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Office of
Electricity Delivery
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MODERN DISTRIBUTION GRID

Volume II: Advanced Technology Maturity Assessment
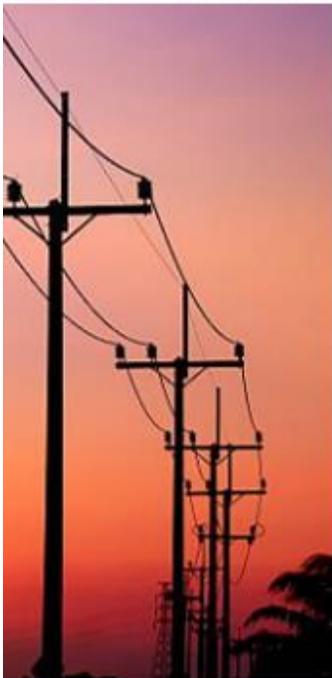
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INTRODUCTION

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 that are needed to enhance reliability and operational efficiency, and integrate and utilize distributed energy resources. 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 represents Volume II of a three-volume set that is intended to support additional discussions on evolving grid structure and function. Volume I, "Customer and State Driven Functionality," provides a taxonomy of functional requirements derived from state policy objectives, and includes a discussion of grid architecture. Volume II, "Advanced Technology Maturity Assessment," examines the maturity of technology needed to enable the functions presented in Volume I. Volume III, "Decision Guide," presents considerations for the rational implementation of advanced distribution system functionality.

This volume contains a survey of current commercial technologies mapped against the functions associated with distribution grid planning, operations and markets. Each technological category is described briefly and assessed with respect to the level of market adoption. The purpose of Volume II is to stimulate a discussion on the application of advanced technology and addressing the remaining technological gaps.

GLOSSARY

Advanced Distribution Management Systems (ADMS) are software platforms that integrate numerous operational systems, provide automated outage restoration, and optimize distribution grid performance. ADMS components and functions can include distribution management system (DMS); demand response management system (DRMS); automated fault location, isolation, and service restoration (FLISR); conservation voltage reduction (CVR); and Volt-var optimization (VVO).[1]

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.[2] 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.[3]

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.[4]

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.[5]

Demand Response Management System (DRMS) is a software solution used to administer and operationalize DR aggregations and programs. Building on a legacy of telephone calls requesting load reduction, DRMS uses a one-way or two-way communication link to effect control over and gather information from enrolled systems, including some commercial and industrial loads, and residential devices such as pool pumps, air conditioners and water heaters.[6] DRMS allows DR capacity to be scaled in a cost-effective manner by automating the manual events that are typically used to execute DR events, as well as most aspects of settlement.

Distribution Management System (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 geographic information systems (GIS), outage management systems (OMS), and CIS to create an integrated view of distribution operations.[7]

Distributed Energy Resource Management System (DERMS) is a software-based solution that increases an operator's real-time visibility into the status of DER, and allows for the heightened level of control and flexibility necessary to optimize DER and distribution grid operation.[8] A DERMS can also be used to

monitor and control DER aggregations, forecast DER capability, and communicate with other enterprise systems and DER aggregators.[9]

Distribution SCADA (DSCADA) is the application of supervisory control and data acquisition software to the distribution grid. SCADA is defined below.

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.[10] The EMS is the transmission system's analog to the DMS.

Fault Location, Isolation and Service Restoration (FLISR) includes 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.[11] FLISR may also be known as Fault Detection, Isolation and Restoration (FDIR).

Geographic Information System (GIS) is a software system that maintains a database of grid assets, including transmission and distribution equipment, and their geographic locations to enable presentation of the electric power system or portions of it on a map.[12] GIS may also serve as the system of record for electrical connectivity of the assets.

Global Positioning System (GPS) is a system of satellites and receivers that determines the position (latitude, longitude and altitude) of a receiver on Earth.[13] 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.[14]

Land Mobile Radio System (LMRS) is a central radio communication system that provides voice and data communications to a variety of endpoints including push-to-talk, walkie-talkies, and data modems for digital devices. They operate on licensed radio frequencies.[15]

Microgrid Interface is the set of power electronics at the Point Of Interconnection (POI)[1] between the "island-able" portions of a grid, and the larger distribution grid, that support the essential microgrid[16] functions of islanding and reconnection.[17] The microgrid interface may also have the capability to provide services to the macro grid including Volt-var control.[18] As services are dropped from the distribution grid side of the interconnection, the microgrid interconnect disconnects, and the microgrid continues to provide service to critical loads in the islanded area.

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.[19]

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[1] Transitions at the POI are managed by the microgrid controller, see IEEE p2030.7.

Optical Fiber communication systems send data via modulated light through a transparent glass or plastic fiber. Optical fiber systems are capable of very high bandwidths and form the backbone of high capacity communication systems.[20]

Outage Management System (OMS) is a computer-aided system used to better manage the response to power outages or other planned or unplanned power quality events.[21] It can serve as the system of record for the as-operated distribution connectivity model, as can the DMS.

Peer-to-Peer Communication (P2P) may be a network service or standalone capability that permits two devices to communicate with one another. 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 and is a dedicated channel between devices.[22]

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.[23]

Reliability Metrics[24] 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 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.

Satellite Radio Frequency Communications is one of the services provided by the more than 2,000 communication satellites in orbit around the Earth. Satellites have the advantage of unobstructed coverage requiring only a suitable ground station. Satellite radio is used in remote locations where the construction of radio towers or other land-based infrastructure is cost-prohibitive.[25]

Supervisory Control and Data Acquisition (SCADA) is a system of remote control and telemetry used to monitor and control the transmission system.[26]

Time Division Multiplex Communication (TDM) is a method of transmitting and receiving independent signals over a common signal path by means of synchronized switches at each end of the transmission line so that each signal appears on the line for a fraction of time in an alternating pattern. This form of signal multiplexing was developed in telecommunications for telegraphy systems in the late 19th century, but found its most common application in digital telephony in the second half of the 20th century.[27]

Worldwide Interoperability for Microwave Access (WiMAX) is a standards-based radio technology enabling the delivery of wireless broadband access to system end points.[28]

Wireline Communication is communication using twisted pair or coaxial cable as the transport medium. Some usages of "wireline" include optical fiber to distinguish from wireless (radio) communication. Use of the physical wire, coax, or fiber in communications can be any of a wide range of technologies including analog, digital, TDM, or IP technologies.[29]

1. MAPPING OF TECHNOLOGY TO FUNCTIONS AND ELEMENTS

1.1.   OVERVIEW

Volume II 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. Commissions and industry can use Volume II 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 Volume III, "Decision Guide."

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.

In the following diagrams, each technology category is named and connected via a colored line to one of the three functional areas. Within each technology category, specific grid modernization technologies are listed to the right and connected by same-colored lines.

1.1.1. Distribution System Planning

Distribution system analysis tools and technologies are identified within their respective technology categories in Chapter 2. Section 2.1 assesses the technologies required by the functional elements of Distribution System Planning described in Volume I.[2] A discussion of the capital budgeting and expenditures required to acquire or develop these planning technologies is not within the scope of this report. Furthermore, not all of the technologies mentioned 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. The mapping below in Figure 1 groups relevant technologies, in order for them to be responsive to the functions and elements presented in Volume I:

Figure 1: Distribution System Planning

Functional Area | Technology Category | Technologies

- Distribution System Planning
  - Forecasting
    - DER Forecasting
    - Load Forecasting
  - Power Flow Analysis
    - Peak Capacity Planning Study
    - Voltage Drop Study
    - Ampacity Study
    - Contingency and Restoration Study
    - Reliability Study
    - Time Series Power Flow Analysis
    - Load Profile Study
    - Stochastic Analysis
    - Volt-var Study
    - Balanced and Unbalanced Power Flow Analysis
  - Power Quality Analysis
    - Voltage Sag/Swell Study
    - Harmonics Study
  - Fault Analysis
    - Arc Flash Hazard Analysis
    - Protection Coordination Study
    - Fault Probability Analysis
  - Advanced Optimization

For context, the functions in Volume I and the technology categories described in this volume are mapped to an overall planning process. An Integrated Distribution Planning (IDP) framework[30] as discussed in several states includes the functional components illustrated in Figure 2 below.

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[2] See Section 5.1, Distribution System Planning
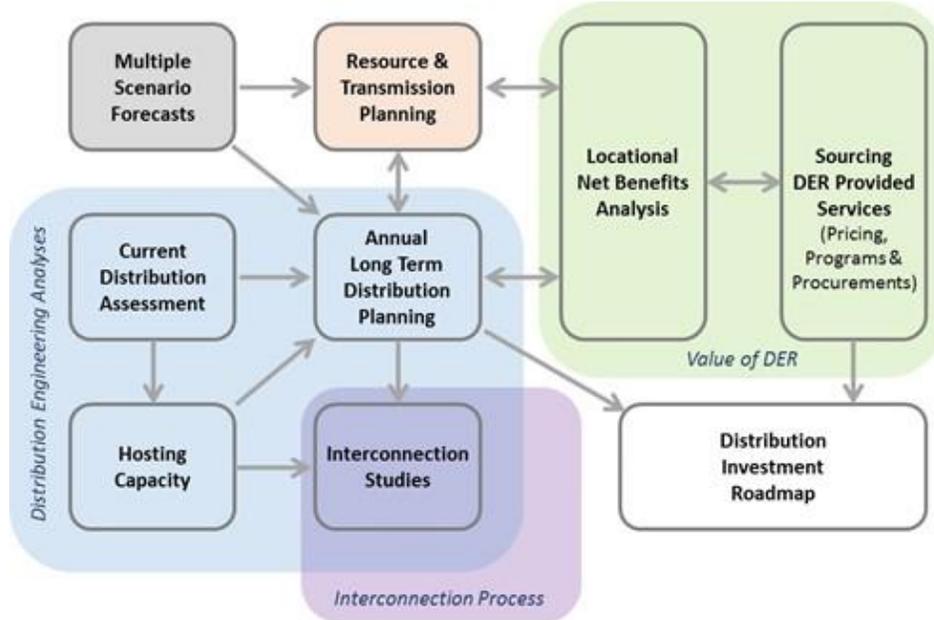
Current Distribution System Assessment

An assessment of current feeder and substation reliability, condition of grid assets, asset loading and operations is needed, along with a comparative assessment of current operating conditions against prior forecasts of load and DER adoption. The following technology categories map to this functional area:

- Power Flow Analysis,
- Power Quality Analysis, and
- Fault Analysis.

Multiple DER and Load Scenario Forecasts

The uncertainty of the types, amount, and pace of DER expansion make singular deterministic forecasts ineffective for long-term distribution planning. Also, the changing nature of customer demand and related net demand requires more granularity than in the past. Additionally, the use of multiple DER growth and demand scenarios is recognized as beneficial. The following technology categories map to this functional area:

- Forecasting.

<u>Hosting capacity</u>

Hosting capacity methods[3] quantify the engineering factors that increasing DER penetration introduces on the grid within three principal constraints: thermal, voltage/power quality, and protection limits. These methods can be applied to interconnection studies and long-term distribution planning. Hosting capacity utilizes a combination of tools identified above and the following specialized tools:

- Advanced Optimization.

<u>Interconnection Studies and Procedures</u>

Interconnection engineering studies utilize the tools in the categories above and are expected to use the following specialized tools as variable DER adoption increases:

- Dynamic Analysis.

<u>Annual Long-term Distribution Planning</u>

The annual distribution planning effort involves two general efforts: 1) multiple DER and load forecast scenario-based studies of distribution grid impacts leveraging a combination of the tools above to identify "grid needs," and 2) a solutions assessment including potential operational changes to system configuration, needed infrastructure replacement, upgrades and modernization investments, and potential for non-wires alternatives.

<u>Integrated Resource, Transmission and Distribution Planning</u>

At high levels of DER adoption, the net load characteristics on the distribution system can have material impact on the transmission system and bulk power system operation.[4] Today, distribution planning is typically done outside the context of integrated resource planning and transmission planning. To the extent DER is considered in resource and transmission planning, it is essential to align those DER growth patterns, timing and net load shape assumptions and plans with those used for distribution planning. Over the next five-year scope of this volume, an integrated transmission and distribution planning tool is not expected to be available. Instead, an iterative process between resource, transmission and distribution planning is beginning to be employed.

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[3] Staff, The Integrated Grid: A Benefit-Cost Framework, EPRI, 2015, and T. Lindl, *et al.*, Integrated Distribution Planning Concept Report, Interstate Renewable Energy Council, Inc. and Sandia National Laboratory, 2013.

[4] "Net load" here refers to the amount of load that is visible to the TSO at each T-D interface, which can be expected to be much less than the total or gross end-use consumption in local areas with high amounts of DERs. The term "net load" is also used at the transmission system level to refer to the total system load minus the energy output of utility-scale variable renewable generation, as illustrated by the CAISO's well known "duck curve." In this report we are focusing mainly on the first sense of the term—i.e., the impact of DERs on the amount of load seen at each T-D interface.

<u>Locational Net Benefits Analysis</u>

The value of DER on the distribution system is locational in nature associated with a distribution substation, an individual feeder, a section of a feeder, or a combination of these components. The distribution system planning analyses, described above, identify incremental infrastructure or operational requirements (grid needs) and related potential infrastructure investments. The cost estimates of these investments form the potential value that may be avoided by sourcing services from qualified DERs, as well as optimizing the location of DERs on the distribution system.

1.1.2. 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. Volume I developed the need for and presented an architectural approach for control federation and control disaggregation.

Section 2.2 assesses the technologies required by the functional elements of Distribution Grid Operations described in Volume I.[5] These technologies are grouped together into technology categories as depicted in Figure 3. The groupings, based on discussion and review with industry experts, show the primary and most direct relationships:

- Distributed Resource Management,
- Field Automation,
- Substation Automation,
- Operational Communications Infrastructure,
- Sensing and Measurement,
- Operational Analytics, and
- Optimization Analytics.

