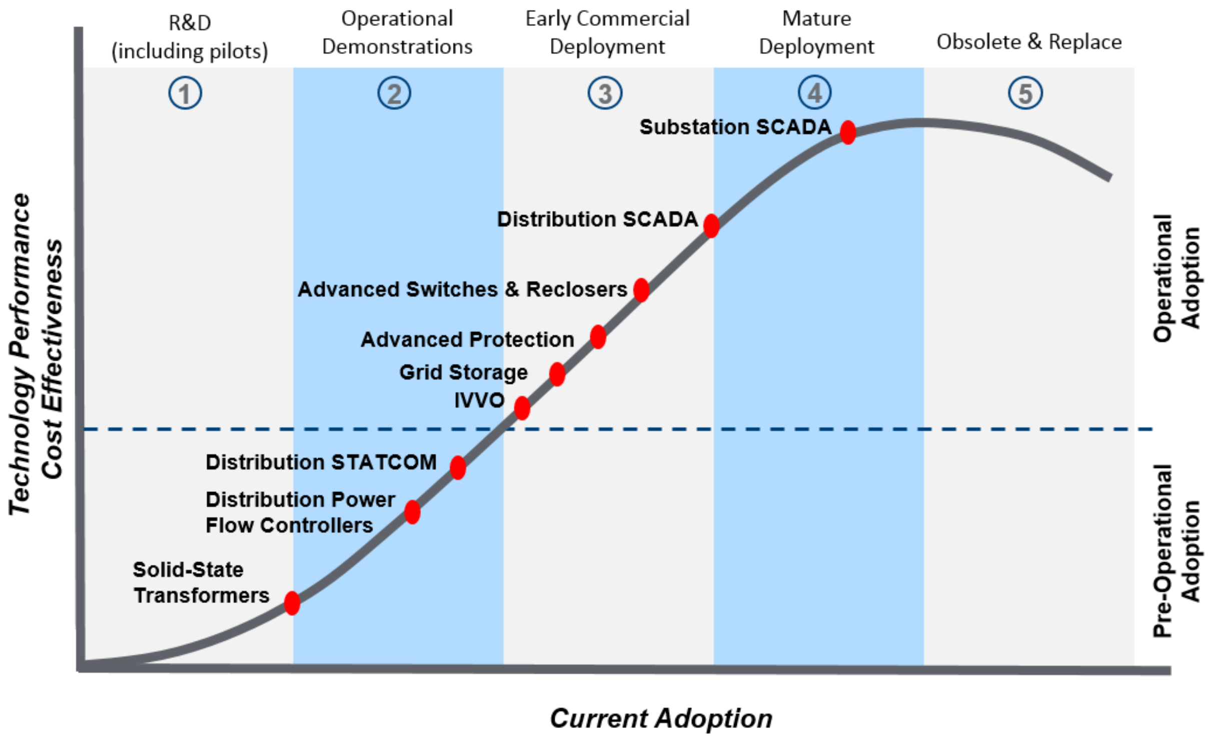
Next-generation solid-state transformers (SST) are engineered with intelligent power electronics, as opposed to traditional, static coil-based transformers. A typical SST consists of an AC-DC rectifier, a DC-DC converter, a high frequency (HF) transformer, and a DC-AC inverter, as well as a communications interface. A key use for SSTs are as service transformers and may include other functions, such as grid sensing, Volt-var management, and switching.[54, 55]

Grid Energy Storage

Grid energy storage is the application of energy storage technology on transmission or distribution systems (e.g., compressed air energy storage, various types of batteries, flywheels, electrochemical capacitors, etc.) to provide grid resilience and reliability by acting as a buffer to stabilize the system or absorb overloads, for example.

2.2.3.3 ADOPTION MATURITY ANALYSIS

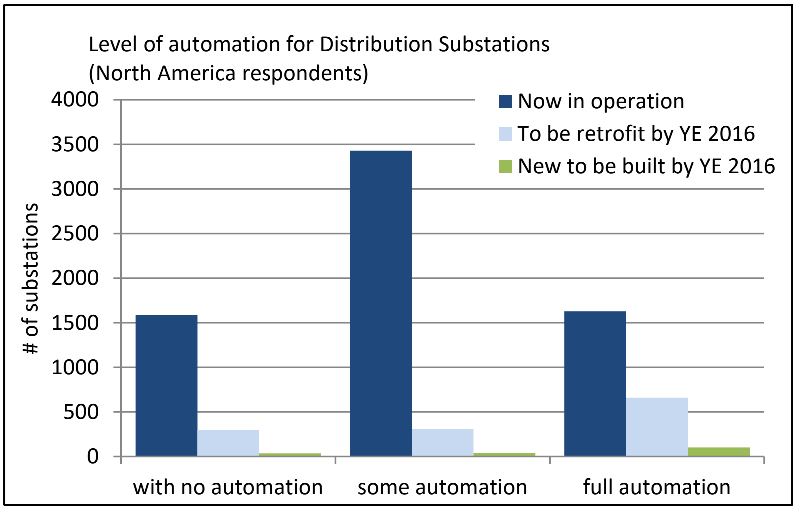
Figure 10: Distribution Automation and Controls



Smart substation, distribution, and field automation technologies enable new capabilities to automatically locate and isolate faults using automated feeder switches and reclosers; dynamically optimize voltage and reactive power levels, and monitor asset health to effectively guide the maintenance and replacement of equipment. In addition, field automation can enhance reliability and resilience while improving operational efficiency and DER integration.

Substation SCADA technology is mature and widely deployed in larger transmission-distribution substations. However, installations in smaller distribution substations are growing in response to the need for distributed analytics and advanced DMS. Figure 11 below illustrates the level of adoption.

Figure 11: Distribution Substation Automation



Advanced protection relays are beginning to be deployed as part of aging infrastructure replacement and as required for reliability enhancement and DER integration.

DSCADA devices are widely deployed and mature in modules with basic DA functions. A wide number of vendors offer devices with DSCADA capability[56] with a range of capabilities. Advanced features differ in maturity by function (such as field equipment management and, identification of feeder fault events) as indicated in the other technology categories in this document.[57]

Advanced switches are being installed on distribution systems. These are more likely to be installed at voltages above 4 kV. The higher the feeder voltage, the more likely it is that at least some of the feeders would be fully automatic and have SCADA-controlled sectionalizing switches and reclosers installed.[58] Advanced switches within a FLISR scheme reduce customer downtime, improve SAIDI performance, provide faster and more accurate localization of faults, and reduce repair time and expenses. Advanced switches are in early commercial deployment.

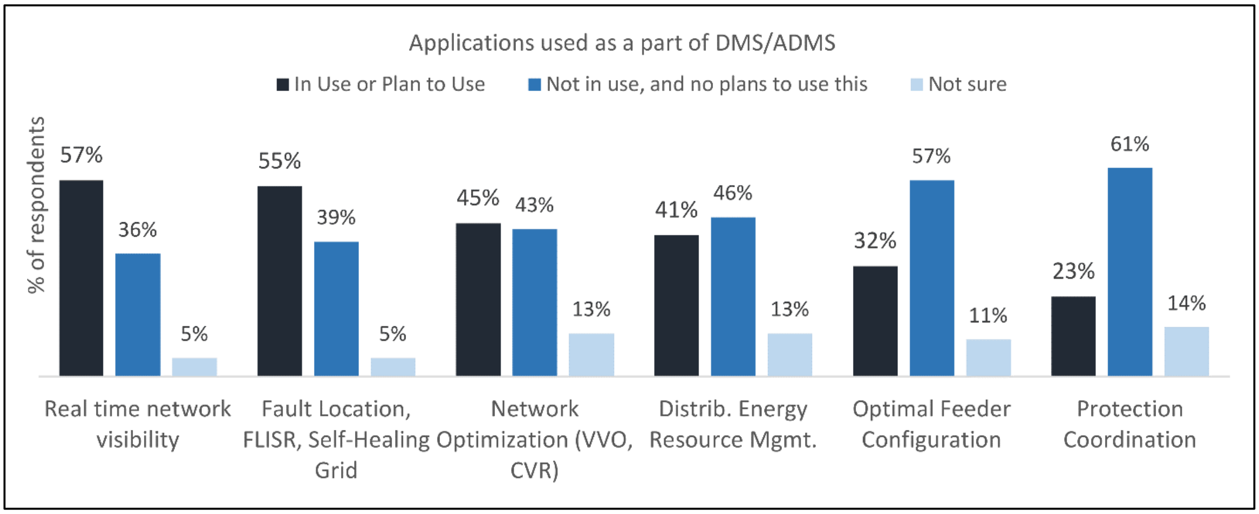
The distribution-STATCOM can be a cost-effective and reliable solution to reduce voltage variations, such as sags, surges, and flicker, and to address the instability and rapidly varying reactive power demand caused by increasing DER penetration on the distribution system.[59, 60] This technology is in a transition from operational demonstrations to early commercial deployment.

Distribution Power Flow Controllers are in operational demonstrations as an alternative to manage significant voltage variations due to high solar PV adoption on distribution circuits. SSTs are still in product development (the R&D stage) with limited initial pilots.[61]

To implement automated capabilities properly on the distribution grid, it is necessary to integrate communications networks, control systems, and field devices. In addition, testing and evaluation is required to determine whether the equipment is performing as designed. Training of field crews is required to ensure the safe and efficient use of technologies. For example, an integrated FLISR operation requires coordination between smart relays, automated feeder switches, and the DMS. Thus, it is important to understand how these devices and systems work together to achieve the desired functionality.

While several key technologies are still in operational demonstrations and early commercial deployment, it is clear that over the next five years the maturity of field automation technologies will advance significantly, as identified in the adoption survey results below.

Figure 12: ADMS Applications[62]



Additional discussion of technology needs and related research and development for distribution market operations is discussed in Chapter 5.

2.2.4 Workforce and Asset Management

2.2.4.1 TECHNOLOGY CATEGORY DESCRIPTION

Workforce and asset management technologies are advanced tools and software that enhance worker safety and productivity in an increasingly complex cyber-physical environment resulting from the digitalization of the grid. Workforce management includes the use of distributed wearable personal computing, higher bandwidth mobile computing that links workers to operational and productivity software. Asset management tools include the application of sophisticated machine learning/artificial intelligence algorithms to assess asset condition and determine preventative maintenance to improve both productivity and important public safety.

2.2.4.2 TECHNOLOGY DESCRIPTIONS

Advanced Safety Tools

Some utilities have started using virtual reality (VR), augmented reality (AR), and mixed reality (MR) in applications that enhance workforce training and safety. IEEE is in the process of developing standard IEEE P2048.5 for VR and AR.[63,64]

Digital Workforce Tools

Digital workforce tools are integrated applications to increase workforce safety and productivity through improved information access, training, and communication, collaboration, and connections with each other, including mobile and offline workers. This may include AR/MR capabilities.

