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Grid Modernization, the Feeder and Substation of the Future, and Utilizing Advanced Metering Infrastructure (AMI) as a Foundational Component of a Grid Modernization Roadmap

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SUMMARY

Challenges on the distribution grid are driving the need for new solutions at the substation, feeder, and application levels. All utilities are adapting to (i) the growing adoption of Distributed Energy Resources (DER), (ii) expanding electrification, and (iii) the increasing frequency of major weather and climate events that are impacting the distribution grid and driving resiliency concerns. To address customer expectations regarding service reliability, resilience, and power quality, utilities are implementing new grid modernization plans. One of the key issues for utilities implementing grid modernization is the availability of communications across the distribution grid. When Advanced Metering Infrastructure (AMI) was first introduced, one of the goals was to provide the last mile communications on the grid. While initial AMI deployments have greatly advanced metering accuracy and capabilities, outage detection, and other functions, AMI still has the potential to be leveraged for more functions to support a grid modernization plan.

This paper outlines the concept of a grid modernization and creating a grid modernization roadmap, focuses on the concepts of the distribution substation and feeder of the future, and provides an overview of AMI and how AMI can play a larger role in future distribution systems grid modernization.

KEYWORDS

AGI: Advanced Grid Infrastructure**,** AMI: Advanced Metering Infrastructure, FoF: Feeder of the Future, Grid Modernization

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GRID MODERNIZATION ROADMAP

Traditionally, a utility's primary concern was the delivery of reliable power to its customers. While this remains a critical aspect, the utility landscape is changing due to technical and societal drivers. A grid modernization roadmap is a plan to prioritize investments to address these drivers, which include:

- Stresses and requirements imposed on the existing grid by the adoption of new technologies, such as DER and electrification.
- Evolving changes to climate and weather patterns (e.g., more frequent and more severe storms and catastrophic events, such as hurricanes and wildfires).
- Aging infrastructure.
- Evolving expectations of customers regarding reliability, resilience, and power quality.
- Impacts from human events (e.g., sabotage, terrorism, etc.).

Grid modernization enables key capabilities and features for a modern and future grid, including [1]:

- Improved reliability for everyday operations.
- Increased sustainability through energy-efficiency, demand response, and renewable resources.
- Greater resilience to hazards of all types.
- Enhanced physical and cyber security from an increasing and evolving number of threats.
- Long-term affordability to maintain economic prosperity.
- Superior flexibility to respond to the variability and uncertainty of conditions at one or more timescales, including a range of energy futures.

An envisioned evolution of the distribution grid is illustrated in the figure below.

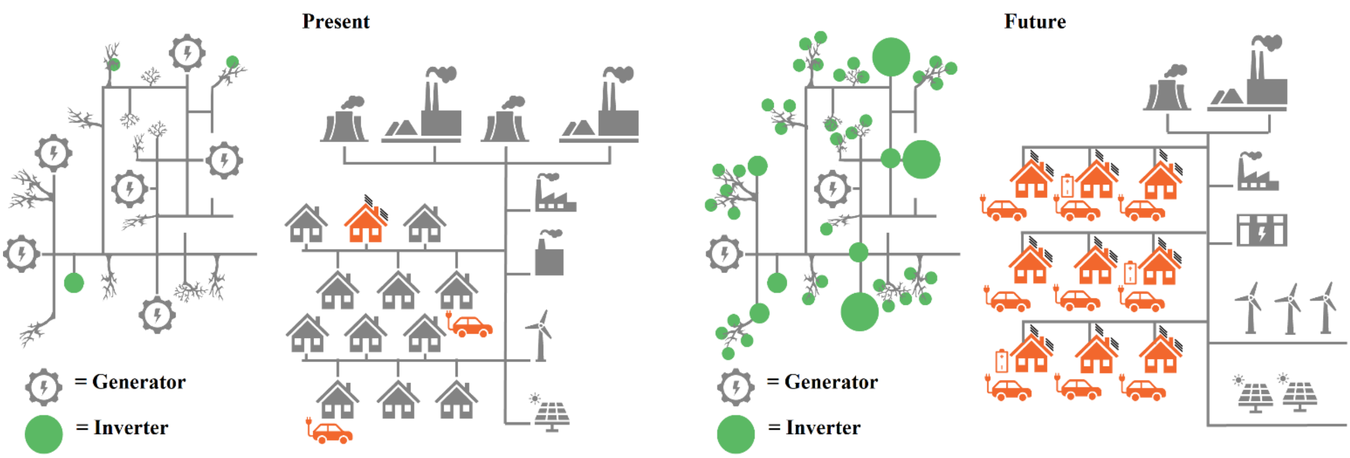

Figure 1 Grid Evolution

The grid modernization roadmap is dependent on the utility's vision of its role in the future. To take a utility's vision and then create a roadmap, a cross-functional team involved from beginning to end is important to have. The communication plan should include the utility's departments but could also include other critical stakeholders.