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[5] See Volume 1, Section 5.2, Distribution Grid Operations

Functional Area — Technology Category — Technologies

Distribution Grid Ops

- **Distributed Resource Management**
  - DERMS
  - DRMS
  - Microgrid interface
- **Field Automation**
  - Distribution Automation
  - Volt-var Management
  - Power Flow Controllers
- **Substation Automation**
  - Substation SCADA
  - Advanced Protection
- **Operational Communications Infrastructure**
  - Wide Area Network
  - Field Area Network
  - Neighborhood Area Network
  - Communications Network Management System
- **Sensing & Measurement**
  - Advanced Customer Metering
  - Production Metering
  - Grid Asset Sensors
  - Environmental Sensors
  - Grid Sensors
- **Operational Analytics**
  - Field Data Management
  - Electrical Network Connectivity model
  - Distribution State Estimation
  - Outage Management (OMS)
  - Geographic Information System
- **Optimization Analytics**
  - Asset Management
  - DER Optimization

1.1.3. 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.[6] Section 2.3 assesses the related technology categories required by the functional elements. These technologies mirror those used in bulk power markets with important distinctions that are identified. These technologies are grouped into technology categories as depicted in Figure 4. This mapping was developed based on inputs, reviews, and discussions with industry experts and includes:

- Distribution Operational Market

Figure 4: Distribution Market Operations

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

2. TECHNOLOGY ADOPTION ASSESSMENT

The following sections assess each technology's position on the technology adoption cycle. Figure 5 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 5: Technology Adoption Cycle
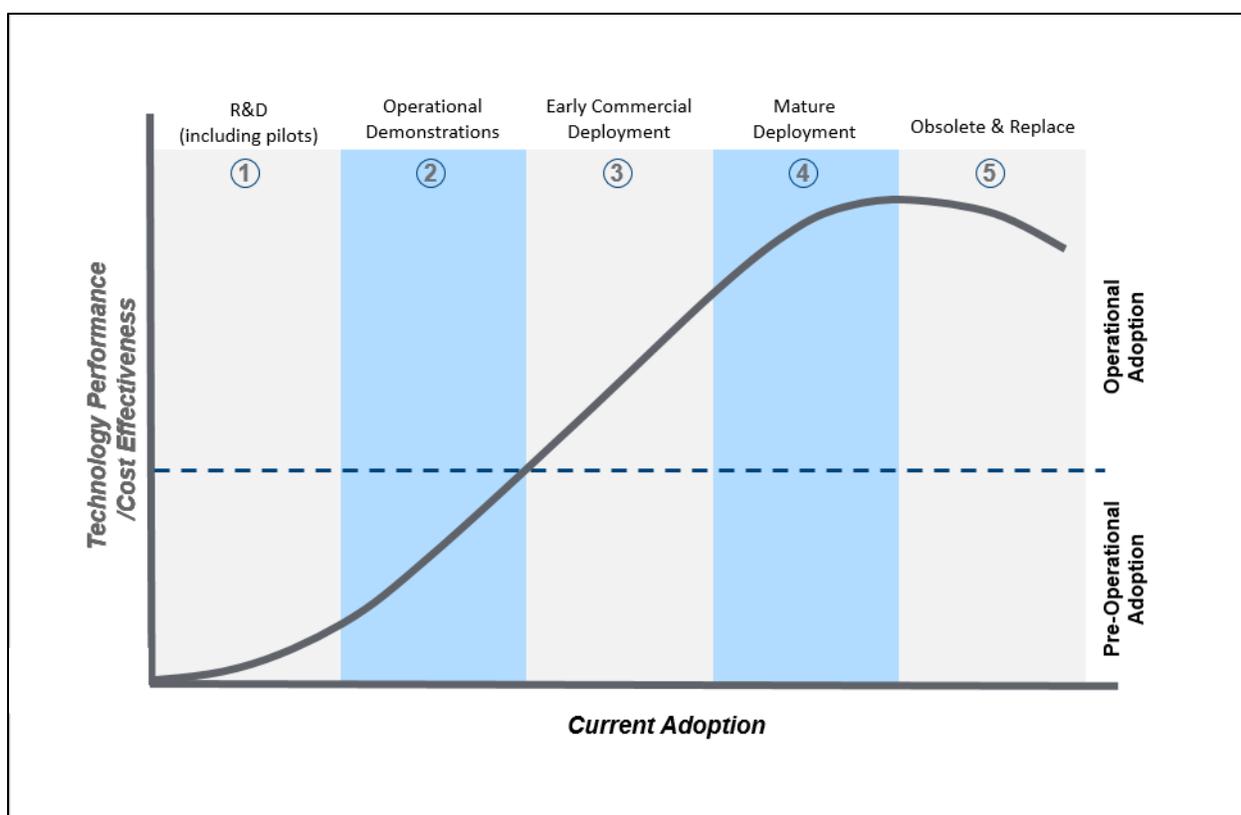
The technology adoption cycle X-axis, "**Current Adoption**," identifies the stage of adoption for a specific technology. The horizontal dashed line represents the crossover point from stages that are **Pre-Operational** (i.e., under test and/or evaluation) to those designated as **Operational** (i.e., 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 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. The pace of product change slows. At this point, 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 characterized by multiple vendors each 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 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.

2.1.   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," which is expected to be published in April 2017.[31]

2.1.1. Forecasting

2.1.1.1.   TECHNOLOGY CATEGORY DESCRIPTION

The development of 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 DER growth 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, typical size of DER generation facilities, 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 the ways in which 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 presented by the load and DER forecasting functions are integrated in an analysis of the impact of DER on customer electricity net demand. These functions are supported by analytical tools and methods that include the use of software tools that draw on data from various external inputs, and by established tools that use econometric and predictive models.

2.1.1.2.   TECHNOLOGY DESCRIPTIONS

Load Forecasting

Load forecasting for the distribution grid involves the use of computer software 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, 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.[32]

DER Forecasting

DER operational forecasting tools are software solutions that can be used for near-term operational forecasts. This tool assesses the "hidden load" challenge faced today, which hinders operational ability to distinguish between supply resources (distributed generation and storage) and gross demand to accurately forecast impacts under various operating conditions, such as routine switching or outage restoration.[33,34]

Customer-adoption Models for DER

Customer adoption models for DER combine technology diffusion and economic models. Inputs include market information (e.g., fuel prices, existing electricity tariff), customer load information (e.g., hourly end use loads), and DER technology information (e.g., capital costs, operating and maintenance costs, performance data) and other customer decision factors.[35]

Figure 6: Schematic of information flow in DER Customer Adoption Models (CAM)[36]
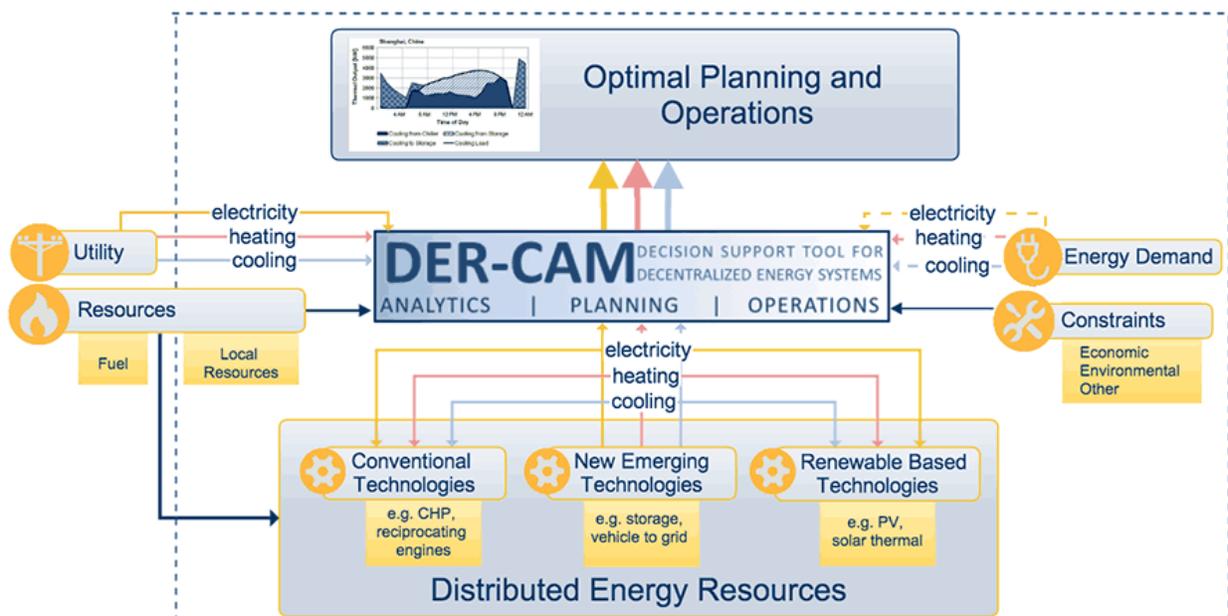
2.1.1.3. ADOPTION MATURITY ANALYSIS

Figure 7: Forecasting DER and Demand
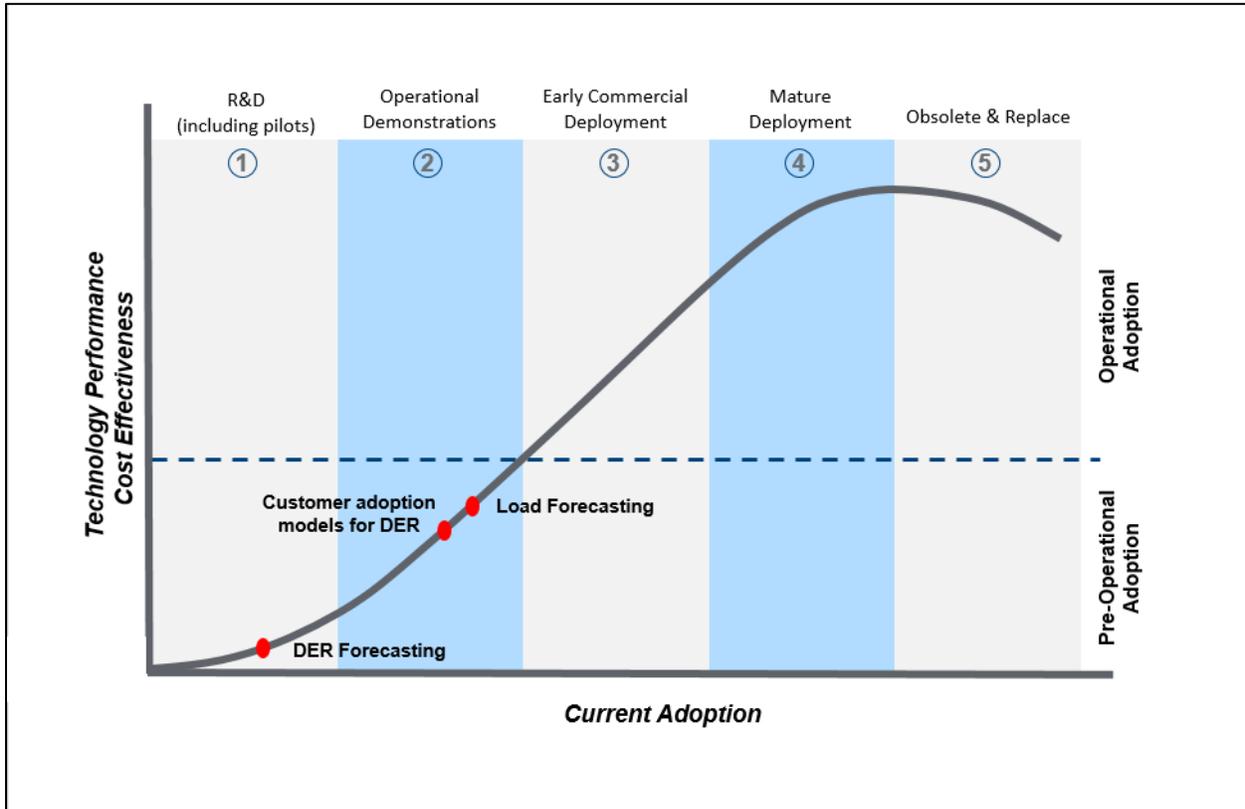
The application of demand forecasting techniques and DER operational forecasts to high DER penetration systems is inherently different from traditional top-down forecasting models. For high DER distribution systems, the need for granular circuit level accuracy becomes very important, as does alignment 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. The varying availability of this data across disparate distribution systems is a hindrance to the technology vendors who seek to develop of a cost effective technical solutions. Detailed load forecasting tools for distribution grid planning is in the operational demonstration 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 firm and not as commercial tools. As such, these tools have been deployed in limited use. As a result, these are in a state of operational demonstrations.[37]

DER operational forecasting tools are in the R&D stage.

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2.1.2. Power Flow Analysis

2.1.2.1.   TECHNOLOGY CATEGORY DESCRIPTION

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 snap-shot 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.

A comprehensive power flow analysis software includes the following functions and studies:

- Peak Capacity Planning,
- Voltage Drop,
- Ampacity,
- Contingency and Restoration,
- Reliability,
- Time Series Power Flow Analysis,
- Balanced and Unbalanced Power Flow Analysis,
- Load Profile,
- Stochastic Analysis, and
- Volt-var Study.

2.1.2.2.   TECHNOLOGY DESCRIPTIONS

Peak Capacity Planning Study

Peak capacity planning study tools examine load growth 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 snap-shot 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 Calculator

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 Calculator

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, and thermal resistance and related loss factors.[38,39]

Contingency and Restoration Tool

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 and removal of induction and synchronous motors.

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 for the overall system and their corresponding protection zones such as SAIFI, SAIDI, and CAIDI. 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 (tree trimming, cable replacement, DA, inspection/maintenance, etc.) on an individual feeder basis and produces a plan on how to spend reliability improvement budgets to maximize impact.

Time Series Power Flow Analysis[7]

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.

Balanced and Unbalanced Power Flow Analysis

The load flow or power flow calculation analysis tool is the software module 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.[8]

Load Profile Study Tool

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.[40]

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)

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

[8] 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.

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.[41]

Volt-var Study Tool

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).