Workforce Management Systems (WMS)

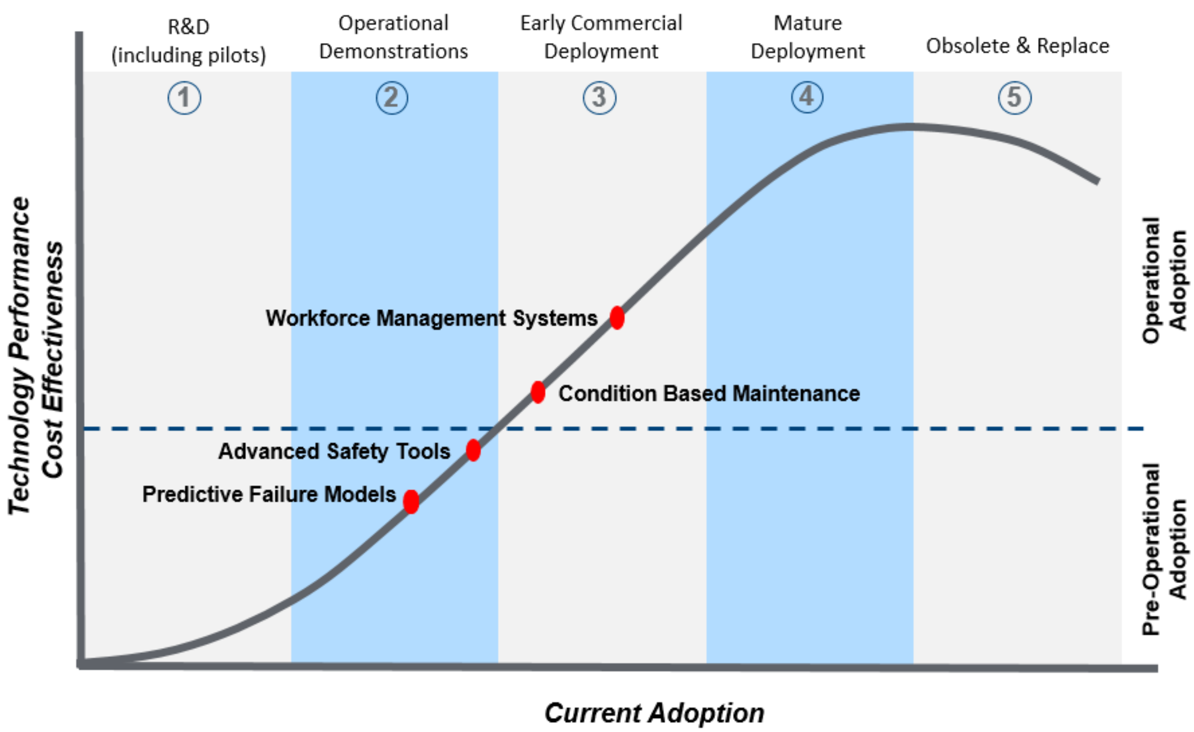
A WMS is a software that supports the operation and maintenance of distribution systems and related workflow including crew dispatch, trouble tickets, and work orders under normal and emergency restoration conditions. The system may include geospatial information reflecting personnel locations to facilitate response times.

Asset Management

Asset condition analytics integrates grid sensing intelligence with both existing asset management and predictive failure analysis applications. For example, condition based maintenance (CBM) system collects data on distribution assets to ensure maintenance is performed only when needed. CBM systems leverage asset data to reconcile maintenance schedules with actual asset conditions, organizational priorities, and changes in operating environments.[65, 66] Predictive failure tools assess grid data, asset sensors, and other environmental sensors/information to assess the health of assets to avoid catastrophic failure of grid infrastructures (e.g., transformers, conductors, etc.) that may create public safety issues.

2.2.4.3 ADOPTION MATURITY ANALYSIS

Figure 13: Workforce and Asset Management



Advanced workforce safety technologies such as AR are in the operational demonstration stage and various digital productivity technologies began commercial deployment over the past decade. Workforce management systems are mature, but advancements linked to mobile computing and logistics analytics have resulted in a new generation of solutions that are in early commercial deployment.

Reactive and preventative asset management programs have been widely used by utilities for a long time. However, the integration of CBM programs using software tools is a recent development. Typically, source data is generally available and commercially available analytics are sophisticated. However, integration between the two is often challenging given non-standard data formatting and other data quality issues. For this reason, CBM, as described, is in early commercial deployment. Predictive failure tools are in development and undergoing operational demonstrations.

2.2.5 Distributed Resource Management

2.2.5.1 TECHNOLOGY CATEGORY DESCRIPTION

Distributed Resource Management is the set of capabilities and technologies necessary to have visibility into and control over DER integrated into the operation of the distribution system. The types of DER that would be included, but not limited to, are energy storage, generation, smart inverters, and responsive load.

The technologies discussed in this section are differentiated from the technologies used for DA, which are covered in the next section. In the context presented within This volume, DA relates to the visibility and control of the distribution grid. Technologies supporting distributed resource management include:

- DERMS,
- DRMS,
- Microgrid interface,
- Advanced inverters, and
- EV Charging infrastructure.

2.2.5.2 TECHNOLOGY DESCRIPTIONS

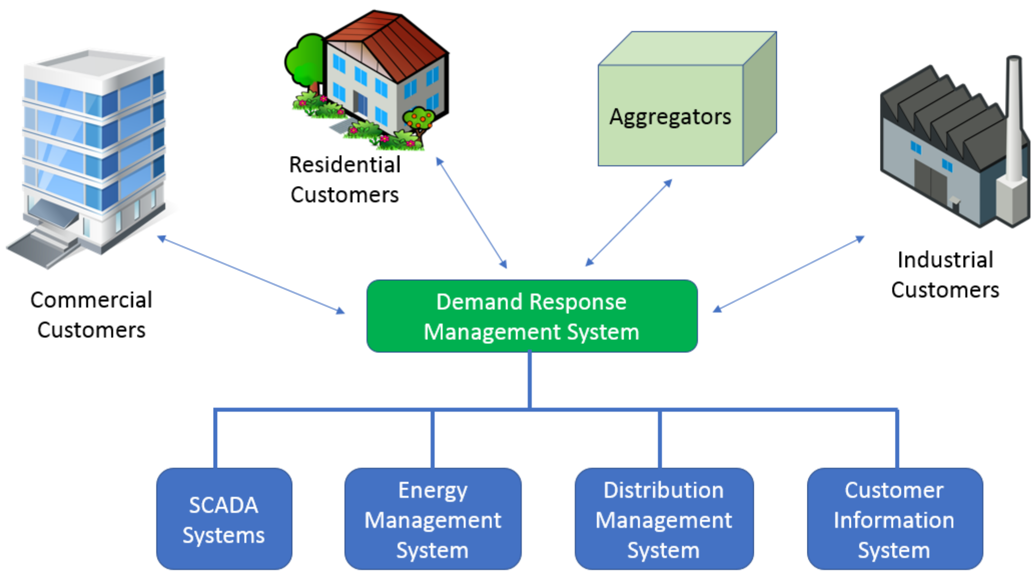
Demand Response Management System (DRMS)

The specific functions or modules of a DRMS may include support for the following administrative and business functions for DR management:

- Program creation
- Marketing program performance tracking
- Scheduling
- Work order management of field installation of the DR devices
- Dispatch optimization
- Customer event notification
- Tracking of customers' participation
- Measuring and verifying participation
- Providing reports
- Customer enrollment
- Device installation
- Device asset management
- Capacity forecasting
- Event creation
- Event dispatching
- Real-time performance monitoring
- Calculating settlements
- Acting as the system of record for all activities

As shown in Figure 14, the DRMS coordinates several key systems involved in DR. The DRMS may potentially interact with the EMS or DMS operational systems, responding to a request for a reduction in demand. However, today that is rare and more typically involves a human operator interface. The DRMS also relies on the customer information contained within the CIS for customers enrolled in DR programs, so that it may communicate with commercial, industrial, and residential customers, and with aggregators, to deliver the results required by the operational systems.

Figure 14: Demand Response Management System



Distributed Energy Resource Management Systems (DERMS)

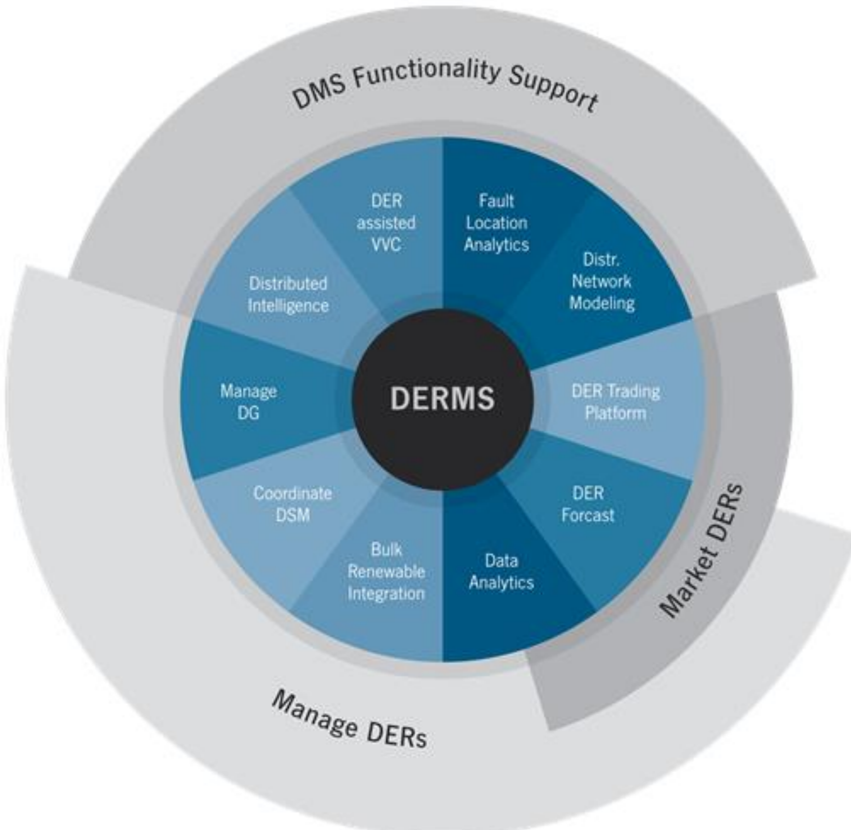
A DERMS is a software solution that incorporates a range of operations to adjust the production and/or consumption levels of disparate DER directly or through an aggregator. The visibility of a DERMS within the distribution grid is typically from the substation downward (or outward) to the low-voltage secondary transformer and includes different levels of aggregation, such as at the substation bank, individual feeders, segments comprising a feeder, and distribution transformers. A DERMS may individually address disparate DER at the edge of the distribution grid by communicating directly with smart inverters, DC converters, other equipment, or communicating with third-party providers who have aggregated DER in an operational area and are presenting the aggregated DER as a combined controllable resource.