The development of a grid modernization roadmap includes the following steps:

1. Identify key components of the utility's vision and goals.
2. Develop a preliminary list of key programs needed for achieving the utility's goals.
3. Benchmark existing utility practices and potential programs against industry trends and leading practices.
4. Develop a benefit-cost analysis to create a metric for prioritizing grid modernization programs. Costs and benefits should be weighted by relative importance to meet the utility's goals (e.g., reliability and resilience, sustainability, efficiency, etc.) and parameters such as investment, risk, complexity, maturity, and others.
5. Sequence and categorize programs. Once the programs are prioritized, proper sequencing of the programs must be considered. Programs are categorized as foundational and non-foundational. Foundational programs impact one or more subsequent programs and are direct pre-requisites. Foundational programs must be deployed first and are given higher priority in the overall roadmap timeline.

The process for creating a grid modernization roadmap shown in Figure 2. The team must determine the appropriate balance of quantitative and qualitative analysis. A utility's goals, best practices, cost, risk, and technical options all play a role in the overall evaluation.

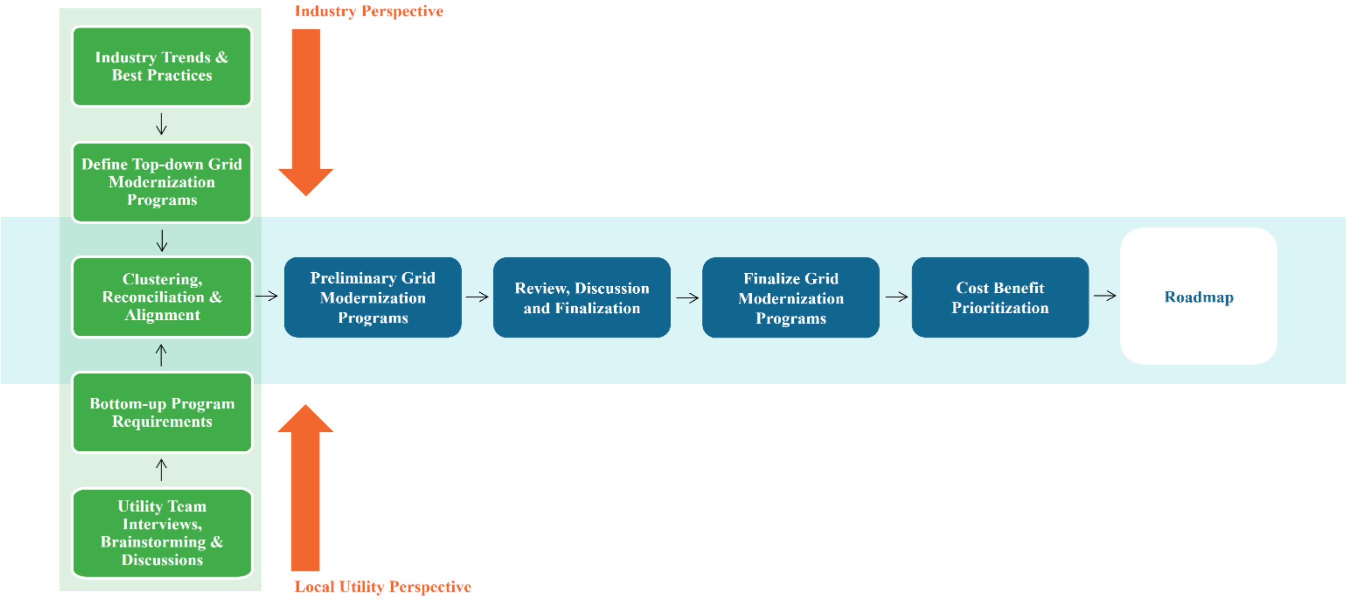

Figure 2. Grid Modernization Process Overview

A grid modernization roadmap consists of a prioritized portfolio of programs. Programs are projects or initiatives that can be implemented to realize the desired functionality, capability, or other specific utility goals. For example, if one of the utility's key drivers is reliability improvement, then