2.1.2.3.   ADOPTION MATURITY ANALYSIS

Figure 8: Power Flow Analysis
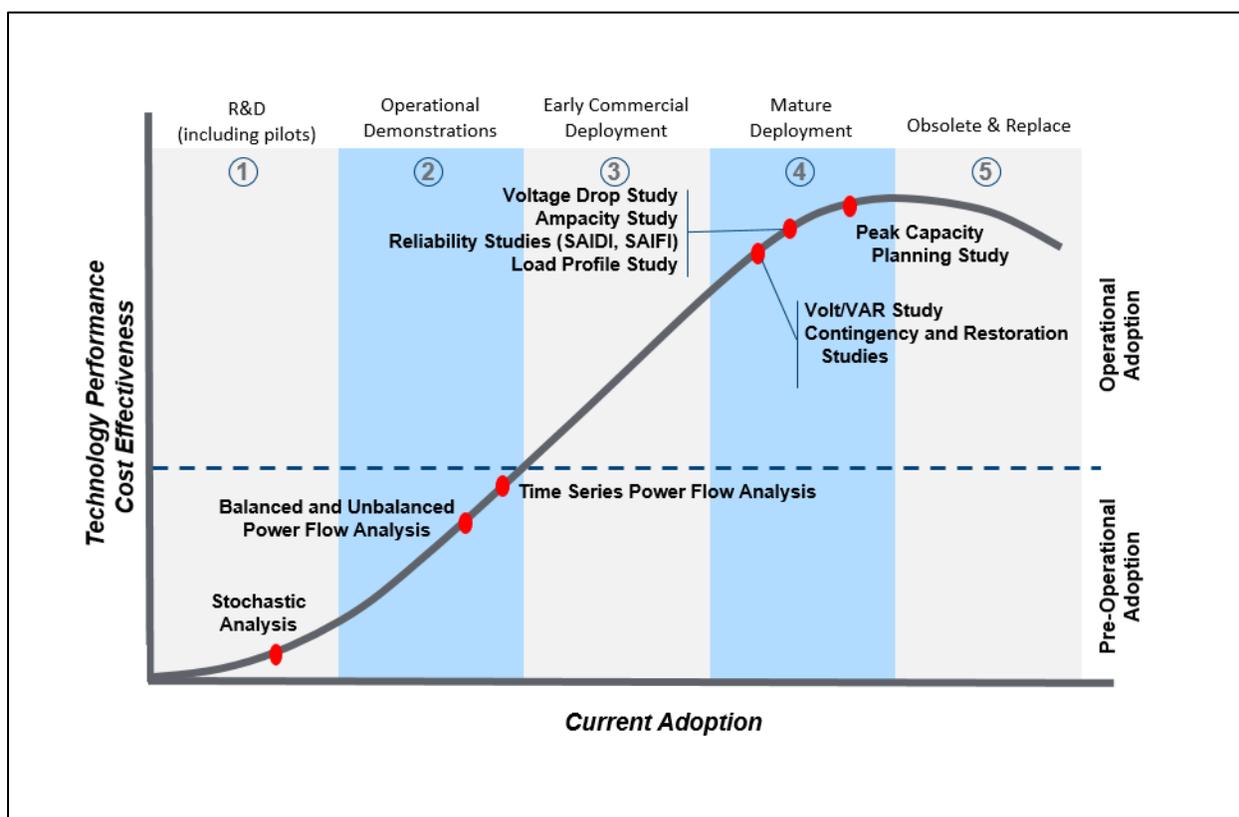
All of the power flow analyses listed below are frequently used by planners, and can be considered to be in a state of mature deployment:

- Peak capacity planning study,
- Voltage drop study,
- Ampacity study,
- Contingency and restoration study,
- Reliability study,

- Load profile study, and
- Volt-var study.

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).

As DER penetration increases, a single distribution system software tool to calculate single phase, three phase, balanced, and unbalanced power flows may be required. 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.

2.1.3. Power Quality Analysis

2.1.3.1.   TECHNOLOGY CATEGORY DESCRIPTION

Power quality is defined as maintaining voltage, frequency, and waveform to defined standards.[42] 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 and mitigate the impacts 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[43] and also decrease 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 voltage sag and swell studies and harmonic studies.

2.1.3.2. TECHNOLOGY DESCRIPTIONS

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[9] technique. This is achieved by scaling up all the loads by bus, areas, zones 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[10] calculations. The module allows the user to model non-linear loads and other sources of harmonic currents such as converters and arc furnaces, and to detect resonant frequencies due to capacitor banks.

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[9] 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.

[10] 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.

Figure 9: Power Quality Analysis
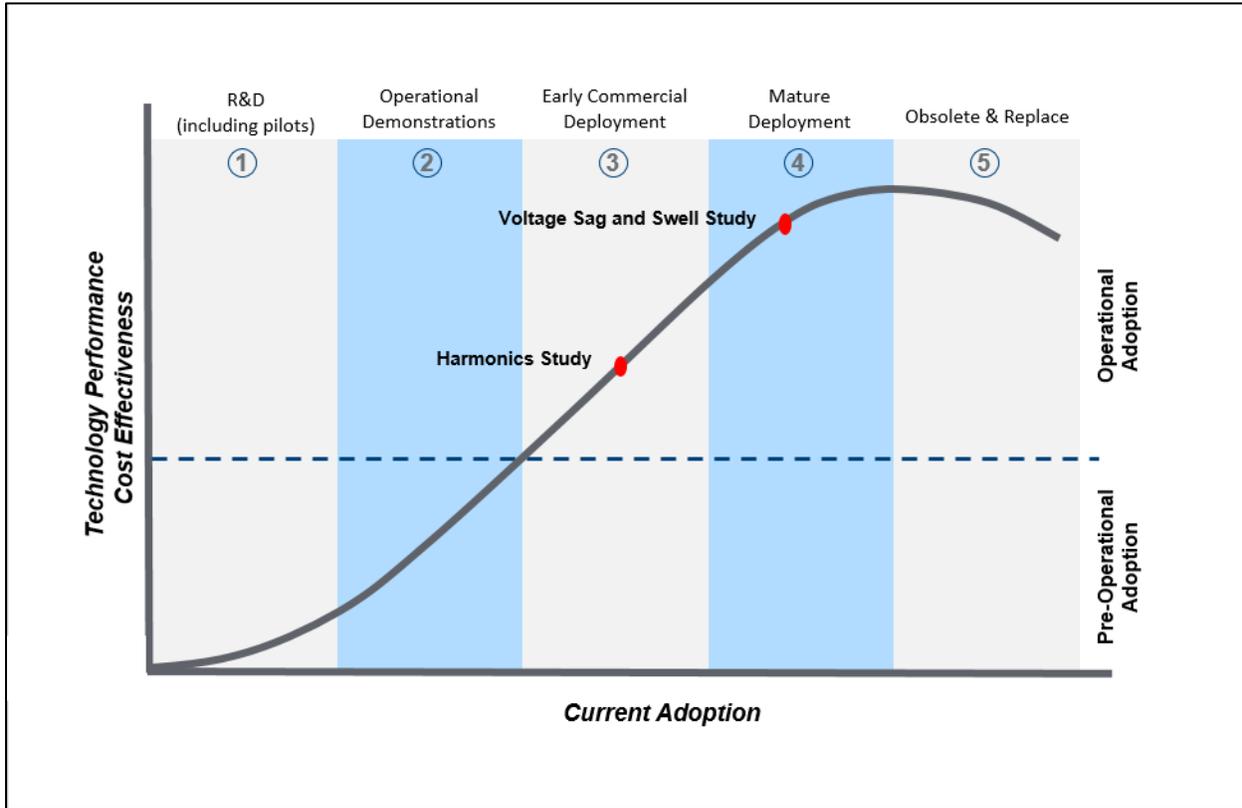
Several distribution grid software tools are capable of <u>voltage sag and swell studies</u>. As a result, this module of the tools is in mature deployment. However, poor quality and availability of network model data from Geographic Information Systems (GIS) or other systems may pose challenges to the 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 <u>harmonics studies</u>. Software modules for harmonic studies are currently in a state of early commercial deployment.

2.1.4. Fault Analysis

2.1.4.1. **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.

2.1.4.2. TECHNOLOGY DESCRIPTIONS

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.

2.1.4.3. ADOPTION MATURITY ANALYSIS

Figure 10: Fault Analysis
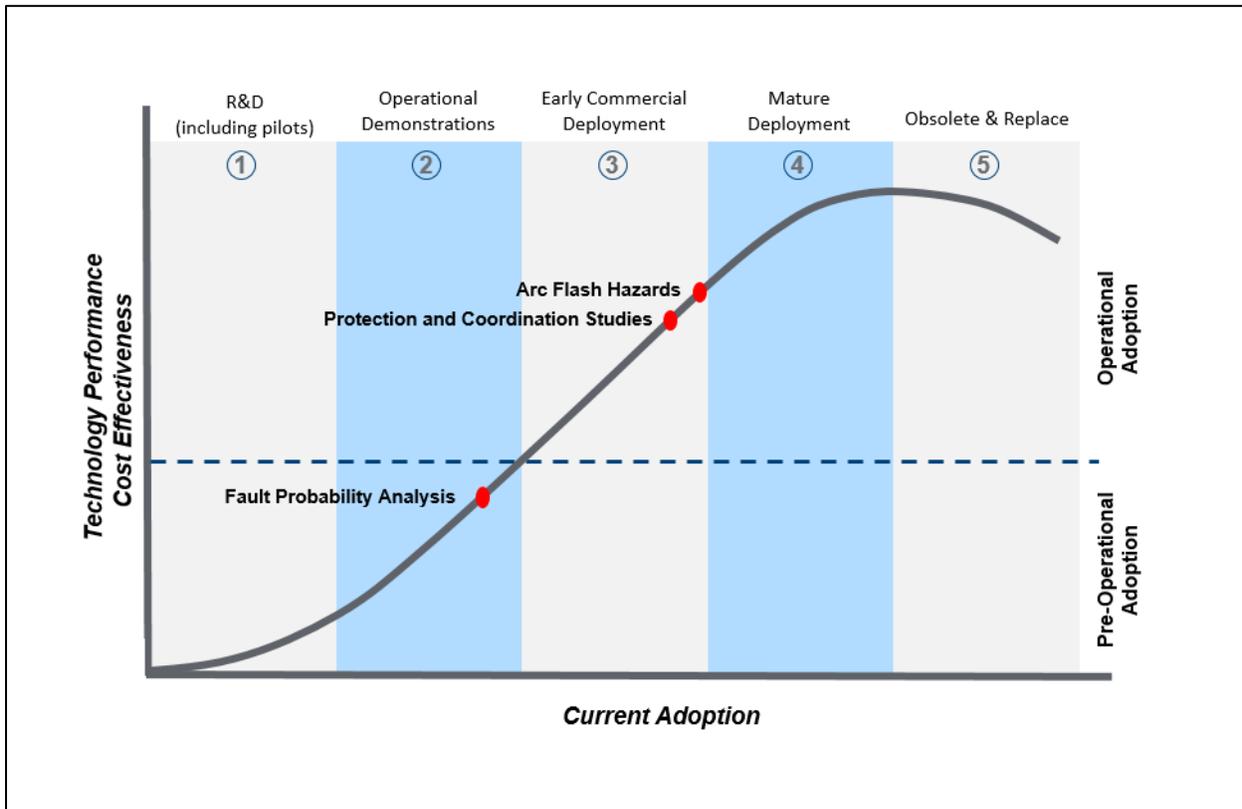
Software modules can be used for arc flash hazard studies and protection coordination studies. Arc flash hazard studies are needed to define the danger to people working on or near live equipment. Arc flash models, based on Institute of Electrical and Electronics Engineers (IEEE) 1584 standard, are used to estimate the incident heat energies that 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 mature stage of adoption.

Detecting temporary and high impedance faults and failures, including voltage dips and 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 <u>fault analysis tools</u> 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 great proliferation of DER, is not yet common and will be impeded by the lack of accurate model network model data.

2.1.5. Advanced Optimization

2.1.5.1. TECHNOLOGY CATEGORY DESCRIPTION

Advanced optimization tools are used to identify and select the optimal sizes and locations for interconnection of DER to the distribution grid, within acceptable accommodation limits, to meet economic objectives. Optimized DER can mitigate load relief needs on a circuit by transmission and distribution (T&D) capital infrastructure deferral, resolve power quality issues, reduce emissions impacts, and provide societal and other benefits while maintaining acceptable voltage profiles along the feeder with minimized costs. Such optimization tools can capture the economic potential and size of DER planners may build a portfolio of DER to provide grid services, or identify locational value, or to enable policy makers and planners to assess policy options in relation to DER adoption and locational deployment.

The modules of a distribution grid software tool that can carry out an advanced optimization study are DER impact evaluation tools.

2.1.5.2. TECHNOLOGY DESCRIPTIONS

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.