A DERMS can be integrated at a wide range of levels and can vary broadly in scale. Regardless of the placement or scale, a DERMS provides several key functions:

- Aggregation: DERMS take the services of multiple (potentially millions) individual DER and present them as a smaller, more manageable, number of aggregated virtual resources that are aligned with the grid configuration. How DER are organized into groups is in itself a research question and must be flexible.
- Translation: Individual DER may speak different languages, depending on their type and scale. DERMS handle these diverse languages, and present to the upstream calling entity (e.g., a DMS) in a cohesive way.
- Simplification: DERMS provide simplified aggregate services that are useful to distribution operations. The services are power system centric rather than DER-type centric. Complex device-level settings, such as volt-var curve points and fast iterative settings updates are abstracted away as services are achieved and sustained. The simplified services provided by DERMS are standardized supporting the ability of multiple upstream calling entities.
- Optimization: A given service to be provided by a DER group may be achieved in many ways. Different smart inverter functions may be best at different locations or times. Different types of DER (e.g., storage, advanced loads, or solar) may make more sense in one circumstance than in another. DERMS provide requested grid services in the optimal way – saving cost, reducing wear, and optimizing asset value.

These functionalities integrating with established systems such as a DMS and DRMS, a DERMS can be used to monitor, optimize and dispatch DERs, including energy storage, DR and EVs.[67] This requires standardized protocols, telemetry and control interfaces. The functions described above are depicted in Figure 15.

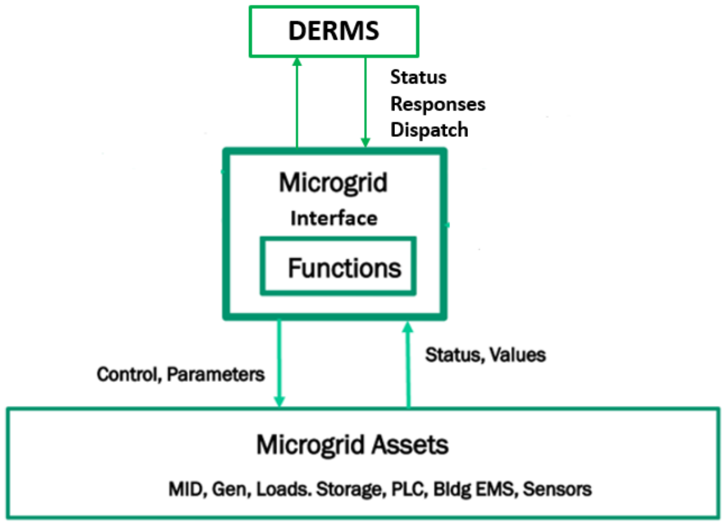
Figure 15: Key DERMS Capabilities[68]



Microgrid Interface

A microgrid is a group of interconnected loads and DER within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in grid-connected mode or island mode.[69] As such, the microgrid interface includes load disconnect/reconnect capability (e.g., isolation breakers); measurement; communications; protection devices that can enable seamless interoperability between interconnected, islanded modes; and synchronized reconnection.[70] Figure 16 conceptually illustrates a microgrid interface to the distribution grid. Microgrid specific standards such as IEEE 2030.7-2017 also apply to these interconnections.[71] The microgrid and its internal systems and controls, such as a microgrid controller, are not within the scope of this volume.

Figure 16: Microgrid Interface Framework[72]



Advanced Inverters

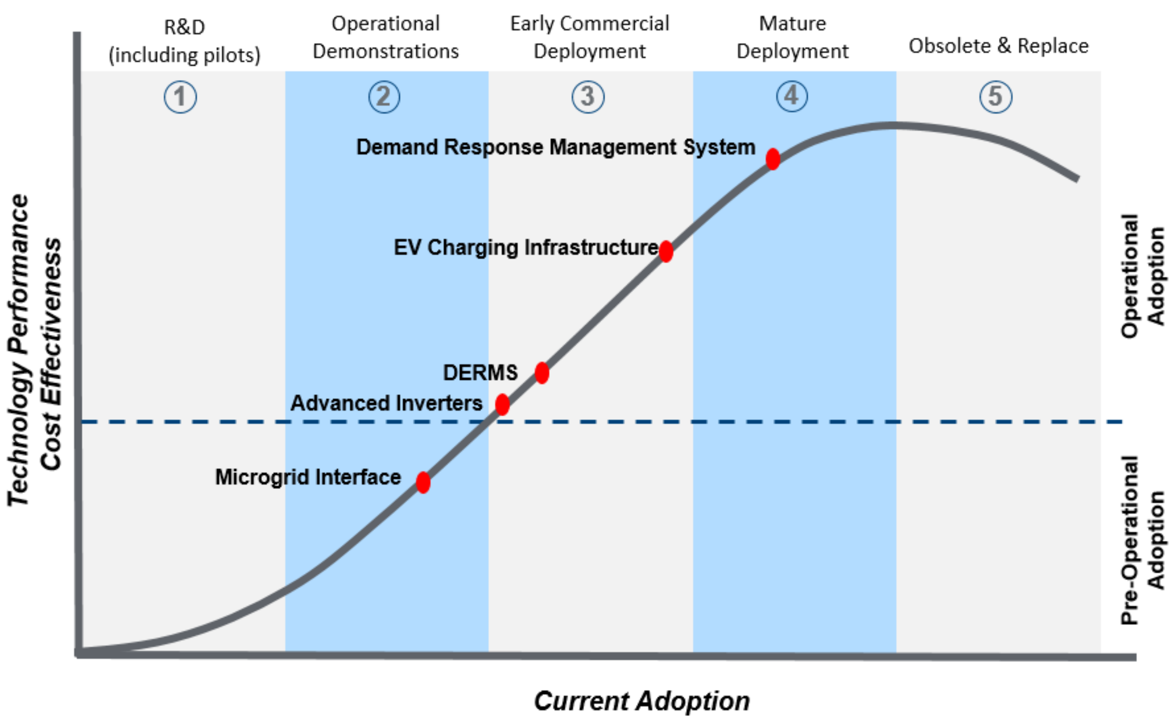
Advanced inverters are DC to AC inverters compliant with IEEE 1547-2018[73] and UL 1741 SA[74]. Advanced inverters (also referred to as smart inverters) have autonomous functions including volt-var, volt-watt, frequency-watt and are capable of supporting the grid during normal and abnormal conditions. This includes supporting operating voltage and frequency system conditions. Advanced inverters may also provide dynamic reactive/real power support, voltage and frequency ride-through, ramp rate controls, and secure communications with the ability to accept external commands.

EV Charging Infrastructure

EV charging infrastructure includes stations that supply power to EVs (light-duty or heavy-duty). EV charging stations typically come in three configurations: level 1 (120 V), level 2 (240 V), DC Fast Charging (DCFC) at 50 kW or greater.

2.2.5.3 ADOPTION MATURITY ANALYSIS

Figure 17: Distributed Resource Management



DRMS functionality to aggregate and programmatically manage DR assets is at a mature stage with wide adoption. Multiple vendors' commercial products are available in the market and have been operationally deployed over the past decade.[75] It should be noted that current solutions rarely coordinate with transmission system or distribution system operations technologies. This is an area of future concern as the number of subscribers in DR programs increases. Also, as the use of other types of DER for grid operations increase, it may be necessary to consider a single software system to optimize the use of all DER and third-party aggregations of DER, which currently installed DRMS' are not able to provide this capability. As such, it is possible that DRMS will be subsumed by DERMS.

DERMS are in an early stage of operational demonstration with market and operational factors driving the various levels of maturity of DERMS products. The power industry grapples with a single, unified definition of DERMS. This is due to varying opinions of the operational and technical capabilities envisioned. DERMS that have been deployed to date are also highly dependent on protocols and custom interfaces specific to each project, as the uniform application and availability of certain interoperability standards is a significant gap. [76, 77, 78 79]

Currently, a DRMS and DERMS may coexist in transition, but the industry is moving toward a single unified system to manage all DER providing grid services, including those in DR programs, individual assets, and third-party aggregated resources. Irrespective of this evolution, both alternatives drive similar needs in grid modernization as described in Volume I.

Microgrid interfaces for more complex resynchronizing interconnections including those hybrid microgrids that use utility distribution infrastructure to form a microgrid are in the operational demonstrations stage. At present, each microgrid interface is specifically defined according to the uniqueness of each implementation for each respective distribution system and microgrid. Commercialized technology solutions for distribution grid interfaces to support microgrid islanding and reconnection are needed to achieve a microgrid per the DOE definition. There are relatively few microgrids that fit the DOE definition, and hence commercial support and industry adoption is pre-operational.[80, 81, 82, 83, 84, 85]

Advanced inverters compliant with IEEE 1547-2018 and UL 1741 standards are in early commercial deployment.

EV charging infrastructure for Level 1 and 2 are mature technologies, but in early commercial deployment in terms of the scale of installations. Level 3 charging is undergoing rapid technology improvement. While some commercial products have been deployed, the rate of technological advancement suggests some potential for product obsolescence risk until products reach commercial maturity in terms of fast charging functional parameters.

Additional discussion of technology needs and related research and development for distribution market operations is discussed in Chapter 5.

2.2.6 Operational Data Management

2.2.6.1 TECHNOLOGY CATEGORY DESCRIPTION

Operational data management encompasses the software systems that are used to verify, store, and share data used by the operational analytic and control systems discussed. These operational data management systems are distinct from enterprise data management systems in relation to the operating performance requirements for availability, reliability, and most importantly, cybersecurity. Operational data management systems are typically physically separated from enterprise data systems. Additionally, distribution operational data management systems may be separated from transmission systems due to NERC cybersecurity requirements.

2.2.6.2 TECHNOLOGY DESCRIPTIONS

Meter Data Management System (MDMS)

MDMS are digital systems and processes to store, organize, and normalize meter data and share it with other applications, including customer billing, grid controls, and outage management. Advanced MDMS include integrated applications for analytics and interfaces with other operational systems such as GIS and OMS. MDMS include specific provisions for both data security and data privacy.[86]

Distribution Data Historian

Data historian is software to archive and query time series data. Data historians used in electric utilities receive data mostly from DSCADA systems and support communication protocols and interfaces for data transfer. Occasionally, data historians receive data from external entities, such as DER operational information or meteorological forecasts.

Operational Service Bus

System integration software technology connects applications and services, support service composition and workflow management, and provides asynchronous data and state transfer among data sources, applications, and processing or transaction services.