programs that reduce the frequency and duration of service interruptions are potential options to be considered (e.g., implementing feeder automation, deploying an outage management system (OMS), or enhancing vegetation management practices). If a utility wants to support providing enhanced information to customers, program options could include website upgrades to enhance customer interaction or an interface to hourly consumption from an AMI program with smart meters. Note: A program can support several of a utility's drivers. For example, AMI will improve reliability. This is accomplished by faster notification of service interruptions via last gasp messages (instead of customer trouble calls) and will enhance customer information by providing usage information. Figure 3 shows examples of potential grid modernization programs.

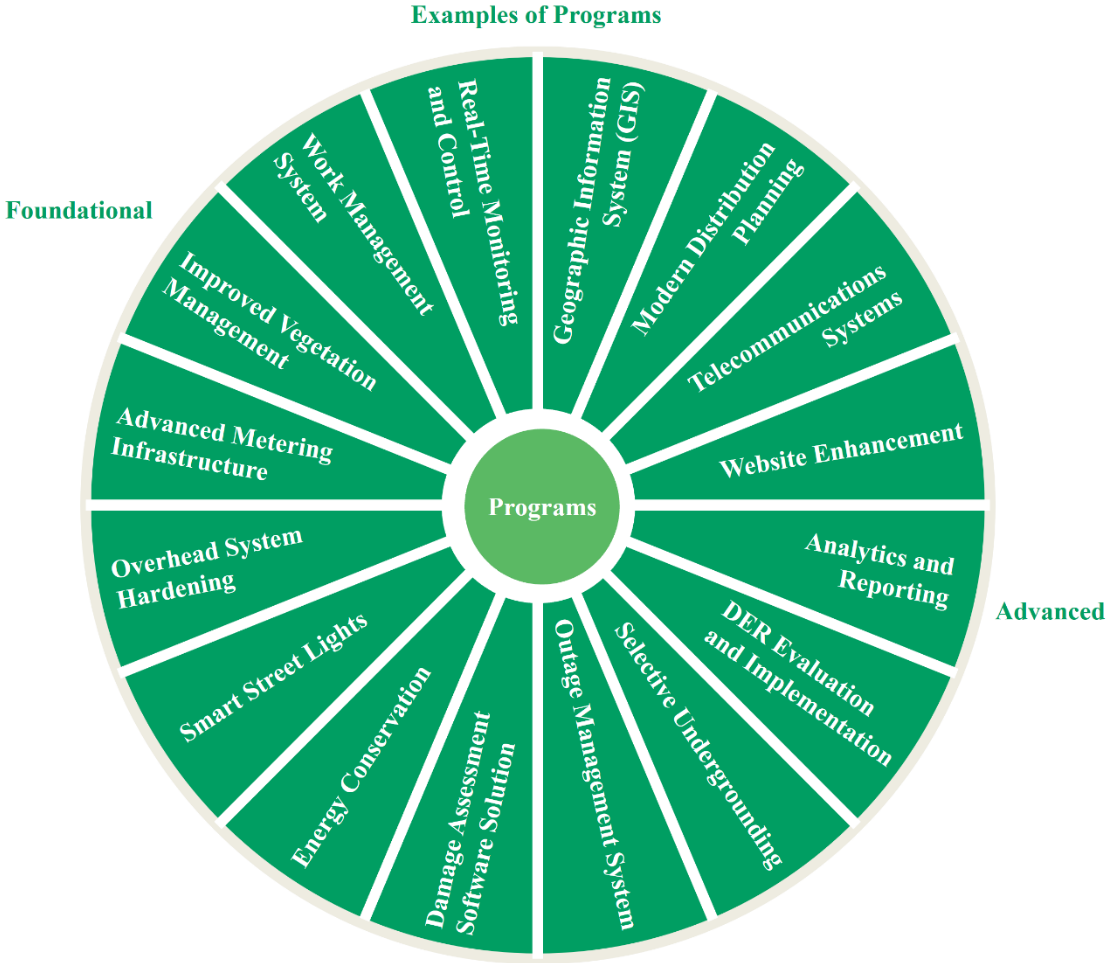

Figure 3. Programs Realize Key Features and Capabilities of a Modernized Grid

Once a program is identified, it is prioritized based on information such as: (i) Benefits: quantitative and qualitative benefits from implementing the program, (ii) Capital costs: initial, fixed, one-time investment required to implement program, (iii) O&M costs (annual): recurring costs, including operations, maintenance, licenses, etc., (iv) Anticipated savings: qualitative discussion of areas for expected savings, and (v) Assumptions: relevant assumptions used to calculate costs (e.g., unit costs, customer base, etc.). Additional factors such as program complexity, technology maturity, implementation risks, organizational readiness, etc., can be considered in the benefit-cost analysis and prioritization. Figure 4 shows examples of prioritized programs.