2.1.5.3.   ADOPTION MATURITY ANALYSIS

Figure 11: Advanced Optimization
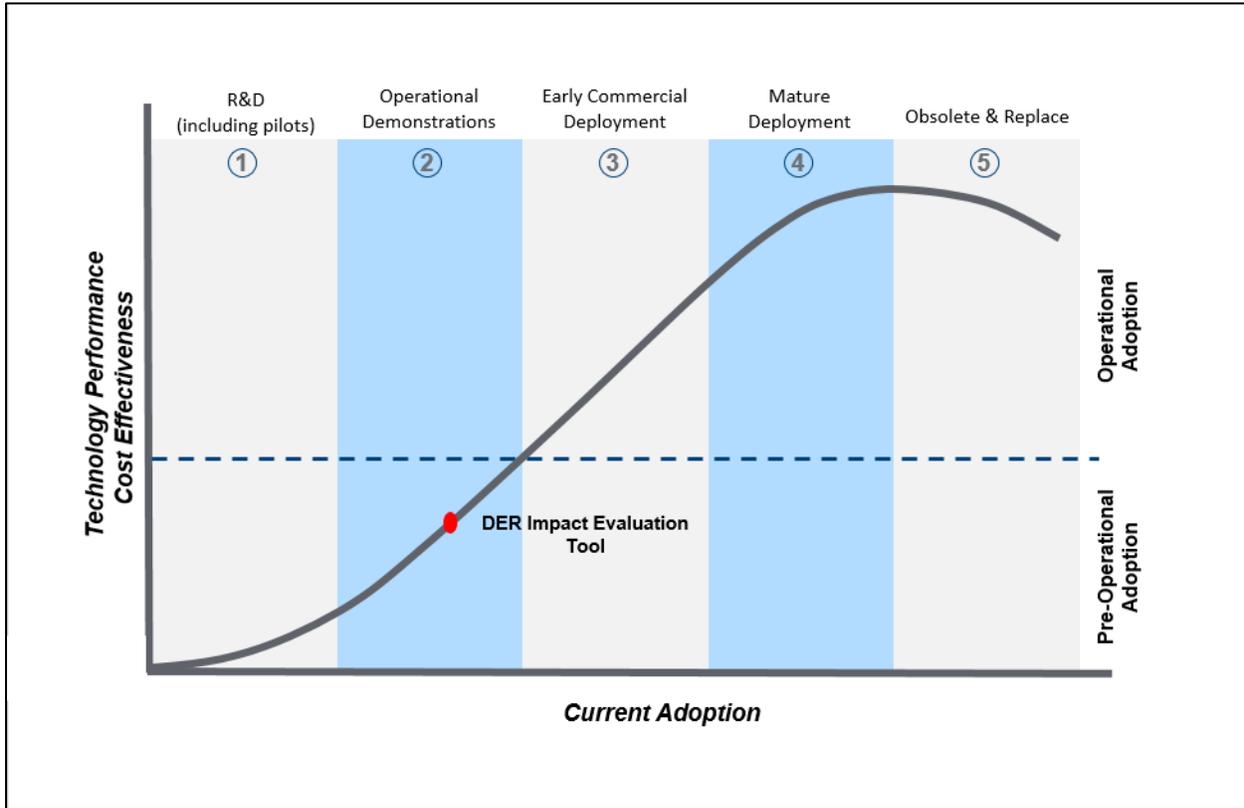
While most distribution system analysis tools have software modules with the capability to conduct basic distribution engineering studies and time-series simulations with the integration of DER, notable gaps exist in the ability to conduct advanced engineering optimization studies, and to reconcile these 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. 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. DER impact evaluation tools are considered to be in the operational demonstration stage.

2.2. DISTRIBUTION GRID OPERATIONS

2.2.1. Distributed Resource Management

2.2.1.1. 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, including energy storage, generation, smart inverters, and responsive load.

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

- Distributed Energy Resource Management System (DERMS),
- Demand Response Management System (DRMS), and
- Microgrid interface.

2.2.1.2. TECHNOLOGY DESCRIPTIONS

**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, or 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.

DERMS may be deterministic or predictive in behavior. Deterministic behavior generally waits until an alarm event occurs, after which the DERMS immediately initiates a power flow analysis, using the most recent telemetry, to determine the type and magnitude of a voltage or power violation. Based on this output, a DERMS recruits the necessary DER assets to perform whatever functions are necessary to mitigate the affecting alarm.

Predictive DERMS uses advanced analytics to perform forecasts to anticipate voltage or power flow violations. Advanced capabilities use weather forecasts, historical loading, and known profiles of DR, as well as committed schedules for smart inverter (storage and solar) systems. Anticipated violations are identified and schedules are created to pre-position DER systems to specific levels of operation (and notify customers of pending obligations).

DERMS can also be used for non-violation operations. Specifically, when combined with optimization analytics, DERMS can provide optimal economic and energy management schedules that allow reliable operation of increased amounts of DER growth more cost-effectively than traditional wires upgrades. By integrating with established systems such as a Distribution Management System (DMS) and DRMS, a DERMS can be used to monitor, optimize and dispatch DERs, including energy storage, DR and electric vehicles.[44] This requires standardized protocols, telemetry and control interfaces. The functions described above are depicted in Figure 12.

Figure 12: Key DERMS Capabilities[45]
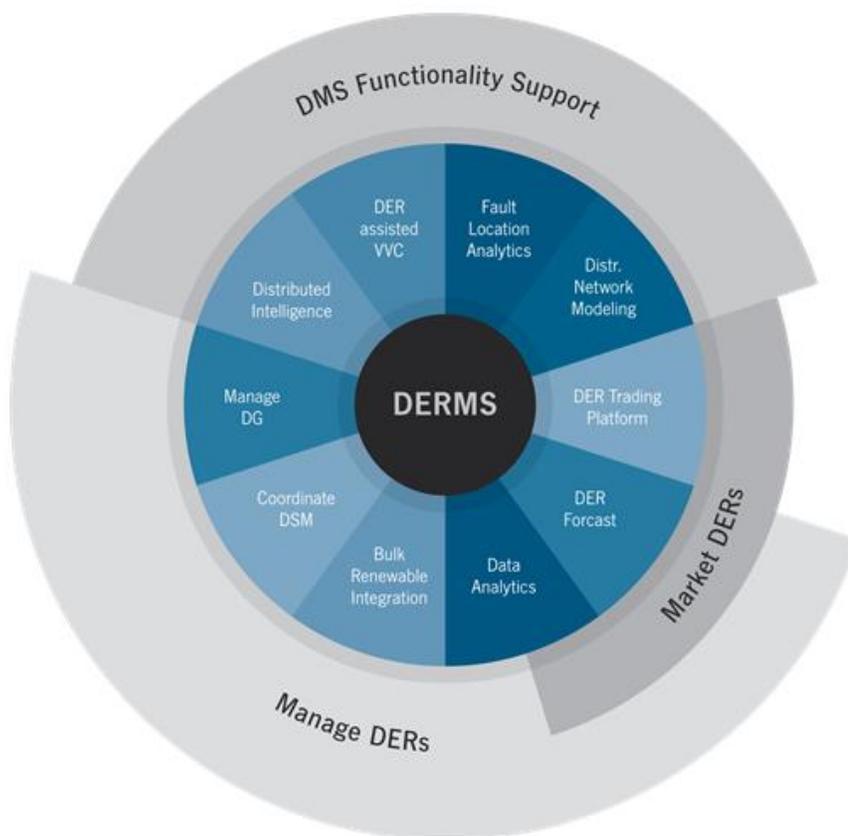
Demand Response Management System (DRMS)

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 enrollment
- Device installation
- Device asset management
- Capacity forecasting

- Event creation

- Customer event notification
- Tracking of customers' participation
- Measuring and verifying participation
- Providing reports

- Event dispatching
- Real-time performance monitoring
- Calculating settlements
- Acting as the system of record for all activities

As shown in Figure 13**,** 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 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 Customer Information System (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. Not all customers are necessarily enrolled in a DRMS.

<div align="center">Figure 13: Demand Response Management System</div>
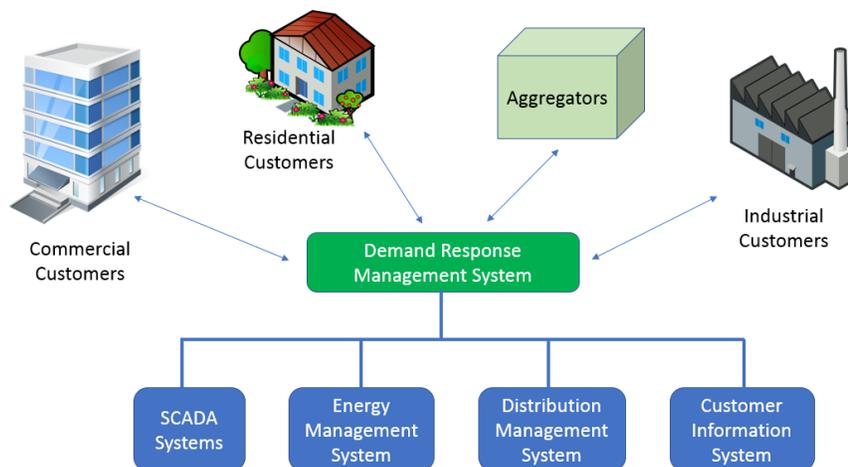
Microgrid Interface

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.[46] As such, the microgrid interface includes load disconnect/reconnect capability; measurement; communications; protection devices that can enable seamless interoperability between interconnected, islanded modes; and synchronized reconnection.[47] Figure 14 conceptually illustrates a microgrid interface to the distribution grid. The microgrid and its internal systems and controls are not within the scope of Volume II.

Figure 14: Microgrid Interface Framework[48]
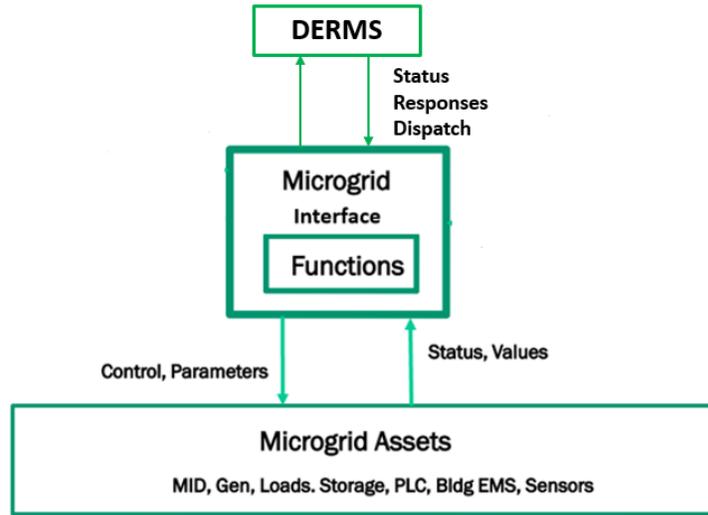
2.2.1.3. ADOPTION MATURITY ANALYSIS

Figure 15: Distributed Resource Management
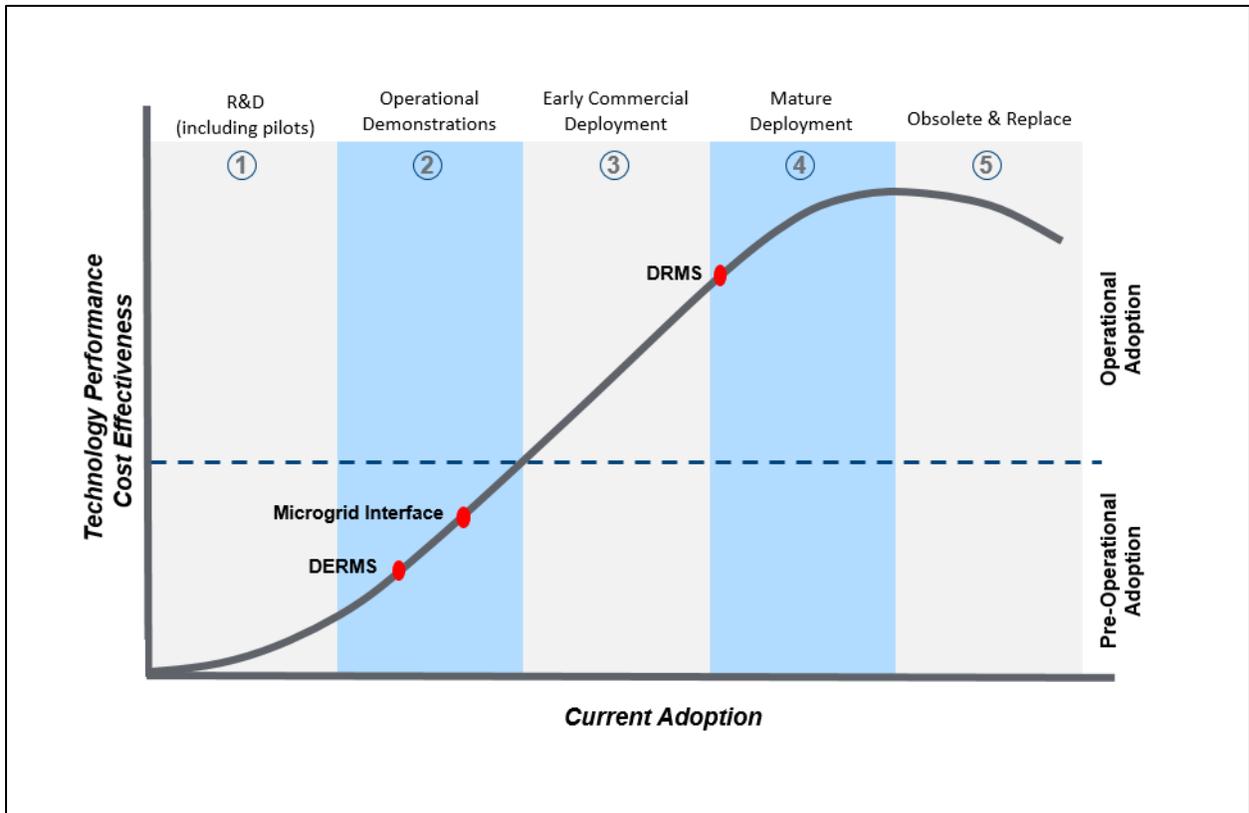
DRMS functionality to aggregate and programmatically manage DR assets is at a mature stage with wide adoption. Multiple vendors' commercial products are available in the market and have been operationally deployed over the past decade.[49] It should be noted that current solutions rarely coordinate with 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. As such, it is possible that DRMS will be subsumed by DERMS.

DERMS is 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. [50, 51, 52 53]

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 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. IEEE interconnection standards are being updated to address DER and microgrid interfaces. 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.[54, 55, 56, 57, 58, 59]

2.2.2. Field Automation

2.2.2.1. TECHNOLOGY CATEGORY DESCRIPTION

Power delivery functions can be more efficiently monitored and controlled in real time with field automation assistance. Field devices such as reclosers, switches, capacitors, and transformers can all be monitored—if not controlled or operated—remotely. Automation 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.[60]

The technologies that can support field automation include:

Distribution Automation

Distribution automation 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.