Data Warehouse / Data Lake

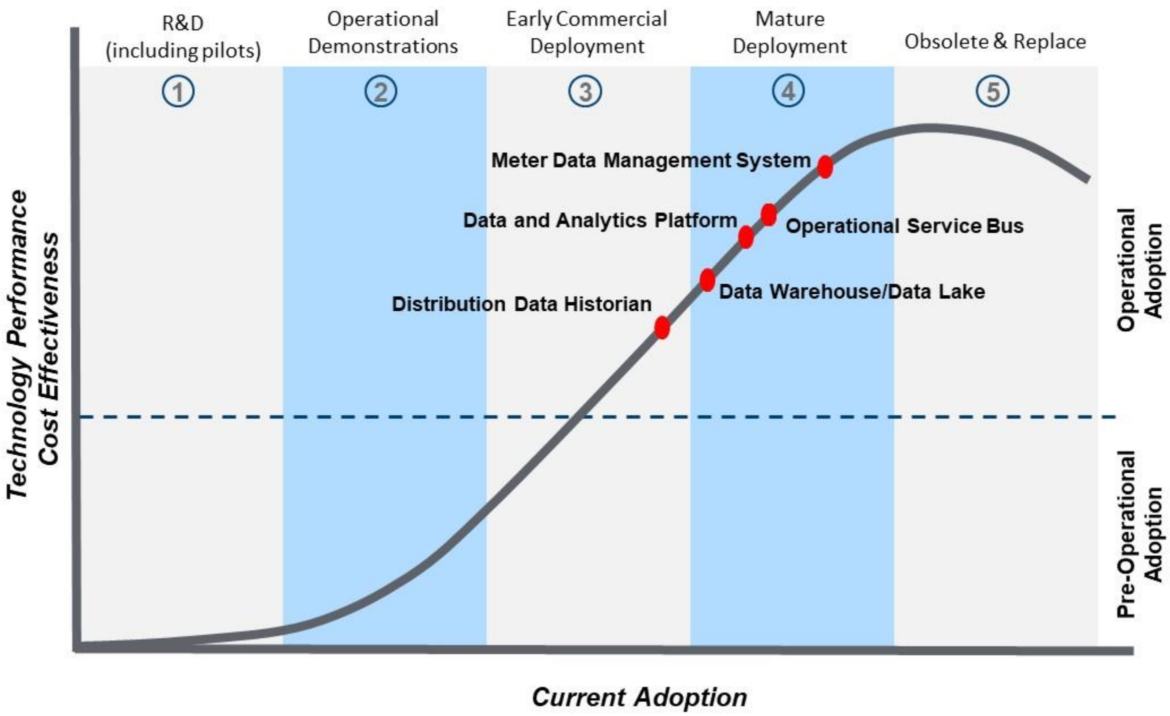
A data warehouse or data lake is a repository of data collected from one or more disparate sources and integrated to support business or operational analysis.

Data and Analytics Platform

A data and analytics platform is an organized and integrated combination of tools designed to provide contextual analysis from large datasets. It combines techniques and mechanisms for obtaining and preparing data, an execution engine, and various analysis and visualization tools to present information.

2.2.6.3 ADOPTION MATURITY ANALYSIS

Figure 18: Operational Data Management



The underlying technologies used for operational data management systems are mature and in various stages of deployment in the industry for distribution data management purposes concurrent with the implementation of sensing and measurement, operational analytics and control systems. Additional discussion of technology needs and related research and development for distribution market operations is discussed in Chapter 5.

2.2.7 Operational Communications Infrastructure

2.2.7.1 TECHNOLOGY CATEGORY DESCRIPTION

Communication technologies may be considered from two aspects:

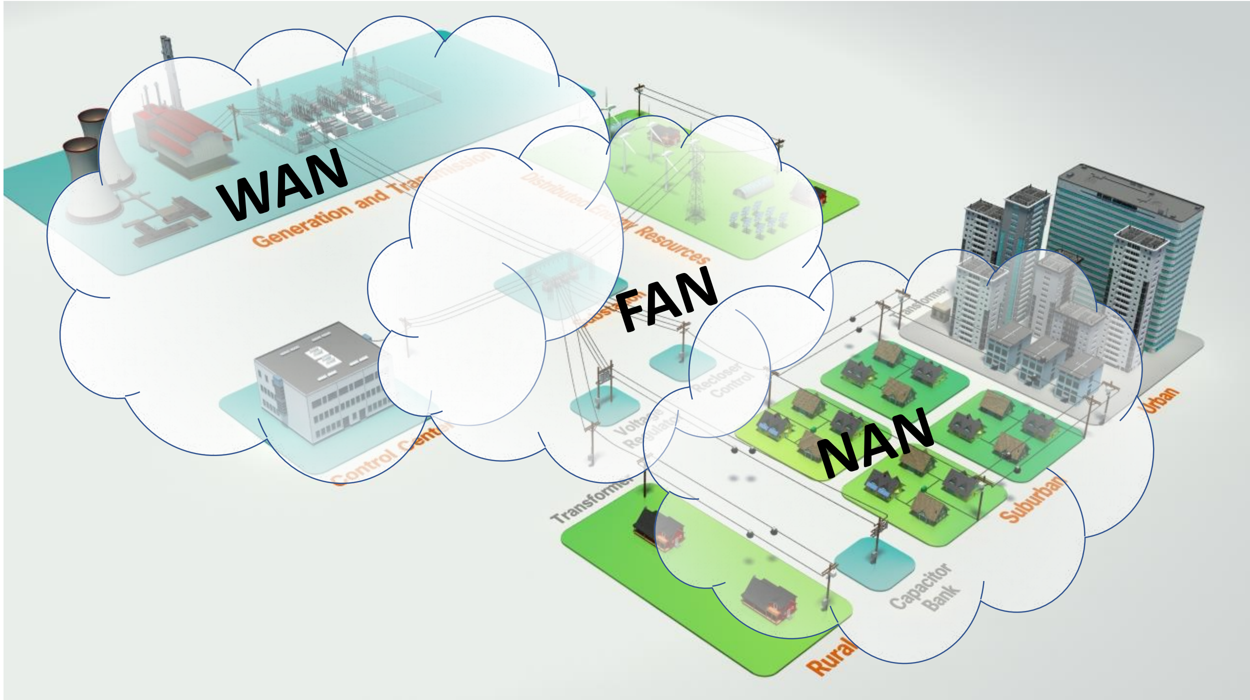
1. The way in which data is conveyed, which for the purposes of this volume falls into one of two general groups: Internet Protocol (IP) packet technologies (which includes Multiprotocol Label Switching (MPLS) and Carrier Ethernet), and Time Division Multiplex Communication (TDM)/analog technologies.
2. The physical media that carries the signal. Physical media may be wireline, such as optical fiber, twisted pair/cable, or coax or wireless. Wireless physical media may include satellite,

Worldwide Interoperability for Microwave Access (WiMAX)/ LTE, microwave, cellular mobile, land mobile radio (LMR), or other radio services such as paging that may also be referred to as radio or radio frequency (RF). In many cases, a physical link may be used for either IP packet or TDM communications by changing the telecommunications equipment at each end.

Operational communication infrastructures for the distribution grid include wide area networks (WAN), field area networks (FAN), and neighborhood area networks (NAN).[87] The diagram in Figure 19 is an idealized representation of such a hierarchical network architecture. Some network designs may have a flattened architecture with one or two tiers. Larger networks over wider geographies may have multiple dedicated networks for siloed applications using a variety of transport technologies and infrastructures. Technologies supporting distributed resource management include:

- WAN
- FAN
- NAN
- Communications Network Management System

Figure 19: Operational Communications Infrastructure[88]



WAN

There is generally an enterprise WAN that transmits organization information and voice communications as well as a grid operations WAN which is primarily involves grid operational information, and controls and protection signals. The enterprise network transport infrastructure may overlap with the operations WAN. Material differences exist between business and operational networks related to performance quality, reliability, and cybersecurity. This volume is focused on operational networks. Within the context of the distribution grid, the WAN spans up to an entire service area, linking substations, and operating or control centers. Older implementations of WAN may consist of multiple networks. The WAN may also provide the two-way network needed for SCADA, and points of presence for interconnection of FANs and specific high bandwidth and/or low latency applications (e.g., teleprotection).

FAN

As with WAN, a FAN may be multiple siloed purpose-built networks. FAN connects the NAN with the WAN by providing a link to transmit data, signals and other (backhaul services) from NAN concentrators or access points to WAN points of presence. Interconnection between substations is provided by the WAN. Substations may provide the physical location of a WAN point of presence used by the FAN. FAN services also include low latency and peer-to-peer (P2P) communications for protection and control.

NAN

A NAN supports information flow for grid edge devices (e.g., smart meters or DA devices) and the FAN. It enables data collection from customers in a neighborhood for transmission to a control center. NAN enables a range of smart grid applications, such as smart metering, service disconnect switches, and power outage notification messages. The typical technology deployed for NAN is narrowband mesh radio supporting P2P connection among edge devices to route information to access or collection points with FAN communication.

Because meters are located in a wide diversity of environments, there is no single technology that is capable of reaching every meter cost-effectively. In order to communicate with meters in particularly challenging environments, technologies generally used for FAN or WAN may be used for NAN applications on a specific basis.

Other Radio Services (including Paging)

There are a multitude of fixed and mobile radio systems that operate at different frequencies and different licensed or unlicensed Federal Communications Commission (FCC) requirements. It is beyond the scope of this volume to cover these in any depth. The Utilities Technology Council[89] provides a wealth of information on communications on both private infrastructure as well as telecommunications service provider (SP) offerings.

2.2.7.2 TECHNOLOGY DESCRIPTIONS

WAN Technologies

The following technologies may be leveraged to create WAN communications networks to address unique operational requirements for specific geographic and topological conditions. Rarely can one communications technology provide complete coverage and meet performance requirements. Telecommunications engineering includes consideration of various technologies to address the complete solution in the most cost-effective manner.

<u>Multiprotocol Label Switching (MPLS)</u>

MPLS is an IP packet-based data-carrying technique for high-speed, high-performance telecommunication networks and enterprise users. MPLS uses packet labeling for faster packet forwarding on networks, rather than long network addresses. The labels identify virtual links (paths) between distant nodes rather than endpoints. MPLS is a multi-services network technology that facilitates transport of most forms of traffic, from traditional serial-based technologies such as SCADA RTUs to International Electrotechnical Commission (IEC) 61850 packet-based microprocessor-based devices. [90,91, 92]

MPLS is often regarded as more costly and complex than single service technologies and may require skills more commonly found in information technology (IT) rather than operational technology (OT).

SP MPLS is MPLS service provided by telecommunication service providers to their customers. Private MPLS is MPLS technology implemented on communication infrastructure.

<u>Carrier Ethernet (CE)</u>

CE is IP Ethernet presented without exposing the complexity (or flexibility) of the underlying technology that is used to provide the service, such as MPLS. CE is available from telecommunication service providers or may be deployed on private network infrastructure.