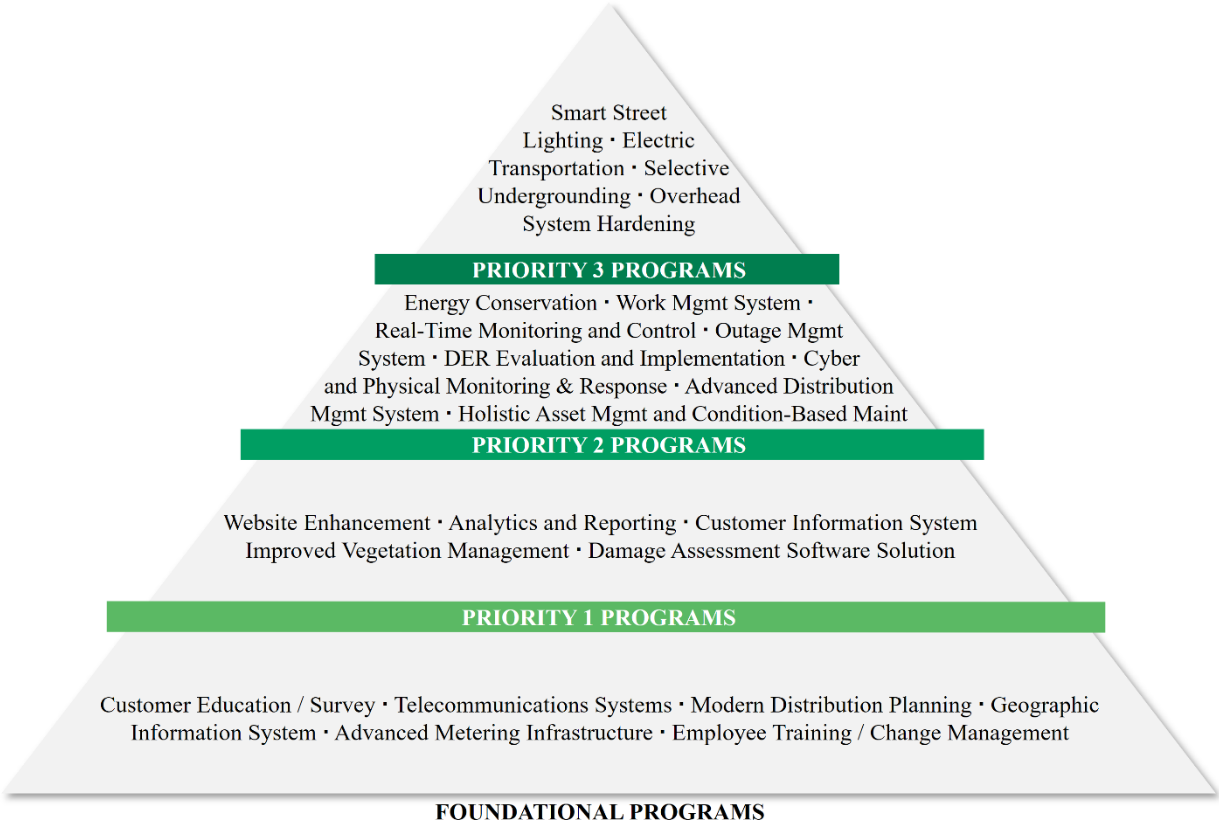

Figure 4. Prioritized Programs are the Building Blocks of a Grid Modernization Roadmap

As can be seen above, the programs in a grid modernization roadmap are comprehensive and can cover many areas. However, for the remainder of the paper the focus will be on the distribution feeder of the future and AMI in grid modernization.