Volt-var Management

The objectives of a Volt-var management system include minimizing distribution system and customer voltage variation, reducing system-wide losses, reducing maintenance costs, and increasing the power delivery hosting capacity of existing equipment.[61]

Power Flow Controllers

The power flow controller is an electrical device comprised of power electronics, control software and communication interfaces used for providing fast-acting reactive power compensation. The controllable parameters of the power flow controller are reactance in the line, phase angle and voltage. The power flow controllers can also provide harmonic cancellation, power quality functions and typically include sensing and measurement capability.

2.2.2.2.   TECHNOLOGY DESCRIPTIONS

Distribution Automation

Distribution SCADA

Distribution SCADA is the extension of SCADA capabilities to distribution substations and basic distribution automation (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 (Advanced 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

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

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is done though 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.[62]

Distribution Management System

The DMS is a decision support tool that assists with monitoring, control, and optimization of the distribution system. The advanced iteration of the DMS represents an evolution of the control room technology by integrating the DMS, Outage Management System (OMS) and SCADA operational systems into one comprehensive network management solution. While the functionality and capabilities are inconsistent among the advanced DMSs in development, new feature modules may include but are not limited to: distribution network modeling, unbalanced load flow and network topology processing, centralized FLISR (automated restoration), integrated Volt-var optimization, load forecasting, and dispatcher training simulation. [63, 64, 65, 66]

Volt-var Management

Integrated Volt-var Optimization (IVVO)

An IVVO 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 load tap changers, voltage regulators, capacitor banks, power flow controllers, and smart inverters.

Distribution-STATCOM

The distribution-static compensator (distribution-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 distribution-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 distribution-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. [67, 68]

Power Flow Controllers

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 IVVO system and may

provide voltage regulation, reactive power compensation, harmonic cancellation, 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.[69, 70]

2.2.2.3. ADOPTION MATURITY ANALYSIS

Figure 16: Field Automation
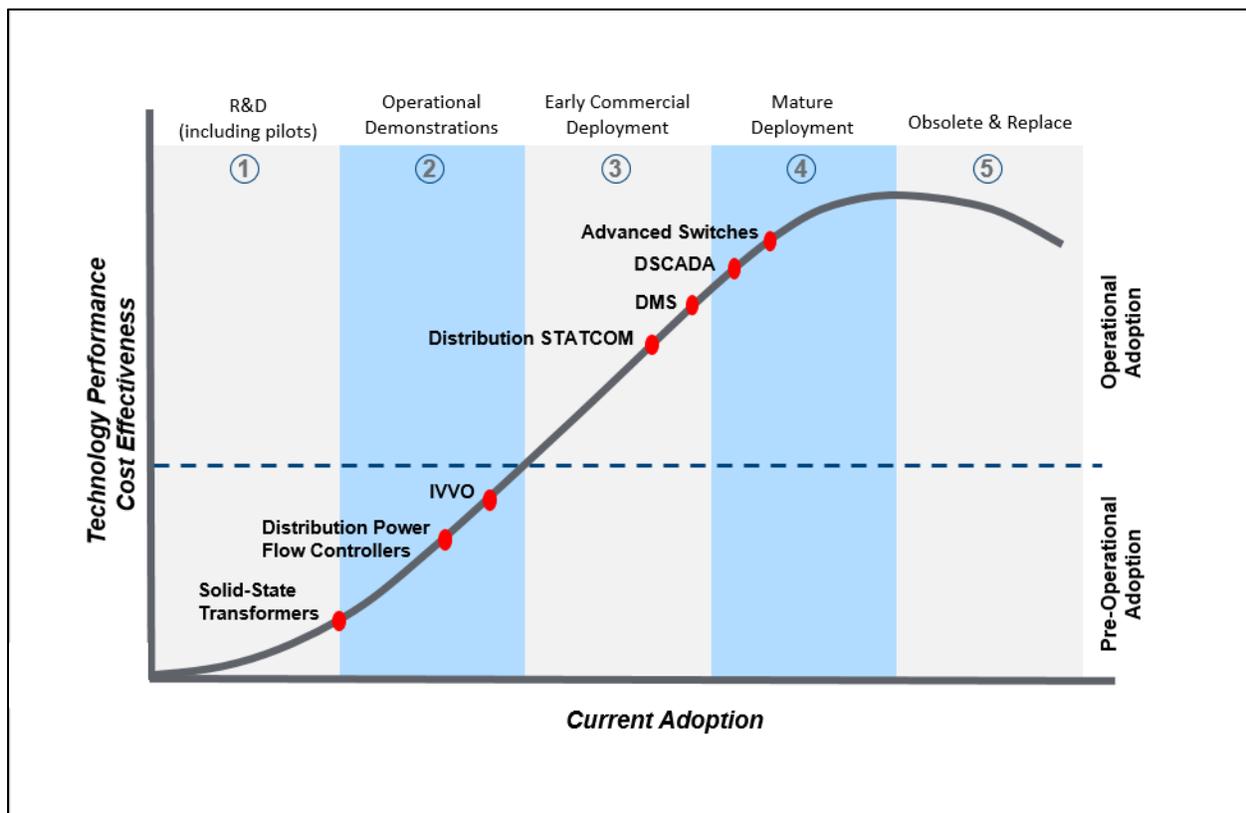
Smart distribution and field automation technologies enable new capabilities to automatically locate and isolate faults using automated feeder switches and reclosers; dynamically optimize voltage and reactive power levels; and monitor asset health to effectively guide the maintenance and replacement of equipment. In addition, field automation can enhance reliability and resilience while improving operational efficiency and DER integration.

Distribution SCADA (DSCADA) devices are widely deployed and mature in modules with basic distribution automation functions. A wide number of vendors offer devices with DSCADA capability[71] 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.[72]

A number of DMS implementations are underway, each with a unique definition of the functionalities that the new system should enable. Most commercialized advanced DMSs 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 DMSs has been increasing, DSCADA systems are often used to manage a growing portfolio of distribution automation 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.[73]

Figure 17: ADMS Deployment Survey[74]

Do you have an Advanced DMS (ADMS)? (i.e., Does it provide SCADA, DMS and OMS together in one user interface?)

Yes	9%
Not yet, but plan to by Year End 2019	20%
Not yet, but plan to after 2019	16%
No, and no plans for ADMS	55%
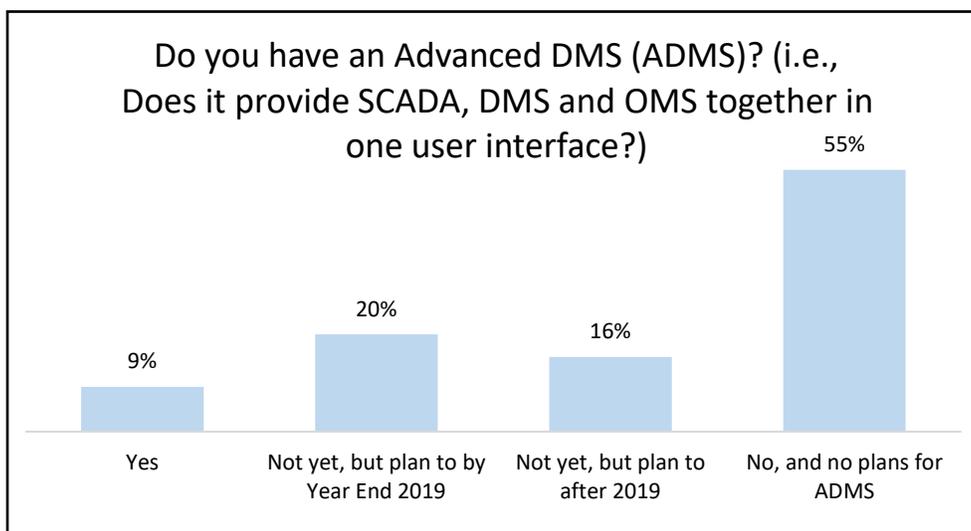
Advanced switches are being installed on distribution systems. These are more likely to be installed at voltages above 4 kV. The higher the feeder voltage, the more likely it is that at least some of the feeders would be fully automatic and have SCADA-controlled sectionalizing switches and reclosers installed.[75] 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.

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

The distribution-STATCOM has proven to 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. [76, 77] This technology is in 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.[78]

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, to be implemented successfully, the 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.

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 18: ADMS Applications[79]
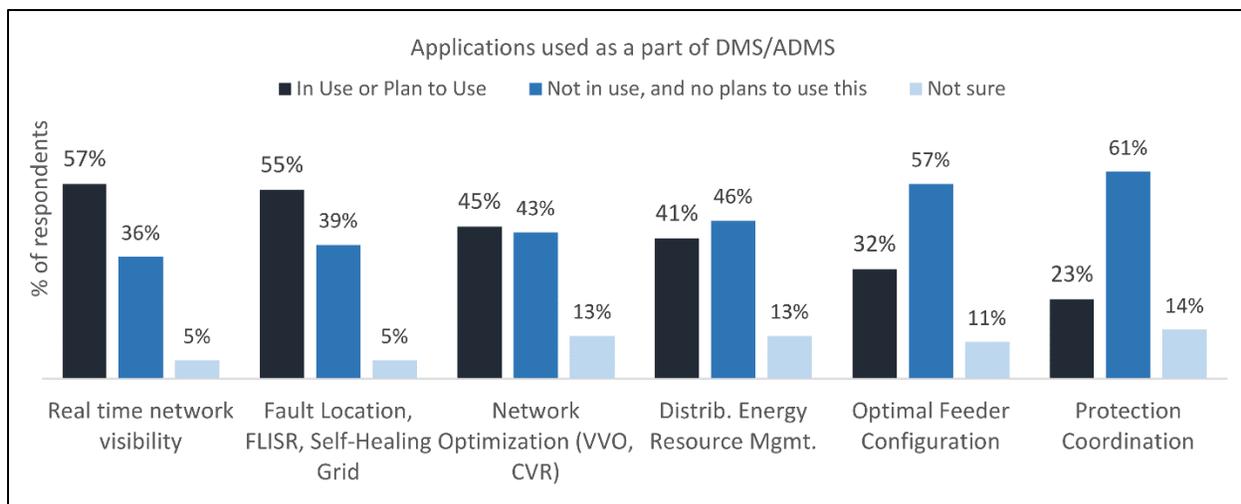
2.2.3. Substation Automation

2.2.3.1. TECHNOLOGY CATEGORY DESCRIPTION

Substation automation is the deployment of substation and feeder circuit breaker operating functions and applications ranging from SCADA and advanced protection relay systems. These functions optimize the management of capital assets and enhance operation and maintenance efficiencies with minimal human

intervention.[80] Substation automation systems are designed to behave in a coordinated and integrated fashion. Unlike transmission substations, distribution substations in many cases are largely analog with 1980's era communications, electromechanical relays and no SCADA control. This has been changing over the past decade, but given the very large number of distribution substations and cost considerations it will take some time to upgrade, absent a need such as DER integration.

The specific underlying components considered are substation SCADA devices and advanced protection relays.

2.2.3.2.   TECHNOLOGY DESCRIPTIONS

Substation SCADA

Several manufacturers supply substation SCADA for use in electrical substations that are compliant with well-established standards.[81] These SCADA measurement, controls and computing platforms are available in a wide range of processing power and capacity. The distributed computing capability in a substation provides support for several functions, such as analytics, 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 electro-mechanical 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. [82, 83, 84]

### 2.2.3.3. ADOPTION MATURITY ANALYSIS


Figure 19: Substation Automation
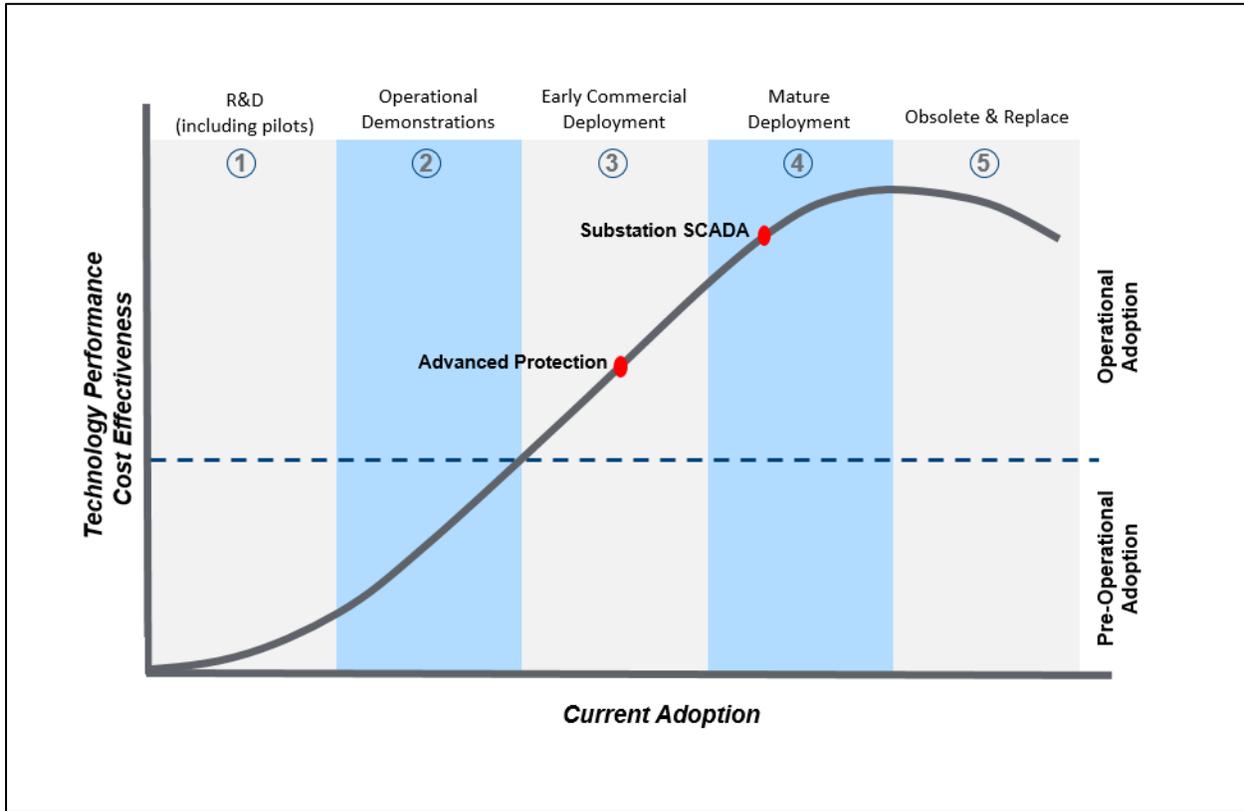
Substation SCADA is mature and widely deployed, although primarily in larger distribution substations. Installations in distribution substations are growing in response to the need for distributed analytics and advanced DMS.[85] Figure 20 below illustrates the level of adoption.