<u>Time Division Multiplexing (TDM) and Analog</u>

TDM and analog are two families of communication technology that form the legacy infrastructure of grid communications. TDM is a method of transmitting different signals over a common path by synchronized timing of when each signal appears. This provides easy access to timing and synchronization that has been useful for a number of grid applications, such as SCADA control of switches or relays and coordinating actions between substations. Analog communications are direct circuit connects, including dedicated lines, between two or more points that may carry voice or encoded data.

Public Switched Telephone Network (PSTN) is the circuit-switched analog network that provided telephony, leased lines, and modem lines before telecommunication carriers converted to digital packet-switched infrastructure.

<u>Paging Systems</u>

Traditional paging involves the sending of a one-way signal from a central station to a device that alerts the user when it arrives with a short text or data message. When used for load shed programs, the receiving device activates a load shed device(s) based on the contents of the message. Some paging systems also provide limited two-way communication with the capability for a message to be acknowledged, or for the receiver to send a short reply.

Satellite Communication

Satellite communication is seen in many aspects of wide-area communication. Direct digital satellite communications can be established via a satellite telecommunications SP and a satellite antenna such as a Very Small Aperture Terminal (VSAT)[93] at the ground site. Satellite communication has the distinct advantage of being available anywhere, independent of any ground infrastructure apart from the satellite antenna.

Mobile

Broadband mobile telephony services (i.e., cellular) can be provided by infrastructure that is owned and operated by a telecommunications SP, or by infrastructure that is owned and operated by a non-SP entity. Mobile service from a telecommunications service provider is referred to as "SP LTE." Mobile infrastructure owned by a non-SP entity is referred to as "Private LTE."

Applications of mobile services include:

- Backup communication for one of the other WAN technologies;
- Substation communication for remote or small substations, if in the coverage area;
- FAN communication connecting NAN mesh networks to the distribution company's WAN or directly to the company's data or control center;
- FAN communication to specific devices on the distribution network such as sensors (see Sensing and Measurement section); and
- Voice and data communication with the mobile workforce.

Mobile services currently include 4G, LTE, and LTE Advanced.[94] 5G[95] deployment is underway in selected locations nationally. However, 5G capable grid devices are not yet commercially available.

Private mobile telephony technologies include the same 4G, LTE, and LTE Advanced and 5G, but on licensed radio spectrum and infrastructure (cell towers and central communications equipment) owned by the distribution company.

Land Mobile Radio (LMR)[96]

These systems are primarily used for mobile workforce communication, and occasionally for device data. These may be either owned by the distribution company or contracted from a telecommunications service provider.

FAN and NAN Technologies

The following technologies may be leveraged to create FAN and/or NAN communications networks to address unique operational requirements for specific geographic and topological conditions. Rarely can one communications technology provide complete coverage and meet performance requirements. Telecommunications engineering includes that consideration of various technologies to address the complete solution in the most cost-effective manner.

Worldwide Interoperability for Microwave Access (WiMAX)/LTE

WiMAX is a standards-based technology enabling the delivery of wireless broadband (high bandwidth) access to endpoint devices.[97] The family of standards is based on the IEEE 802.16 set of standards.

WiFi

WiFi and WiFi mesh[5] are high bandwidth systems that use unlicensed radio frequencies, which are also available to personal computers, tablets, and smartphones for data communication. Applications of WiFi within the distribution grid are identical to those listed for mobile telephony.

Radio Frequency (RF) Mesh

Mesh networks are typically narrow bandwidth and useful for transmitting operational data, event information and control signals. Mesh networks enable end devices at each network node or point to communicate to a collector or collection point via multiple RF "hops." The collector may also be called a concentrator, gateway, or network access point. This characteristic of mesh networks allows for a cost-efficient way to deploy and build a network that encompasses greater distances while requiring less transmission power per device. Second, it improves system reliability since each end device can register with the collector via another communication path if the present communication path becomes inoperable. Third, by allowing end devices to act as repeaters, it is possible to deploy more nodes around a collector, thereby reducing the number of backhaul paths. [98, 6] While RF mesh technologies are the most common service for NAN, there are a few other technologies that are also used to support grid edge communication to field automation, direct load control devices, and AMI applications.

Other RF Systems

There are a variety of specialty, proprietary RF systems in use by providers of grid equipment such as protection devices[99] and by AMI vendors.[100] These include both PTP and point-to-multipoint systems.

Power Line Carrier (PLC)

PLC technology is narrow bandwidth and utilizes the same wires that carry electric power to carry communications from smart meters to an aggregation point, usually located at the low voltage distribution transformer. Communication from the aggregation point may be via an RF mesh network if there is one present in the area, or via one of the FAN technologies used to connect RF Mesh and other NAN technologies back to the data center.

Broadband over Power Line (BPL)

BPL is out of scope for this paper. At one time BPL was regarded as having the potential for wide area communication and the ability to provide broadband internet services. However, BPL remains a niche solution and is no longer regarded as viable for industry WAN or the provision of internet services.

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[5] ABB Tropos WiFi Mesh

[6] It should be noted that WiSUN is an industry group working to develop standards for RF mesh communications systems that include interoperability

Peer-to-Peer (P2P) Systems

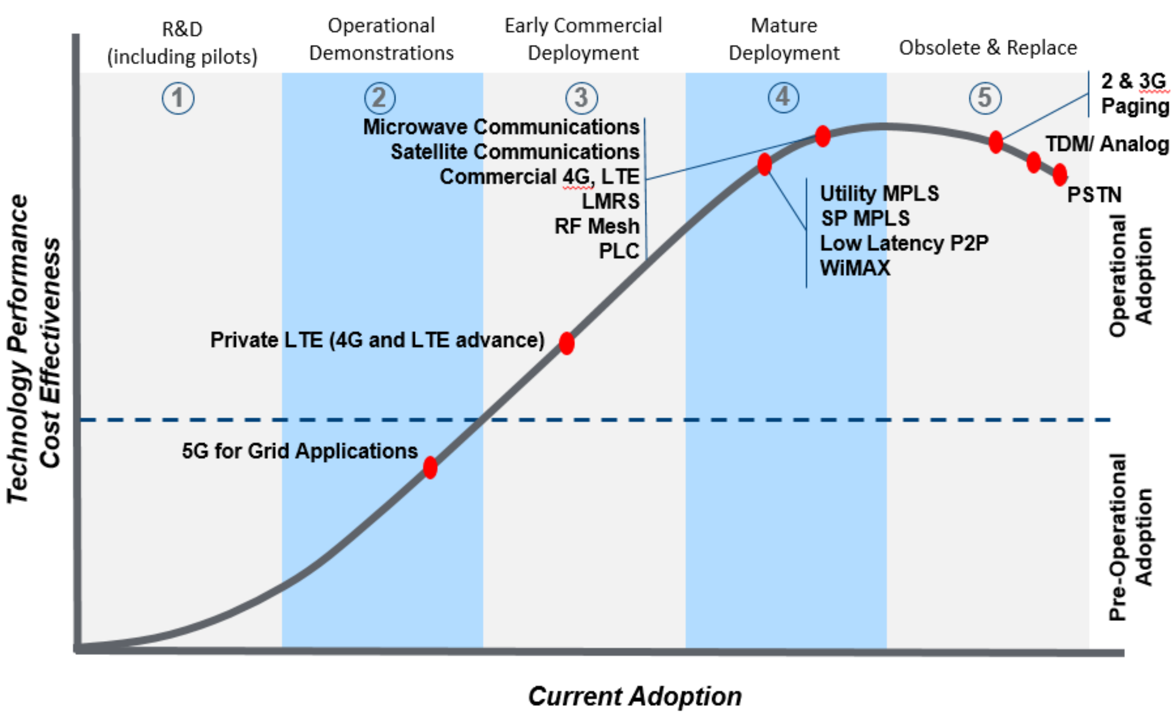
P2P communications enable the direct connection of one device to another. P2P may be a network service or standalone capability. As a network service, the central part of the system responds to a request by providing each device the information and resource necessary to establish direct communication. As a standalone capability, P2P becomes synonymous with point-to-point (PTP) and is a dedicated communication link between devices.

Communications Network Management Systems[101, 102]

Communication Network Management Systems provide insight into the touch points between power and communications equipment to configure networks, monitor performance, and manage behavior. [103] In addition to managing network devices, the same tools can manage and view multiple networks.

2.2.7.3 ADOPTION MATURITY ANALYSIS

Figure 20: Communications Infrastructure



The need for ubiquitous communication in the modern distribution grid stems from the goals and objectives set forth in Volume I. Secure and reliable communication is essential to the operation of a modern distribution grid.

MPLS is a mature technology used in multiple industries. It is the core technology of telecommunication service provider networks. It is widely deployed for both IT and operational networks. However, the cost and complexity of a private, enterprise MPLS implementation need to be considered.

PSTN infrastructure is considered obsolete; carrier revenue for these circuits is declining as carriers choose to move to technologies such as VOIP and LTE. Service providers either have discontinued or have filed regulatory notices to discontinue PSTN communications. PSTN used for the power grid must be replaced.[104, 105] PSTN carrier "private-line," "non-switched," or "leased-line" services have been used for SCADA, protection, and control. These are the services that PSTN carriers have made obsolete and are replacing with MPLS or CE, both of which are viable options.

TDM and analog include technologies such as Synchronous Optical Networking (SONET)/ Synchronous Digital Hierarchy (SDH), which were widely used as the backbone of transmission networks in smart grids as well as in carriers. For the purposes of this volume, TDM/ analog technologies can be considered obsolete. The increased performance and richer features of IP networking technologies such as MPLS have led to SONET/ SDH being almost completely displaced by IP networking in corporate IT WANs. SP backbone networks are now almost exclusively MPLS.

For process control automation, TDM may be considered by some industries to be a legacy technology that is not entirely obsolete. A couple of original equipment manufacturers (OEM) vendors have recently brought new TDM equipment to market to serve such industries. However, because there is no longer a critical mass of R&D investments in new capabilities, security or performance, TDM is likely to become obsolete.

Paging systems are widely regarded as obsolete and are rapidly disappearing as paging vendors have gone out of business and systems have been turned off. Most direct load control programs, which had been using paging systems since the 1980s, have recently been converting to mobile services or NAN connectivity.

Satellite communication is in mature deployment; however, important tradeoffs and limitations include high latency due to connectivity with satellites in a geosynchronous equatorial orbit and recurring cost based on data usage and recurring cost based on data usage.

Microwave communications is in mature deployment, used especially in areas where it is cost prohibitive to construct physical communications infrastructure.

WiMAX is a mature technology with limited adoption for grid communications. Deployments on the U.S. distribution grid have been hampered by lack of licensed spectrum, especially after the change in designation of the 3.65 GHz band from "lightly licensed" to "unlicensed" by the FCC. Also, large carrier deployments of WiMAX have been abandoned (e.g., ClearWire in the US) as the technology lost in the marketplace to LTE. OEM vendors have pivoted to Wireless Internet Service Providers (WISP)[106] and enterprise deployments.