Figure 20: Distribution Substation Automation[86]
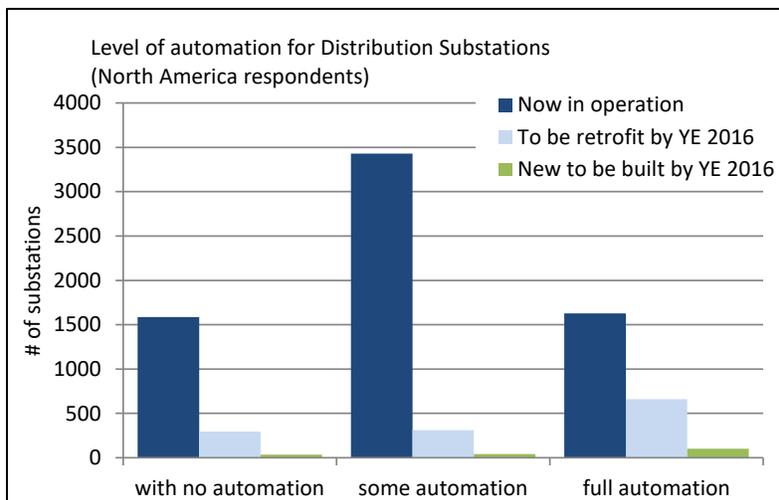
Additionally, research survey results indicate that the majority of distribution substations have a single computing platform as shown by Figure 21 below. Substations that do not have an established computing platform have Remote Terminal Unit (RTU) installations that perform data acquisition tasks and transmit operating data back to a control center-based computing platform. Few substations have two or more computing platforms.

Figure 21: Computer Platforms per Substation[87]
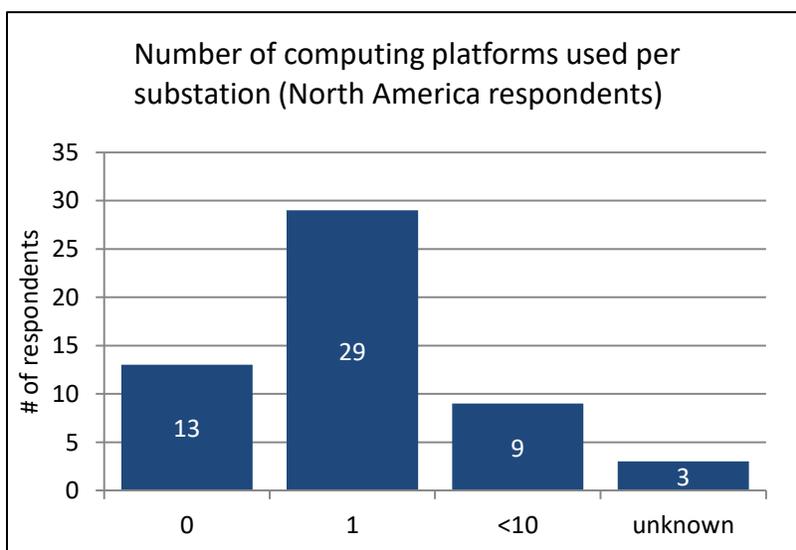
Advanced protection relays are beginning to be deployed as part of aging infrastructure replacement and as required for reliability enhancement and DER integration. [88]

2.2.4. Operational Communications Infrastructure

2.2.4.1. TECHNOLOGY CATEGORY DESCRIPTION

Communication technologies may be considered from two aspects:

1. The way in which data is conveyed, which for the purposes of Volume II 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).[89] The diagram in Figure 22 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.

Figure 22: Operational Communications Infrastructure[90]
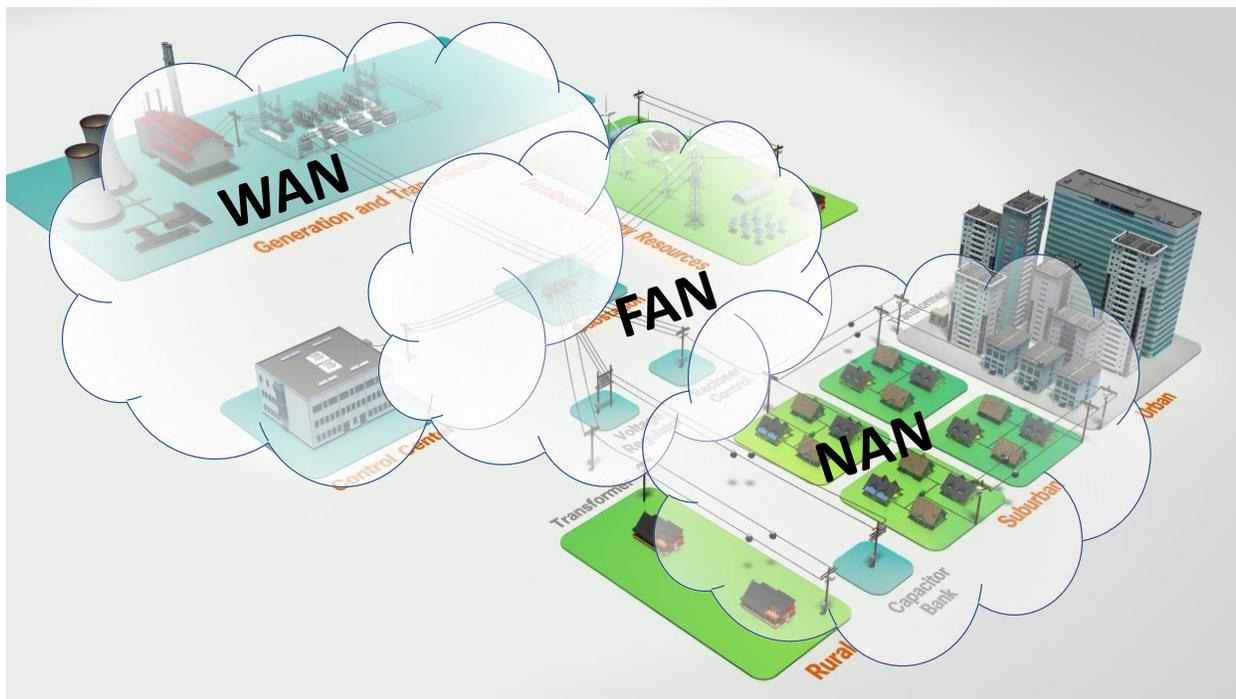
WAN[91]

There is generally a business (enterprise) WAN as well as an operations WAN. The business 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[92]).

FAN[93]

As with WAN, a FAN may be multiple siloed purpose-built networks. FAN connects the NAN with the WAN by providing backhaul services for 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.[94]

NAN[95]

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 Volume II to cover these in any depth. The Utilities Technology Council[96] (UTC) provides a wealth of information on communications on both private infrastructure as well as telecommunications service provider (SP) offerings.

Communications Network Management Systems[97, 98]

Communication Network Management Systems provide insight into the touch points between power and communications equipment to configure networks, monitor performance, and manage behavior. [99] In addition to managing network devices, the same tools can manage and view multiple networks.

2.2.4.2. TECHNOLOGY DESCRIPTIONS

WAN

Multiprotocol Label Switching (MPLS)

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. [100,101, 102]

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.

Carrier Ethernet

Carrier Ethernet (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.

TDM and Analog

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.

Paging Systems

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 service provider and a satellite antenna such as a Very Small Aperture Terminal (VSAT)[103] at the ground site. Satellite communication has the distinct advantage of being available anywhere, independent of any ground infrastructure apart from the satellite antenna.

FAN

<u>Mobile</u>

Broadband mobile telephony services (i.e., cellular) can be provided by infrastructure that is owned and operated by a telecommunications service provider, 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 3G, 4G, LTE and LTE Advanced.[104] 5G[105] is under development, with service providers targeting deployment by 2020 or 2021.

Private mobile telephony technologies include the same 3G, 4G, LTE and LTE Advanced but on licensed radio spectrum and infrastructure (cell towers and central communications equipment) owned by the distribution company. This will very likely be the case for 5G as well.

<u>Land Mobile Radio</u> (LMR)[106]

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.

<u>Peer-to-Peer (P2P) Systems</u>

P2P communications enable 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.

<u>WiMAX/LTE</u>

Worldwide Interoperability for Microwave Access (WiMAX) is a standards-based technology enabling the delivery of wireless broadband (high bandwidth) access to endpoint devices.[107] The family of standards is based on the IEEE 802.16 set of standards.

<u>WiFi</u>

WiFi and WiFi mesh[11] are high bandwidth systems that use unlicensed radio frequencies, which are also available to personal computers, tablets, and smart phones for data communication. Applications of WiFi within the distribution grid are identical to those listed for mobile telephony.

NAN

<u>Radio Frequency (RF) Mesh</u>

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 back haul paths. [108, 12] 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.

<u>Other RF Systems</u>

There are a variety of specialty, proprietary RF systems in use by providers of grid equipment such as protection devices[109] and by AMI vendors.[110] These include both PTP and point-to-multipoint systems.

<u>Power Line Carrier (PLC)</u>

Power Line Carrier (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.

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[11] ABB Tropos WiFi Mesh

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

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.

Communication Network Management Systems

Communication network management system technology is a set of software tools that provide visibility to devices attached to the network and control network parameters, including configuration and security. Virtually every communication equipment supplier and numerous third parties offer a wide range of tools.

2.2.4.3.   ADOPTION MATURITY ANALYSIS

Figure 23: Communications Infrastructure
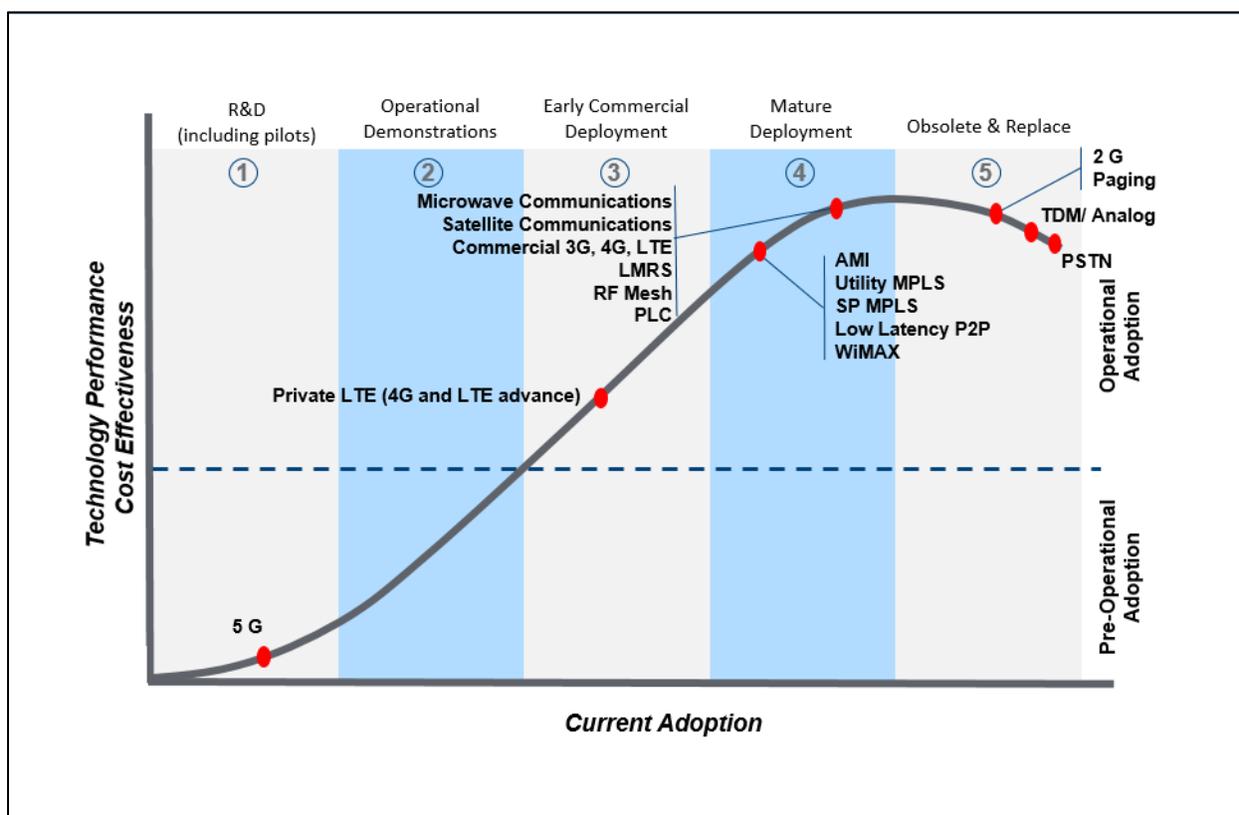
The need for ubiquitous communication in the modern distribution grid stems from all the goals and objectives set forth in Volume I. Secure and reliable communication is essential to the operation of a modern distribution grid.

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 needs 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.[111, 112] 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 Volume II, 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 have dramatically declined in popularity and commercial importance since the availability of short messaging services in mobile telephony. Paging is widely regarded as obsolete and is 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 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)[113] 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 meter reading.

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.[114, 115, 116, 117, 118]

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 Volume II, RF mesh is in mature commercial deployment for AMI and early commercial deployment for field automation.[119] However, it is important to note that RF mesh systems are not interoperable. Wi-SUN Alliance[120] is an industry organization (modeled after the WiFi Alliance[121]) 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.

2.2.5. Sensing and Measurement

2.2.5.1. 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. [122, 123, 124, 125] Sensing and measurement data is also utilized in distribution and system planning. The underlying technology components within sensing and measurement are:

- Advanced Customer Metering,
- Production Metering,
- Grid Asset Sensors,
- Environmental Sensors, and
- Grid Sensors.

2.2.5.2. TECHNOLOGY DESCRIPTIONS

Advanced Customer Metering

Advanced Smart Meters

Smart meters are typically digital, solid-state meters that are used to measure a customer's consumption during configured time intervals through a periodic polling mechanism. Advanced customer metering consists of technologies that can measure and communicate customer energy use or production, power characteristics, operational events, and notifications at time intervals sufficiently granular and latent to support grid and market operations. Advanced meters may include other capabilities such as real and reactive power measurement and power quality (harmonic distortion) measurement.[126] These advanced smart meters can be used as grid sensors 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 Sensors

Grid asset sensing technologies are health monitoring devices that automatically measure and communicate characteristics related to the health and maintenance of the equipment, such as temperature, dissolved gas and loading. These devices can also automatically generate alarm signals if the equipment characteristics reach critical or dangerous levels.[127]

Environmental Sensors[128]

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.[129]

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.[130]

<u>Weather Sensors</u>

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

<u>Solar Irradiance Sensors</u>

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 a knowledge of location-specific solar variance, which in turn can help maintain safe and reliable grid operations.[131]

Grid Sensors

Grid sensors (usually called line sensors) are devices that provide real-time visibility into the operation and performance of the grid, including DER operations, thus allowing for the quick identification of normal, abnormal or emergency situations and preventing interruptions of power. The two primary types of grid sensors are voltage sensors and current sensors. Coupling these sensors with analytical tools enables observability into normal operation, while also improving the ability to locate and de-energize fault locations, such as live electrical wires, which could create public and worker safety risks.[132]

<u>Line Sensors</u>

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.

<u>Voltage Sensors</u>

Electrical voltage sensors measure AC and/or DC voltage levels. They receive voltage inputs and provide outputs as analog voltage signals, switches or audible signals. Voltage sensors vary in terms of performance specifications, optional features and environmental operating conditions.

<u>Current Sensors</u>

Current sensors measure AC and/or DC current levels. Different sensors can have different characteristics for different applications, and current sensors can use a variety of technologies in order to measure current.

2.2.5.3. ADOPTION MATURITY ANALYSIS

Figure 24: Sensing and Measurement
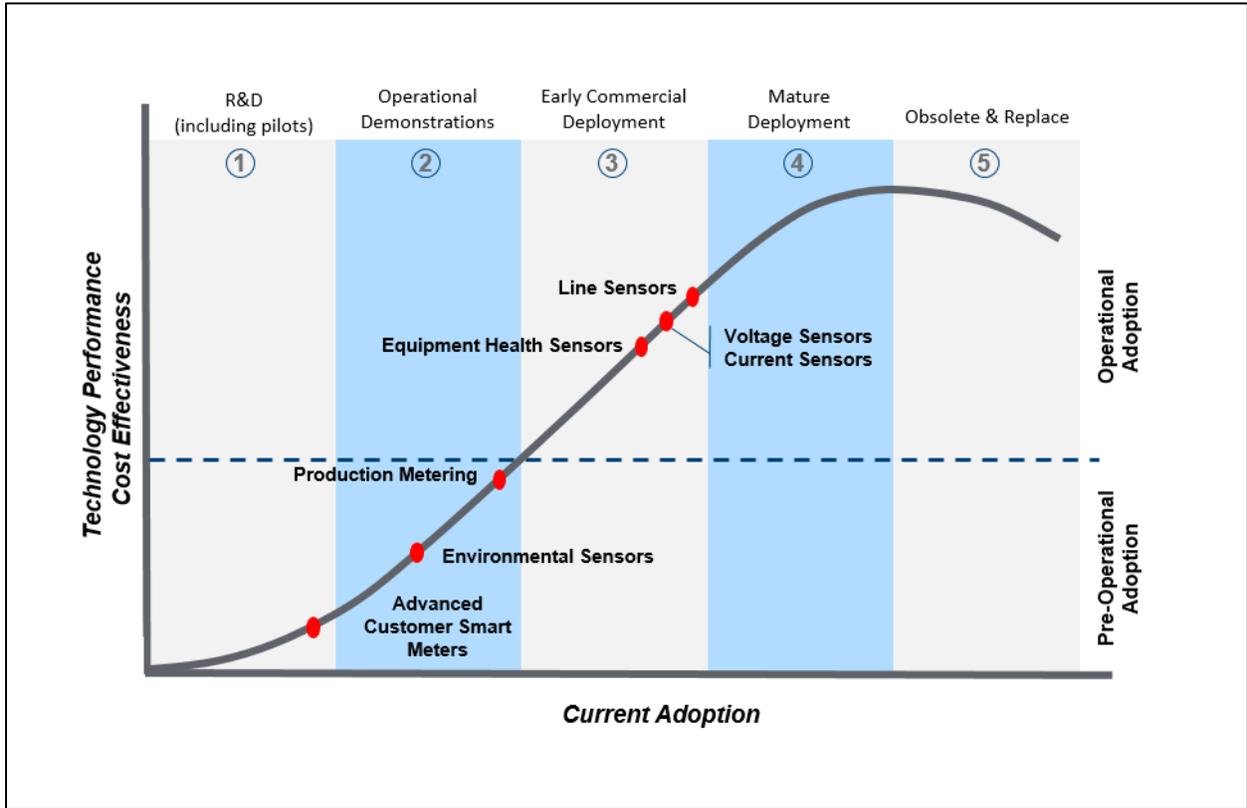
The development of <u>advanced customer smart meters</u> that can fulfill the requirements of a grid sensor is in operational demonstration. Advanced meters and their associated infrastructure require significant investment, and adoption barriers such as an unclear business case for such infrastructure or prior investments in older metering technology.

The adoption of <u>production meters</u> for DER are in the early commercial deployment stage given the limited use since it is typically only installed above a certain size threshold.

The development of <u>equipment health sensors</u> 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.

<u>Environmental sensors</u> 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 large-scale proliferation of intermittent DER may drive the need for cost-effective installation of environmental sensors.[133,134]

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.

2.2.6. Operational Analytics

2.2.6.1.   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.[135] The underlying components that support operational analytics are:

- Field Data Management,
- Electrical Network Connectivity Model,
- Distribution State Estimation,
- OMS, and
- GIS.

Field Data Management

Meter Data Management

Meter data management consists of processes and tools for securely storing, organizing, and normalizing data from advanced meters, integrating data from other meters, and making the data available for multiple applications including customer billing, analysis for grid control, and outage management.

Advanced meter data management systems include integrated applications for analytics and interfaces for integration with other operational systems such as GIS and OMS.

Meter data management systems have specific provisions for both data security and data privacy.[136]

Sensor Data Management

Typical industry functions operate in an independent or siloed fashion. Modern distribution grid sensor data management systems will use advanced "Big Data" analytics and multiple protocols and information silos to integrate disparate data sources and create a single, comprehensible source of data. In order for sensor-based data management to support Big Data analytics, a system or process model must not only

define the context of a sensor within a process and operation, but also provide context management that allows data to be reliably rolled-up and compared to other data streams across operations.

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 employs 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.[137] 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 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; these include reactive power management, outage management, loss reduction, DR, adaptable over-current protection, condition-based maintenance, integration with transmission system operations, and more.[138, 139]

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 and observe 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. [140, 141]

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.[142]

2.2.6.2. TECHNOLOGY DESCRIPTIONS

Field Data Management

Data Management Systems

Data management systems offer a user interface that allows users to view, manage and act on usage and overlay related information such as: weather data, average usage profiles, similar premise usage, AMI events, validation, editing, and estimation, installation and removal activities, outage periods, meter reader remarks, and service orders. Such platforms can also integrate with complementary products and tools such as a CIS, data storage and management systems, infrastructure management systems, and Software as a Service analytics tools.[143]

Analytics Software

Technical analytics are critical software tools and processes that transform raw data into useful, comprehensible information for operations decision making. Technical analytics includes signal analytics (substation and line sensor waveforms, time and frequency domain data), engineering operations analytics (system performance, asset health, load trends and forecasts) and customer analytics (demand profiles, and DR behavior and forecasts).[144]

Electrical Network Connectivity Model

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 and power engineering and planning modeling tools. An operating system such as a DMS unifies data from DMS, SCADA and OMS to maintain a real time "as-operated" distribution network connectivity model.[145]

Distribution State Estimation

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 and 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.[146]

2.2.6.3. ADOPTION MATURITY ANALYSIS

Figure 25: Operational Analytics
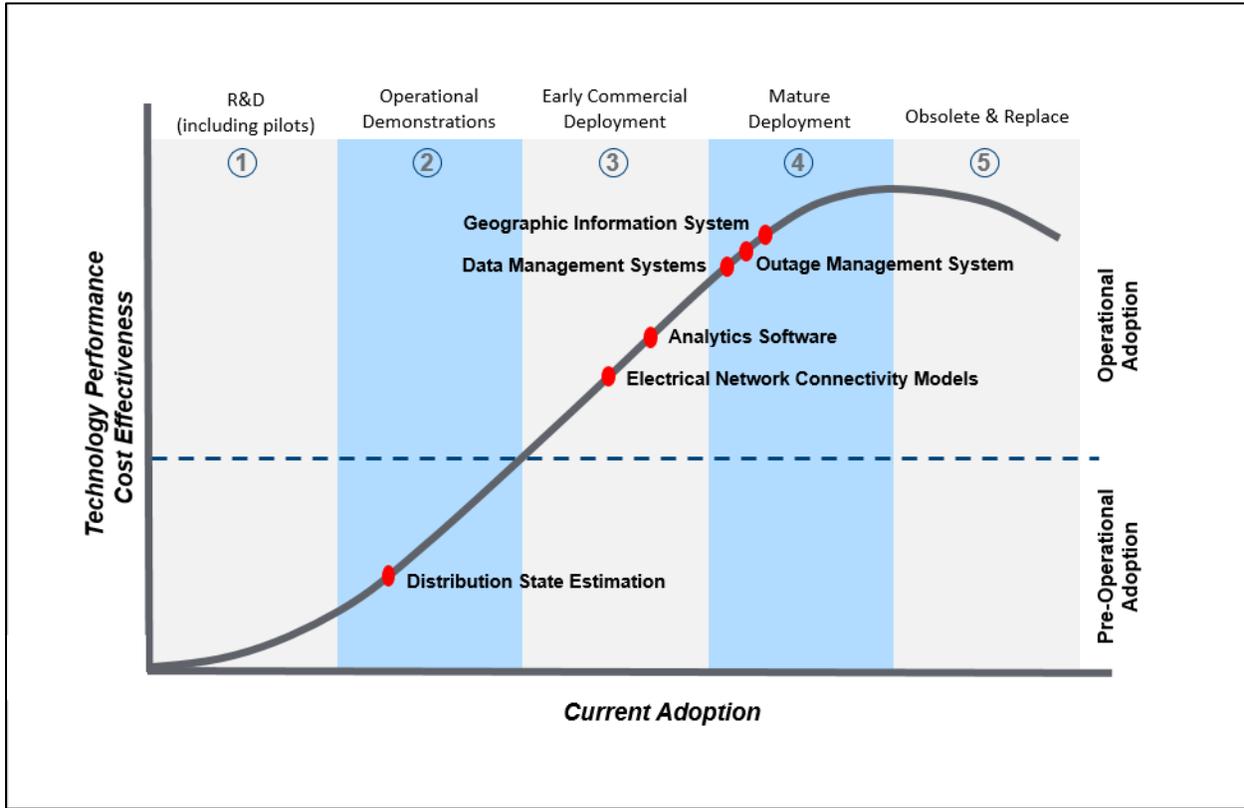
Data management systems consist of servers, networking, data storage and supporting systems software, including operating systems, databases, communications software, and applications monitoring software. They are a key component of sensor and meter data management systems, and have been widely deployed. The installation of these platforms and data management software is driven by the deployment of smart grid devices and AMI. Hence, data management systems are in mature deployment.

Analytics software is deployed in conjunction with IT platforms. These tools are used to clean and analyze data that is eventually visually represented via an IT platform. As a result, analytics software is in mature deployment.

Recent market trends indicate a preference for single vendor outage management systems bundled with DMS, SCADA and Interactive Voice Response (IVR), 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.[147]

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, 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.

2.2.7. Optimization Analytics

2.2.7.1. TECHNOLOGY CATEGORY DESCRIPTION

The availability of additional grid intelligence can, through analytics, extend the life of assets, predictively maintain equipment, and effectively manage a field work force to improve overall system performance and efficiencies. Also, as DER services include non-wires alternatives, there is a need to optimally evaluate a complex portfolio or many portfolios of various individual, programmatic and aggregator services to meet specific locational grid needs. This optimized locational "loading order" utilizes analytics to assess availability and performance attributes to create portfolios for operational dispatch.[148,149]

The underlying components that support optimization analytics are asset management and DER optimization.

2.2.7.2. TECHNOLOGY DESCRIPTIONS

Asset Management

Asset management integrates the grid intelligence acquired in achieving the other milestones with new and existing asset management applications. One important technology is condition based maintenance (CBM) systems.

CBM Systems

A CBM system collects data on distribution assets to ensure maintenance is performed only when needed. A CBM integrates with software-based tools that can be deployed to gather grid data, to aggregate and analyze grid data, and to pinpoint locations to add new data collection monitors and sensors. CBM systems leverage asset data to reconcile maintenance schedules with actual asset conditions, organizational priorities, and changes in operating environments. [150, 151]

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.