SP LTE or mobile services from SPs have been used as the WAN backhaul for most AMI deployments to-date, as wells as an option for replacing paging services for direct load control programs. However, mobile services are not widely used in field automation given the availability, reliability and other performance requirements. This is because commercial mobile services are based on consumer needs that do not have the same service level requirements. For example, this lower level of service is sufficient for a meter reading. Note that 2G/3G is being phased out in the US and globally by the mobile carriers to focus instead on 4G, LTE, and 5G.

Private LTE networks have been deployed in limited numbers and are in a stage of early commercial deployment. Private LTE networks can be used for supervision and communication with grid automation devices and NAN applications such as AMI.[107, 108, 109, 110, 111]

RF Mesh networks have emerged as the leading technology for AMI and DA deployments in North America. The tradeoffs are latency (data transmission timing) and throughput (bandwidth). This requires careful design to balance cost with the number of devices to manage the latency and bandwidth required for grid applications. According to the criteria used for This volume, RF mesh is in mature commercial deployment for AMI and early commercial deployment for field automation.[112] However, it is important to note that RF mesh systems are not interoperable. Wi-SUN Alliance[113] is an industry organization (modeled after the WiFi Alliance[114]) whose goal is to provide industry standards, interoperability and third-party certification.

PLC is primarily used in areas inaccessible to RF. PLC is much more cost-effective for European-type distribution grids as they have much larger low voltage transformers serving 20 to as many as 150 residential customers. There are several standards for PLC communication, including G3 and Prime in Europe and IEEE 1901.2 in the U.S., PLC is a mature technology, available from multiple vendors and deployed in production at a number of distribution companies.

3. DISTRIBUTION MARKET OPERATIONS

Distribution Market Operations technology categories and technologies enable the essential functions of a successful utilization of DER for distribution grid services. Operational market functions include sourcing services from DER providers; measuring and verifying the performance of participating resources, settlements, and payments; and market surveillance and oversight activities to prevent malpractice as described in Volume I.[7] These technologies mirror those used in bulk power markets with important distinctions, which are identified.

3.1 FUNCTIONALITY TO TECHNOLOGY MAP

These technologies are mapped to the primary Volume I functionalities supported, as shown below in Figure 21. This mapping was developed based on inputs, reviews, and discussions with industry experts during DSPx Phases 1 and 2. A discussion of the individual technologies and their respective maturities follows.

[7] See Volume I, Section 5.3, Distribution Market Operations

Figure 21: Distribution Market Operations

Distribution Market Operations	
Functionality	**Technologies**
Solution Sourcing	Procurement Administration Auction Platforms Program Administration
Solution Evaluation	Resource Risk-adjusted Benefit-Cost Evaluation Model Solution-Market Simulation Model Portfolio Optimization Model
Solution Portfolio Optimization	
DER Services to Distribution and/or Wholesale Market	DER Management Platform
Market Clearing & Settlement	Clearing & Settlement Systems Contract Administration Measurement & Verification Systems
Billing	Customer Information Systems Complex Billing Systems
Market Information Sharing	Web Portals
Market Participant Rules	
Market Security & Cybersecurity	Cybersecurity Techniques & Tools
Market Oversight	Market Trend & Behavioral Analysis Tools Ex-post Market Analysis Tools

3.2 DISTRIBUTION OPERATIONAL MARKET TECHNOLOGIES

3.2.1 Distribution Operational Market

3.2.1.1 TECHNOLOGY CATEGORY DESCRIPTION

Distribution operational markets involve the use of DER-provided services as non-wires alternatives[115] and in some circumstances the use of export energy. In addition to the planning and grid operational technologies described above, there are technologies needed to support distribution operational markets over the next five to fifteen years. Other potential market structures and specific market designs are beyond the scope of This volume.

3.2.1.2 TECHNOLOGY DESCRIPTIONS

Procurement/Auction Platforms

Procurement or auction platforms facilitate non-wires alternatives and all resource procurements/auctions as well as potential real-time (day-ahead and intra-day) proposals for distribution grid services by DER services providers. These platforms are adaptations of wholesale market platforms that serve these functions.

Proposal Evaluation Tools

Risk-based evaluation methods and models assess benefits-costs and compare customer and/or DER provider proposals for energy and/or grid services and other alternatives including “wires” solutions.

Portfolio Optimization

Portfolio optimization models determine the optimal mix of proposed non-wires and wires solutions to address distribution needs, as well as the potential for synergistic value for solutions to address more than one need identified in distribution, transmission, and resource planning. The model also supports the operational dispatch of available distributed resources under contract, programs, and/or tariffs within a portfolio designed to meet distribution system needs.

Clearing and Settlement Systems

Clearing and settlement systems support the settlement process, including calculating payment determinants based on performance, contract or tariff terms, and any charges for non-performance. The scale of these complex structured transactions may grow to a large quantity of individual distribution-level transactions, including grid services involving accounting for relatively small units and dollar values (micro-transactions). Traditional CIS billing systems and wholesale settlement systems do not support the potential transaction scale and diversity of pricing schemes and tariff/contract terms. Today, for example, most special retail tariffs and DR programs are handled manually using less sophisticated spreadsheet/database tools that will not scale. This creates the need for settlement systems that automate a settlement process for the potential scale and small unit size of transactions and create visibility into the valuation of services and related monetization methods.[116]

Market Information Portals

Market information portals may include identification of grid services and related locational opportunities, participant registration/enrollment and program/procurement eligibility criteria, pricing information, secure access to participant settlements, and notifications. A market portal may convey different types of information designed for various audiences, such as customers, energy service providers, and DER aggregators, as well as DER provided asset and operational information enabled by standards such as Orange Button Connect.[117]

Compliance and Surveillance Analytics

Compliance and surveillance analytics tools and systems support overseeing and ensuring market participants' compliance with the market rules. Distribution operational market participants would include both DER providers and directly participating customers.

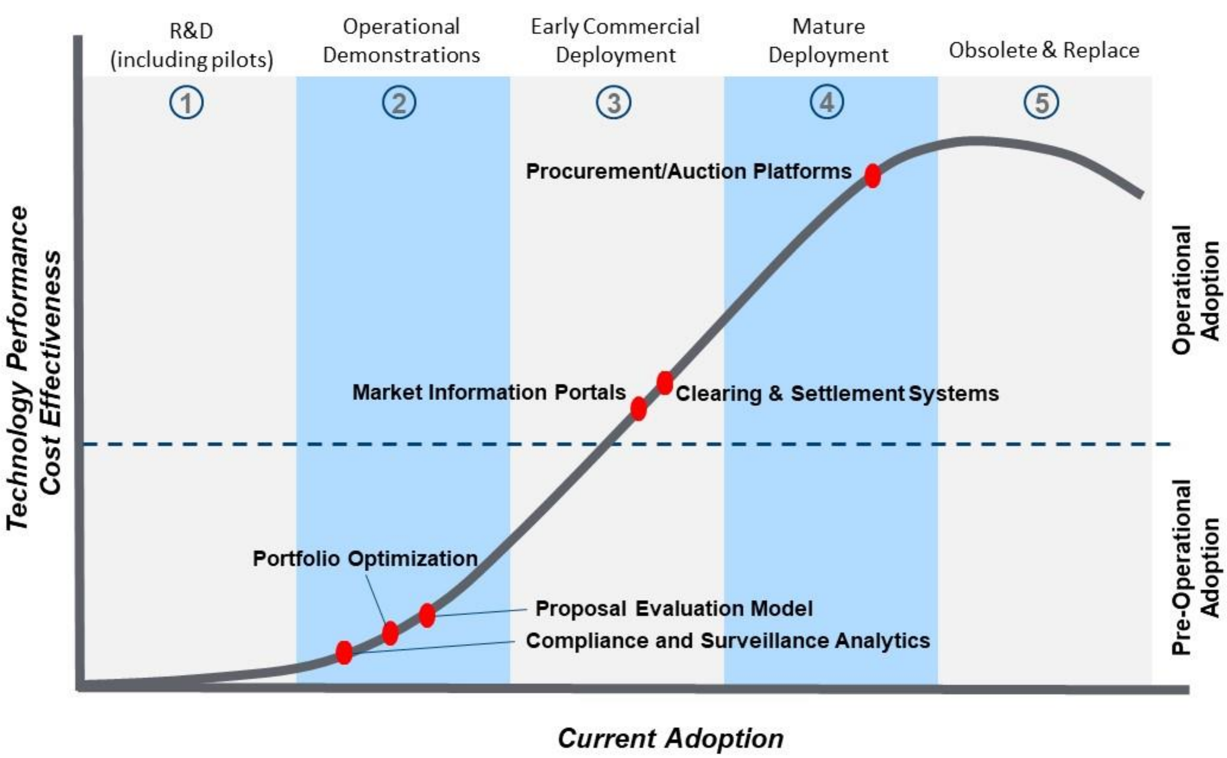
Market participation rules are being defined in terms of the requirements and responsibilities for market participants in order to provide a high quality of service delivery. As such, tools will be needed to oversee and ensure participants' compliance with the new market rules. Expected functionalities will include:

- Qualifying (e.g., credit and performance checking) of new participants;
- Tracking pre-scheduled or real-time service deliveries;
- Managing of participant interactions (e.g., service complaints) and participant non-performance; and
- Monitoring market participation (e.g., liquidity).

Compliance and surveillance tools can provide continuous surveillance and evaluation of distribution markets, which helps prevent any wrongdoing or anti-competitive behavior and ensures markets perform as intended. The functionalities of market surveillance tools can be split into two: identifying and addressing wrongdoing in the bidding process, and auditing of posted clearing prices and the evaluation of efficient functioning of the market.[118]

3.2.1.3 ADOPTION MATURITY ANALYSIS

Figure 22: Distribution Operational Market



Information portals related to customer information access and system data exchange are in early commercial deployment. A few Green Button Connect implementations have been established, or are under development. Portals sharing hosting capacity information through maps and data have begun initial deployments and are in early commercial development. Other information portals such as Orange Button Connect are under R&D, with the data exchange standards in development.[119] It is anticipated that additional locational market opportunities will become available online potentially through a bulletin board, or as additional information provided on the emerging hosting capacity maps. Such a portal could be further extended in functionality to support various sourcing mechanisms such as DER procurement. This sourcing function would require secure, confidential access for market participants.

Settlement systems for distribution operational markets are in operational demonstrations, primarily beginning with the settlement of complex tariffs and DR programs.

Market compliance and surveillance tools are widely used in wholesale markets and are regarded as mature for the wholesale electricity grid. However, these tools are not readily adaptable to the distribution system given the complexities of the network topology, relatively small number of participants and greater potential for market power. As such the wholesale market concepts apply but need to be adapted to distribution needs. Research has begun to identify specific issues to address, but solutions have not yet been implemented for the distribution grid.

Many of these technologies can be adapted for distribution operational market oversight. For distribution operational markets, the oversight scope will include data and information regarding assumptions and methodologies for determining locational and system value as well as sourcing results and market bid information.

Additional discussion of technology needs and related research and development for distribution market operations is discussed in Chapter 5 below.

4. SUMMARY

4.1 KEY CONSIDERATIONS

The previous sections of this volume contain a survey of grid modernization-related technologies mapped against the functions associated with distribution grid planning, operations, and markets. This section highlights a few general areas where there are technology or implementation gaps that must be addressed within the next 5-10 years in order to achieve a resilient future distribution grid potentially with automation and high penetration of distributed and/or variable resources.

Integrated Modeling

Conducting planning studies on the grid has become more complicated to accomplish. Today, models cover nearly every aspect of the electric power system: the transmission grid, the distribution grid, power plants, markets, planning models, optimal power flow, forecasting, end-user modeling, and so on. Up until now, this modular modeling approach has been sufficient with unidirectional flows of control, communication, and power. However, the glaring deficiency of a modular piece-by-piece power system modeling approach is that it ignores the fundamental physical coupling of the entire grid (generation, transmission, distribution, and customer resources) that arises from the fact that power flows through the whole network while load and generation must be instantaneously balanced. The limitations are principally: (1) the lack of an appropriate physical-mathematical model that captures the entire system; (2) the fundamental computational difficulty of solving power flow or optimal power flow (OPF) problems; and (3) the lack of communication and control infrastructure to validate or implement such a model.

High levels of DER adoption create a need to address a number of emergent planning considerations that need to be addressed. Firstly, reverse power flow from distribution feeders back into the transmission network is already a very real possibility in markets with high solar penetration; the assumption of passive and predictable loads in the distribution grid will soon be inconsistent with day-to-day operations. Secondly, non-dispatchable and highly variable renewable sources (solar and wind) could contribute a rapidly increasing share of bulk energy in the grid. This reverses the historical paradigm of dispatchable generation responding to passive load. Thirdly, the end consumer is becoming a more active consumer *and* producer of power. Smart meters and IoT devices are proliferating, allowing customers to understand their consumption of energy in a far more detailed way than was previously possible. With this information, consumers are able to respond to price incentives (e.g. time-of-use rates), and more will participate in power markets. Fourthly, EV charging stations spread across the utility's territory or multiple utility territories will impact the distribution grid on which it operates, the bulk power requirements at the transmission level, and consequently, the interaction of control across the transmission-distribution (T-D) interface.

These shifting paradigms are eroding the traditional compartmentalization of grid functions that has allowed portions of the infrastructure to be modeled independently. Models that give researchers, planners, regulators, and operators better insight into the functioning of the entire grid as a unified system will be essential in the future.

Granular modeling of end use customer behavior is needed for long term planning in order to predict customer adoption of new technology, for understanding usage patterns in operational planning and control schemes, and for market or incentive design. Tools from probabilistic scenario analysis and stochastic optimization will play an important role. Identifying the stochastic parameters in a model enables an explicit characterization of the uncertainty in forecasting. Such a characterization will allow a transparent treatment of risks. Alternately, aggregations of energy-producing devices will have collective dynamics, market effects, and impacts on operations at both the transmission and distribution levels that are worth special consideration.

Progress in grid modeling is needed and validation of which components of the power system impact each other and which can still be safely decoupled is essential. Making complex models easily interpretable through visualization and data summary will be beneficial since illustrative conclusions will be an anchor point for industry and regulatory collaborators to stay engaged.

Risk Quantification

Utility planning and regulatory oversight have traditionally relied heavily on a worst-case deterministic framework for modeling and mitigating risk in the electricity system. This has worked well in the past when uncertainty is low but will become untenable in the future when the proliferation of renewable generations and DER will greatly increase the uncertainty in supply and demand. Moreover, the changing environment and increasingly complex system dynamics can increase the risk of catastrophic failure events. New methods of defining, modeling, quantifying, and mitigating these risks to the power system is of great interest to the utility and regulatory communities.

Risks to "normal" operation have traditionally been incorporated into a reliability framework that must be updated to include uncertainty in equipment operation, possibly unreliable data sources, and variability in forecasts on both the supply side and the demand side. However, risks in "contingency" situations (e.g., major equipment failure, cascading blackouts, widespread weather phenomena, cyberattack) call for different treatment, and the development of system resilience tools. Clear definitions are needed because they determine what sort of modeling and analysis is relevant for estimating their impact or likelihood.

Analyses tools need to quantify the effects of a particular risk on system parameters of interest. Use of a deterministic model of customer growth only allows for worst-case analysis to bound risk or average-case analysis and does not properly take into account random variations around the average behavior. On the other hand, a stochastic model, which defines some of its parameters as random variables/processes, is endowed with inherent randomness and natural measures of variance.

Utilities and regulators talk about the need to evaluate risk and implement risk mitigation measures in the modernization of the grid. This calls for close collaboration between researchers and industry to develop the definitions, models, and to evaluate risk metrics. This will help to improve the resilience of the power system, where the grid can quickly recover from unanticipated disturbances and where the speed and magnitude of the response to a disturbance is proportional to the disruptiveness of the event.

Architecture and Interfaces

The current paradigm for grid control and corresponding electricity services markets exist almost exclusively for the high-voltage transmission network. This includes detailed knowledge of the network state through extensive monitoring of the physical infrastructure and centralized control of dispatchable generation (gas, coal, nuclear) within each ISO/RTO territory. The distribution network has been largely left out of the grid/market operator's view. Instead, end-consumer demand is aggregated by utilities at the substation and fed into the high-voltage network as a passive load. This has been acceptable because of the predominance of one-way power flow from the substation as well as radial grid topologies which have historically allowed utilities to only manage bulk power delivery and congestion in the distribution grid. However, large amounts of DER uncontrollable, under aggregated control (possibly spanning multiple nodes in the transmission network) and distributed generation at customer endpoints (i.e., rooftop solar or home battery storage) are straining the current passive control methods in the distribution grid. Expanding participation in grid control and markets to the low-voltage distribution feeders will necessitate new architectures for control and financial transactions.

A prerequisite for extending active grid control to the distribution grid will require a large improvement in the sensing, monitoring, and actuation capabilities available to utilities. This means making improvements to sensing and actuation hardware, communication networks, data collection, data storage, state estimation models, and computation for solving power flows as well as dispatching resources.

The size and extent of the low-voltage distribution grid (as compared to the transmission system) drives a need for advances in distributed control and optimization. The transmission system paradigm of centralized monitoring, control, and dispatch---while feasible in small networks---would require a massive investment in sensing, communication, and computational infrastructure in a distribution grid. A control and monitoring infrastructure whose architecture allows state information to be produced and consumed locally, in addition to control actions being computed and actuated locally, will reduce infrastructure investment while also improving reliability, resilience, and efficiency compared with a centralized architecture.

Distributed control will be essential for the distribution grid for four reasons, pertaining to communication, computation, uncertainty, and privacy. First, the time and resources required to communicate measurements from an entire distribution network to a control center for processing will create a bottleneck that will be too expensive, if even possible, to overcome as distributed generation and controllable loads proliferate. Distributed or hierarchical control schemes that compute and actuate locally, at the level of individual customers or local communities, will significantly lower that overhead.

Second, a single distribution feeder may have thousands of buses. Given the poor scaling of solving and optimizing power flows, centralized dispatch may take a long time to solve making it less responsive at scale. Parallelizing parts of the optimization computation offers opportunities for faster solutions. Third, with increasing uncertainty due to volatile renewable generations and dynamic loads, future applications may require real-time response when and where disturbances arise. A situation-aware distributed control architecture that senses, communicates, computes, and actuates locally can be much more effective.

Finally, distributed system's involve multiple organizations (e.g., utilities, large industrial and commercial loads, communities, and prosumers), each with its own objectives and constraints that create challenges for operational coordination significant levels of distributed resources. A distributed control architecture should be considered to manage DERs across organizations and balance power over the entire grid in a way that respects organizational boundaries and respective priorities.

Despite their advantages, distributed optimization and control are accompanied by several drawbacks that need further attention from the research community. They include improving robustness to latency and missing data (from faulty communication links), assessing the global optimality and stability of the distributed algorithms (as compared with centralized optimization), and boosting the speed of convergence of solutions.

4.2 TECHNOLOGY GAPS

From this report and discussion between utility industry representatives, regulators, and researchers have identified several themes that highlight distribution grid research areas of common interest to the three communities. This section is not intended to be a complete list of necessary research, nor to imply a prioritization of any of these research directions over others. However, these research areas are considered important to address the concerns brought forward by the utility and regulatory communities in the longer term, to support the development and operation of a modern grid.

Resilience

Resilience---that is, the ability of the grid to resist degradation and to recover from extreme natural or human-caused events in addition to the cybersecurity of grid edge customer-owned devices---will need to be defined particularly for the needs of the distribution grid. Although the transmission system has several well-defined notions of resilience, such as N-1 robustness to line failure and online reserve requirements for generators, these concepts may not be applicable directly to distribution networks. For example, the predominance of radial topologies renders N-1 standard somewhat less meaningful in the latter.

After establishing suitable definitions, resilience standards should be developed that allow the research and industry communities to benchmark the performance of simulated and actual systems in fault situations. These standards may come in the form of technical requirements (along the lines of N-1 reliability) but should also include scenarios similar to the IEEE standard test cases for optimal power flow. Establishing resilience standards and a reference library of outage cases for the distribution grid will accelerate the inclusion of resilience analysis in future distribution system R&D.

R&D is needed to address distribution resilience across the US, including defining the relationship between resilience and reliability while also establishing resilience criteria for distribution grids, resilient distribution system designs, technology development and an investigation of the engineering-economic decision tools required. Some of the specific topics in this area are:

- Develop a structural analysis of resilience, from a system view rather than at a component level.
- The need to understand and manage the transition between normal operations and contingency operations, for utilities, DER providers/aggregators, and regulators. Is it possible to extend normal operational structures to handle more contingencies?
- The need to better characterize resilience. This might be a scenario driven process which develops extreme scenarios to create criteria and metrics as well as an analytic framework.
- The need to develop methods to simulate the effectiveness of resilience investments, in order to quantify the value of resilience for use in investment cost justification.
- Standardized guidance for resilient systems design.
- The need for metrics and progress indicators to evaluate performance of the future grid.

Forecasting DER and Modeling Customer Behavior

Knowing where, how much and when DER will be installed by customers at a granular level is already a challenge today. Electrification (e.g., EVs, fuel switching, etc.) will lead to new loads and load profiles. Turning these future uncertainties into real data is needed today and in the future. Planners need new forecasting data, tools, and methods.