2.2.7.3. ADOPTION MATURITY ANALYSIS

Figure 26: Optimization Analytics
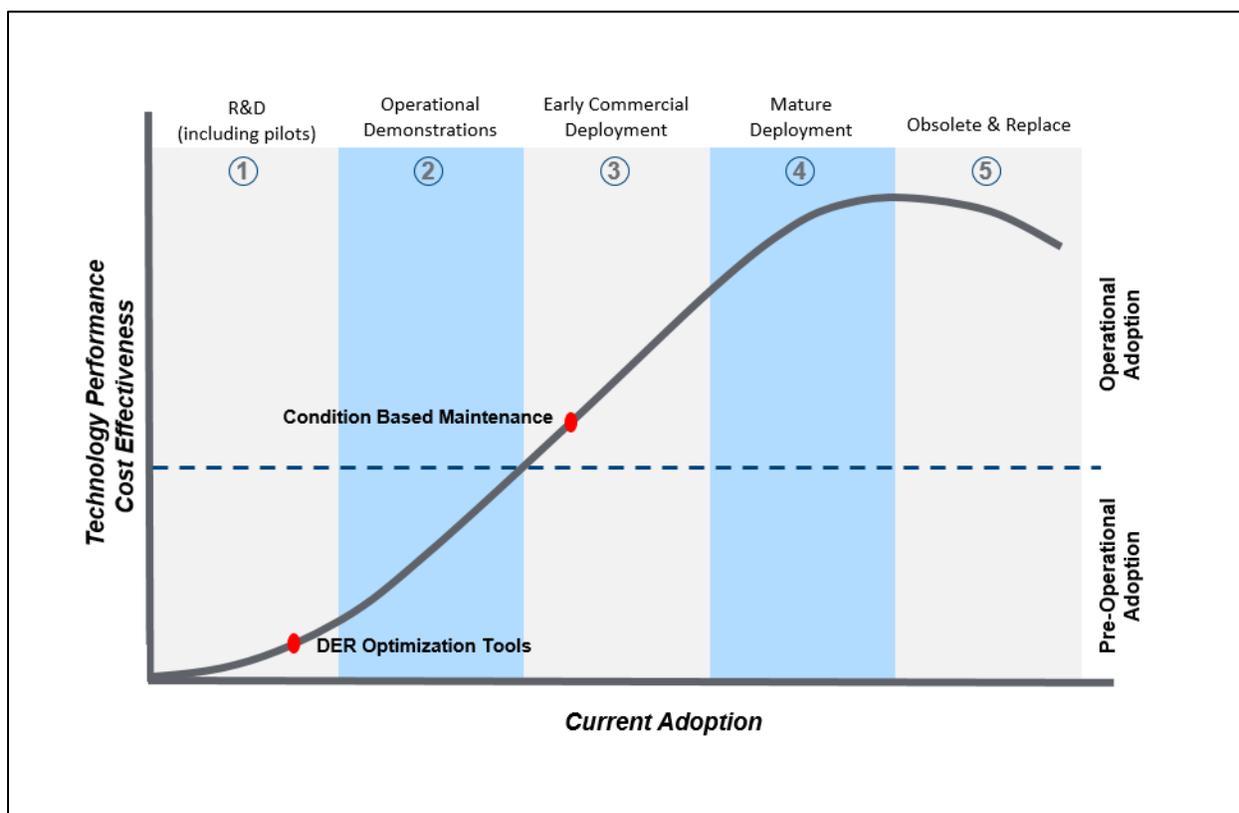
Reactive and preventative grid maintenance programs to respond to grid events have been widely used by utilities for a long time. However, the integration of CBM programs using software tools is a recent development. Typically source data is generally available and commercially available analytics are 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.

DER optimization tools are generally in 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 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.

2.3 DISTRIBUTION MARKET OPERATIONS

2.3.1 Distribution Operational Market

2.3.1.1. TECHNOLOGY CATEGORY DESCRIPTION

Distribution operational markets involve the use of DER provided services as non-wires alternatives.[152] In addition to the planning and grid operational technologies described above, there are initially two technology categories, Market Settlement and Market Portals, that are needed to support a distribution operational market over the next five years. Additionally, market compliance and surveillance tools will be needed. Other potential market structures and specific market designs are beyond the scope of Volume II.

2.3.1.2. TECHNOLOGY DESCRIPTIONS

Market Settlement

The settlement process will include 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 and involve accounting for relatively small units (micro-transactions) that sum to large dollar values. 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, 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 not unlike those used for online digital media, such as for purchasing music, to 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.[153]

Market Portals

Market portals could provide open channels for market participants to view and visualize information related to distribution operational markets for grid services. Market portals will 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.[154] Several standards based approaches are in development to support information exchange including: Green Button Connect and Orange Button Connect.[155, 156]

Additionally, market 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.

Market Compliance and Surveillance

Distribution operational market participants 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).

Market 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.[157]

2.3.1.3. ADOPTION MATURITY ANALYSIS

Figure 27: Distribution Operational Market
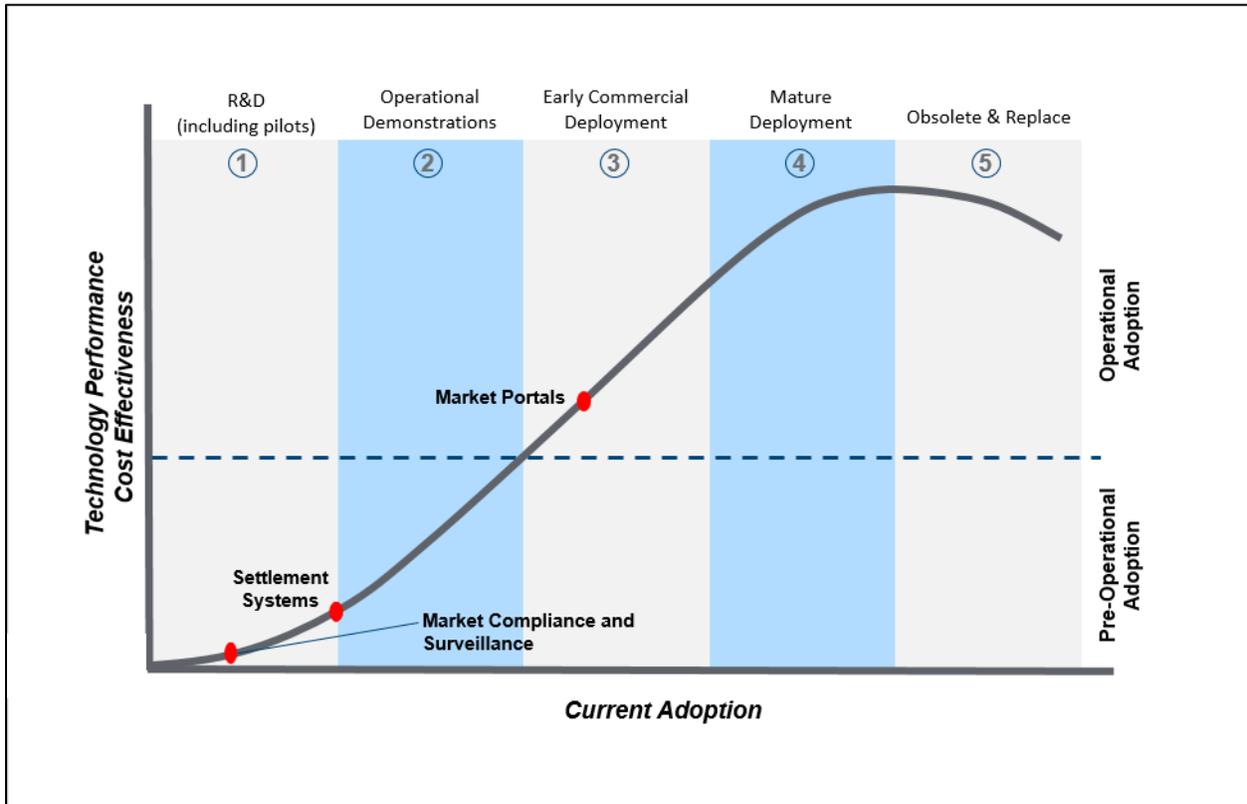
Market portals related to customer information access and system data exchange are in early commercial deployment. A few Green Button Connect implementations have been established, or are under development. Portals sharing hosting capacity information through maps and data have begun initial deployments and are in early commercial development. Other information portals such as Orange Button are under R&D, with the data exchange standards in development.[158] 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 a 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 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, but 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.

3.SUMMARY

3.1. OVERVIEW

Volume II identifies the enabling technologies linked to the functions identified in Volume I of this report. As such, this volume combined with Volume I provides a line of sight from state policy objectives and attributes for a modern grid 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. Additionally, the technologies described in this volume are assessed along a Technology Adoption Cycle to evaluate their maturity through several stages of commercial usage – from research and development activities to mature deployment and eventual obsolescence. It assumed that commercial adoption of advanced grid technology will be driven by customer value and expectations as well as policies.

Volumes I and II serve as industry references and support the discussion in Volume III, "Decision Guide," which addresses key considerations for states and industry contemplating distribution grid modernization to enable one or more of the following outcomes:

- Reliability, safety and operational efficiency of the distribution system
- DER integration to enable customer choice and other policy objectives
- DER utilization in bulk power system and/or as distribution non-wires alternatives

3.2. FINDINGS

A wide range of technologies are discussed in this volume most of which are in a stage of maturity for commercial deployment to support the customer and policy objectives identified in Volume I. However, there are maturity gaps in 5 key technology categories that present potential challenges over the 5-year horizon of the Modern Distribution Grid Report. These are summarized below.

- <u>Multi-DER simulation for planning and hosting capacity analysis</u>

  There is an existing gap in current modeling tools used for hosting capacity analysis and annual distribution planning to be able to assess the simultaneous net effect of various types of DER operating autonomously or optimized at a distribution system location. Given that battery energy storage is rapidly becoming more cost-effective and increasing combined with solar PV system, it will be essential to have this capability to properly conduct evaluations. This gap is understood in the industry, but less so with policy makers. Efforts to facilitate commercial development, testing and deployment are needed.

- Integrated resource, transmission and distribution modeling tools

  As customer adoption and merchant development of DER (e.g., community solar, DER aggregators, microgrids, etc.) increase, they will play an increasingly important role in system resource adequacy and transmission planning in addition to distribution planning. In several states the current and forecast levels of DER are such that it is important to assess DER across the entire power system. Today, that is only possible through an iterative approach linking the results from resource planning to transmission and distribution. It is not possible to conduct a simultaneous (or coordinated) evaluation. This gap will pose a significant challenge to states with high DER forecasts such as Hawaii and California over the next 5 years. Efforts to facilitate commercial development, testing and deployment are needed.

- Distributed energy resource management systems

  DERMS is a key technology for DER utilization for a variety of uses to manage portfolios of aggregated DER as well as direct control of DER. These systems, as noted, are in an early stage of operational demonstration with a large number of vendor products in commercial development. However, further development and adoption will be slowed by the lack clarity on the functionality required. This is due to varying industry opinions of the operational and technical capabilities envisioned of DERMS. Additionally, 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.

  Another challenge is the potential transition from legacy Demand Response Management Systems to a single unified DERMS to manage all DER (incl. existing DR programs) providing wholesale and distribution grid services. The operational demonstrations underway should lead to commercial adoption, but will require regulatory support for "co-development" between technology vendors and the users of these systems. Also, standardization of the several interfaces are needed and support for these activities is also required.

- Integrated Volt-var management w/smart inverters

  Integrated Volt-var systems have not been widely deployed, as traditional voltage management techniques can be used to achieve most of the efficiency gains from conservation voltage reduction. With increasing levels of variable DER such systems will need to be used to coordinate grid devices and smart inverters to maintain voltage quality. However, in practice the design and operation of such a system is still in a development stage. There are several R&D pilots of a Volt-var management system interfacing with smart inverters. However, a revised IEEE 1547 standard is forthcoming that includes significant changes to the autonomous and interoperable functions of inverters. Also, a key interoperability standard is in development by the SunSpec Alliance. Given that these standards have yet to be fully tested and commercially implemented, it may be a couple of years before they are commercially adopted.

Additionally, distribution power flow controllers (DPFCs) are an alternative to smart inverters to dynamically manage voltage and reactive power. A challenge to integrated Volt-var management as envisioned in several states is that there are not yet industry best practices for the application and use of IVVO software, DPFCs and/or smart inverters in addition to existing load tap changes and capacitor banks as part of a holistic system. As a result, gaps exist on actual operational performance due to limited demonstrations, industry accepted design approaches and comparative cost-effectiveness studies for design alternatives.

- Interoperability standards

  Interoperability standards remain a significant challenge to the development of a modern distribution grid. This is true when considering both interfaces between utility systems and customers or energy services organizations or whether considering the intra-faces between grid operating systems including communications. Progress has been made over the past decade through efforts of several organizations such as IEEE, NIST and SGIP (now part of SEPA) and several industry initiatives noted.

  However, much remains to be done to advance interoperability standards and to implement in commercially available technology. For context, utilities and other buyers of this technology are generally technology takers, not market makers. That is, they are not large enough individually in buying power (particularly in a global grid technology market) to dictate fundamental technology capabilities or standards with technology vendors. Regulators have an opportunity to support utility adoption of interoperable technology by more clearly exploring interoperability gaps and the potential courses of action to address. The solution requires all three legs of the stool; regulator, utility and grid technology supplier to address this gap.

  One potential approach to highlight the gaps and areas for development is to create an interoperability roadmap (or roadmaps depending on the function). Such an effort could support a discussion among regulators and industry on priorities for interoperability standards development.

Finally, it should be noted that the underlying physical grid infrastructure is already undergoing improvements and enhancements as part of aging infrastructure replacement. Such investments are rarely exactly like-for-like. Therefore, the result is a more robust distribution grid that provides a solid foundation for more advanced technologies described in this volume. Also, any commercial technology adoption must consider the integration with legacy systems and equipment given that there rarely are deployments done in greenfield environments. Additionally, it is expected that the various communications, information and operational systems discussed in this volume will be built and installed with the necessary cybersecurity protocols and methods, and with the appropriate assignment of security roles and permissions. These issues will be discussed in Volume III, "Decision Guide."

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