To better understand the behavior of consumers, additional research is needed to address the uncertainty with distribution grid forecasting, including customer economic behavioral modeling, integration of top down system forecasts with granular bottom-up forecasts, planning methods under high uncertainty, and quantification of reliability of forecasts. This includes:

- Understanding the response of customers to dynamic price incentives (e.g., time-of use pricing) in the short term.
- Better insights on customer technology adoption rates on a longer timescale. The patterns of adoption---both on temporal and spatial scales---of smart home hardware, rooftop solar, home energy storage, and EVs are critical factors for planning distribution grid infrastructure investment.
- Quantifying and evaluating the uncertainty in forecasting in crucial areas such as population growth/migration, weather, and technology trends. Well-defined measures of uncertainty and risk will benefit grid planners and regulators in applications like building and evaluating utility rate cases.

- The need for stochastic modeling processes for the behavior of customers, which include behavioral science, both for planning (adoption behavior) and for operations (including transactive energy issues, pricing, and feedback mechanisms).
- Advanced forecasting with high DER penetration will require a more granular approach to load modeling, including various spatial and temporal characteristics of different DER. It is possible that connected home devices and the internet of things will simplify this by providing more detailed/granular data.
- The need for scenario-based methods of forecasting that include the uncertainty of any given scenario or the relative accuracy of prediction data, including methods to improve the feedback and control mechanisms for operational forecasting.
- The need for a framework for customer-based pilot/program ideas that allows for a comparative assessment of such programs to understand customer behavior. The transition of consumers from passive to active participants in the power system calls for more detailed modeling of their individual and aggregate behavior. The driving technological and market advancements behind this transition are the quickening penetration of distributed generation (rooftop solar and home energy storage), smart metering and dynamic pricing schemes, smart home devices, and electric vehicle charging.

Planning Models and Tools

Conducting planning studies on the grid has become more complex. New planning models, tools and techniques are needed to analyze the grid as consumers adopt new energy supply technologies, electrification increases and changes load profiles, inverter-based technologies displace synchronous generators, and energy storage systems become more commonplace. Two-way power flow and distribution level energy transactions, microgrid operations, reductions in system inertia and available fault current further complicate Integrated Grid Planning efforts.

Topic areas for future R&D to address integrated distribution planning (integrated with resource and transmission), including integrated transmission-distribution modeling, probabilistic analysis, and risk-based planning tools include:

- The need for developing the capabilities to do co-simulation across transmission, distribution and markets, as well as for key societal functions. This requires a shared approach to data, system interoperability and also ways to model processes and people in the relevant organizations, as long as humans are in the control loop.
- There is a need to develop better tools to model and plan for phase balancing on the distribution system as well as the approximate balance on transmission systems. Widely-used transmission-level models for computing, optimizing power flows and performing market dispatch, that assume flows across all three phases are balanced, are not suited for distribution grid modeling.
- The need for specific models for a multi-phase distribution grid since the distribution grid is low-voltage and unbalanced. One of the R&D gaps in this area consists of open

mathematical challenges with multi-phase optimal power flow, the accuracy of various approximations to AC power flow, and fundamental limits on controllability in unbalanced networks. Understanding where and how traditional methods or tools can, or cannot, be applied will accelerate understanding of the engineering challenges associated with multi-phase networks.

- The need for tools and standards to quantify the accuracy or uncertainty of these models in order to verify or validate their results including the development of standard test cases and reference scenarios specifically for realistic multi-phase networks.
- There is a need to develop tools to translate or visualize these complex full models into simpler, faster running "reduced order" models to help understanding of system function by planners and operators. This might give up accuracy for clarity and system level understanding.
- There is a need to understand with better detail the response of loads to various faults to support building better models.
- As more inverters are placed on the system, a better understanding of the potential cumulative harmonic impact and interaction across the grid will be required.
- There is a need to incorporate risk analysis, options for DER operations, and perhaps future policy decisions/uptake into planning models.
- The impact of the capacity factor on interconnection studies needs to be better understood, including the effects of different DER operational modes or contingencies/resilience events.
- The need for temporal, spatial and scale assessment tools for decision making.
- Development of standards, methods, and tools to incorporate non-wires alternatives from DER into planning models.

Distributed Power Management and Control Systems

Traditional power management, control systems, architecture, and designs are functionally challenged with high levels of DER integration and increasing utilization. New control architectures, designs, and technology solutions are needed to manage voltage, power flow, and faults. R&D is needed to address new distributed power management and control system needs, including distributed protection schemas, real-time distributed power flow and voltage/var controls with performance and robustness guarantees in the presence of uncertainty, and seamless microgrid islanding/reconnect interfaces. Some of the priority areas are:

- The need for robust cybersecurity tools and techniques that can be deployed along with automated control systems.
- The need for metrics to quantify the potential benefits of centralized vs distributed control architectures and intelligence for different distribution system paradigms.

- The need for a variety of sensing technologies to achieve required observability. New models and simulations are needed to determine how much observability is needed for control and how much data is needed to develop that level of observability.
- A methodology to compare the relative value of implementing an advanced control scheme versus the deployment of new infrastructure.
- Planning models and tools must evolve to better represent the system under control within the distribution grid – work to merge planning and operational models for full usefulness.
- Research is needed in the area of cybersecurity for control algorithms, as well as maintaining data protection and privacy.
- The need to improve the understanding of Human – AI interactions in more complex scenarios, and develop failsafe processes out of automation if needed.
- Research into multi-objective optimization for advanced control schemes is required, that might include CO2 reduction as well as system performance as a long-term goal.

Analytics for Distribution Operations

Future distribution grids will likely be very complex owing to increasing DER, IoT and smart city trends. These will require increasing amounts of data to operate the system. The available data will be overwhelming to manage and analyze for today's utility planners and operators. New techniques and tools are needed. The R&D needed to address the analytics required for managing the operations of a more complex distribution system, including the application of AI to improve operational effectiveness & safety, advanced computing to support complex planning and operational analyses, efficient algorithms to process large and noisy datasets with errors, omissions, and attacks, and robustness of operation decisions to data errors include:

- Develop common platforms for data integration and robust interoperability standards with focus on the "five V's" of data - Volume, Veracity, Velocity, Value and Variety, as well as a sixth "v," visualization, to more easily see what data holds.
- Develop new low cost, more ubiquitous sensor technologies.
- The need to employ systems or tools for data synchronization across the distribution grid. It should be possible to leverage existing research on data synchronization methods.
- Improving the understanding of the most effective uses for distributed vs centralized intelligence in operations. When does data need to be sent to a central location, and when can it be used locally for local decisions?
- The need for training models that will allow for machine learning in real-time operations.
- The need to study if blockchain has a role in managing data and analytics.

Data and Machine Learning for the Grid

Machine learning and artificial intelligence have had a massive impact on technology community in the last decade. Despite this, finding a home for machine learning in the power grid has not been straightforward. This has several causes. First, the existing mathematical and engineering tools for grid control are sophisticated and accurate. This does not mean that they are compatible with the challenges described so far, but most low-hanging fruit for efficiency improvement has already been picked. Second, machine-learned models require huge amounts of data. While the grid generates plenty of data, little of it is in the form that can be digested by standard machine learning models. Third, most useful machine learning models do not have provable guarantees on performance and are not readily interpretable. That is, it is not clear why a model makes the prediction it does. Given that the grid is critical infrastructure, standards for performance and interpretability will need to be more rigorous than in traditional applications where machine learning has found success so far.

There are some areas where machine learning research for the grid could have an impact. One is forecasting, both on the transmission side (e.g., improving forecasting for wind farms) and the consumer side (e.g., aggregating demand from customers, granular demand forecasting, and weather forecasting). A second is using data to improve the accuracy of existing models. One promising technique that merits further attention is using online optimization algorithms to solve optimal power flow problem. Measurements from the grid can be substituted for model assumptions during the optimization step, essentially rendering part of the problem model-free. A third, which has already met with success in practice, is using machine learning for commercial building energy management and efficiency optimization.

Any advances in applying machine learning to the grid must be balanced against privacy protection. Because machine learning models are so data hungry, privacy is a pervasive theme wherever they are applied. The research community should be conscious of privacy concerns during model development and make it a priority to minimize data requirements for their models.

Modeling of the Transmission-Distribution Interface

Two-way power flow across the transmission-distribution (T-D) interface requires a reevaluation of the organizational and engineering challenges associated with managing the electric grid on a system level. The paradigm of the distribution feeder substation as a passive node in the transmission system will be disrupted by reverse power flows from the increasing level of DER penetration. Research on the organizational challenges of the future T-D interface should focus on the appropriate distribution of roles and responsibilities between transmission system operators and utilities as well as the allocation of liability during outages or emergencies.

The engineering challenges of the T-D interface are intimately tied to the division of responsibilities across it. Data sharing and control compatibility at the interface will be facilitated by the development of interoperability standards. Research on system-wide models that can accommodate the vast range in temporal and spatial scales as well as the large variability in key system parameters (e.g., voltage) in the combined transmission-distribution system will address fundamental aspects of implementing control across the T-D interface.

Expanding electricity services markets to the distribution grid and the role of aggregators in that expansion will be key motivators for a well-managed T-D interface. Coherent electricity prices in the distribution grid will have logical market rules at the T-D interface as a prerequisite. Research into the market power of aggregators and the effects of aggregators participating in energy services markets at the transmission and distribution levels simultaneously will drive the development of the proper paradigm to govern interactions between the two market tiers.

Transmission to Distribution to Customer Operational and Market Coordination

Consumer choices are growing. More DER options (especially PV, batteries and EVs) are available and the pace and scale of adoption will grow. Integrating these new resources at the customer level into existing and new market structures imposes new issues for T-D and D-C coordination. Identification and development of new grid functionality and technology is needed to manage this new grid platform. The R&D needed to address TDC coordination, TDC standardization and harmonization includes distribution grid codes, operational architectures, designs considerations, policy considerations, and risk-based cost-effectiveness analyses. TDC coordination requires:

- The need for robust cybersecurity tools and techniques required of DER devices and providers interfaced with the electric grid as part of comprehensive distribution grid codes.
- The need to determine the characteristics of diversity in DER for consideration in distribution systems and in the market, with some interface to the transmission system.
- New techniques for operational risk analysis and quantification are needed to support business and regulatory decision making under increasingly more complex operating conditions.
- The need for rules and processes for managing the boundary between customers and the distribution operator, on both the access to and use of data and also on the control and management of interconnected DER.
- The need for methods to prioritize across the value stack and develop rules around which services can participate in which market/operational function, and which are mutually exclusive.
- The need to better understand the use of storage being and its use cases. How can we balance those concerns with ease of interconnection?
- As aggregation business models change, developing clear market rules for aggregators or their contractors is needed.
- Develop a clear metric to quantify the risks, values and costs of various structural approaches to the transmission – distribution interface.
- The need to understand operator processes how those affect the requirements at the distribution – customer interface.
- The need for clear rules governing the regulatory or jurisdictional interfaces.

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