FEEDER of the FUTURE (FoF)

Part of a grid modernization plan includes modernizing the power delivery infrastructure to 1) prepare or "future proof" the distribution grid, to the extent possible, for the adoption of DER (e.g., distributed generation, distributed energy storage, etc.), electrification and emerging technologies, and 2) enable the required capabilities to meet the utility's strategic objectives and regulatory requirements, such as reliability and resilience improvement (e.g. harden the grid against major weather events), decarbonization (e.g., adoption of DER and electric vehicles), and climate change preparedness. This is conceptually shown in Figure 9. The FoF concept is part of a broader grid modernization strategy that involves additional components, including substation modernization, customer technology, AMI, grid hardening, aging infrastructure replacement, advanced planning, electrification, etc, which is illustrated in Figure 6.

The FoF concept addresses key technology areas of interest to utilities, including feeder monitoring, protection, automation, and control, DER integration, microgrids, telecommunications, Advanced Distribution Management Systems (ADMS), grid analytics, and pilot projects, which are conceptually shown in Figure 5.

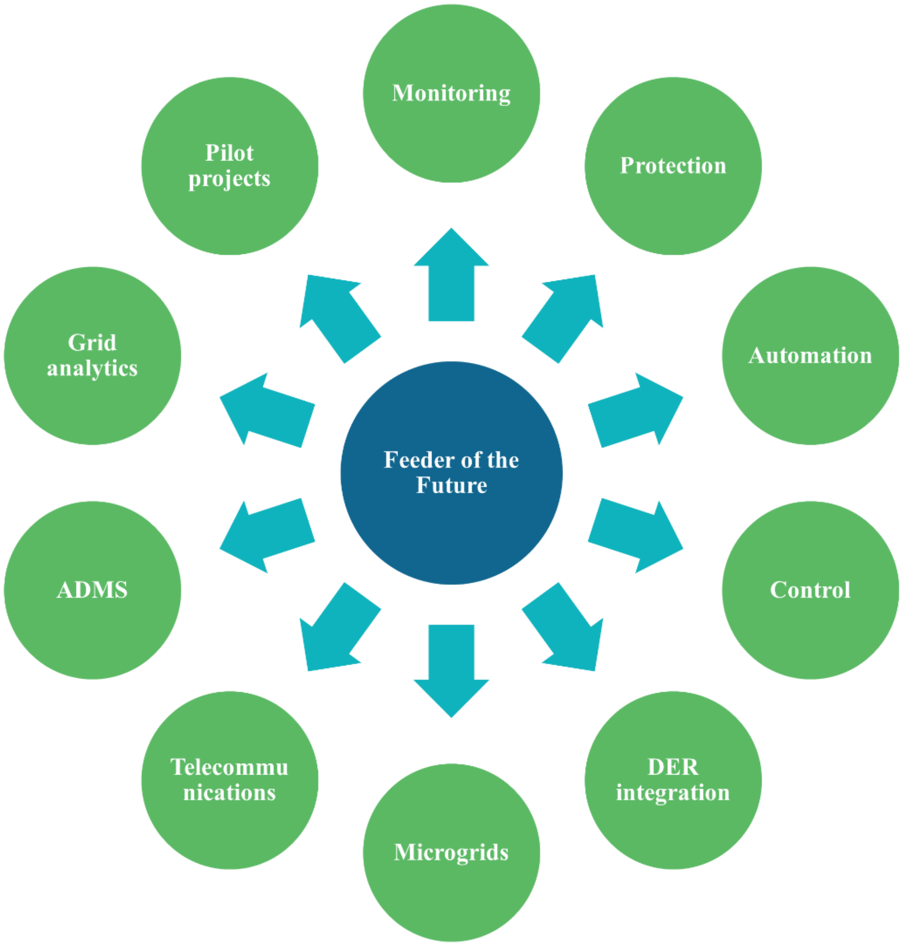

Figure 5. Key Areas of Interest Addressed by the FoF Strategy and Roadmap

Some of these areas involve the implementation of mature technologies, such as distribution automation, while others address emerging areas, such as synchronized measurements. For mature technologies, direct deployment is suitable, while for emerging technologies, the recommended approach is first exploring the concept in a pilot setting that allows investigating a variety of scenarios and develop guidelines and processes, and then operationalize the technology and conduct a wider-scale deployment.

Examples of FoF programs are outlined in Figure 6. In prioritizing these programs, it is important to consider the maturity of the specific technologies, relative implementation complexity, importance and urgency of the need that the component is expected to address, interdependencies with other components, and a component's potential to help achieve strategic goals. Here it is worth noting that all components are important, particularly in the long term, while some are more important in the short term.

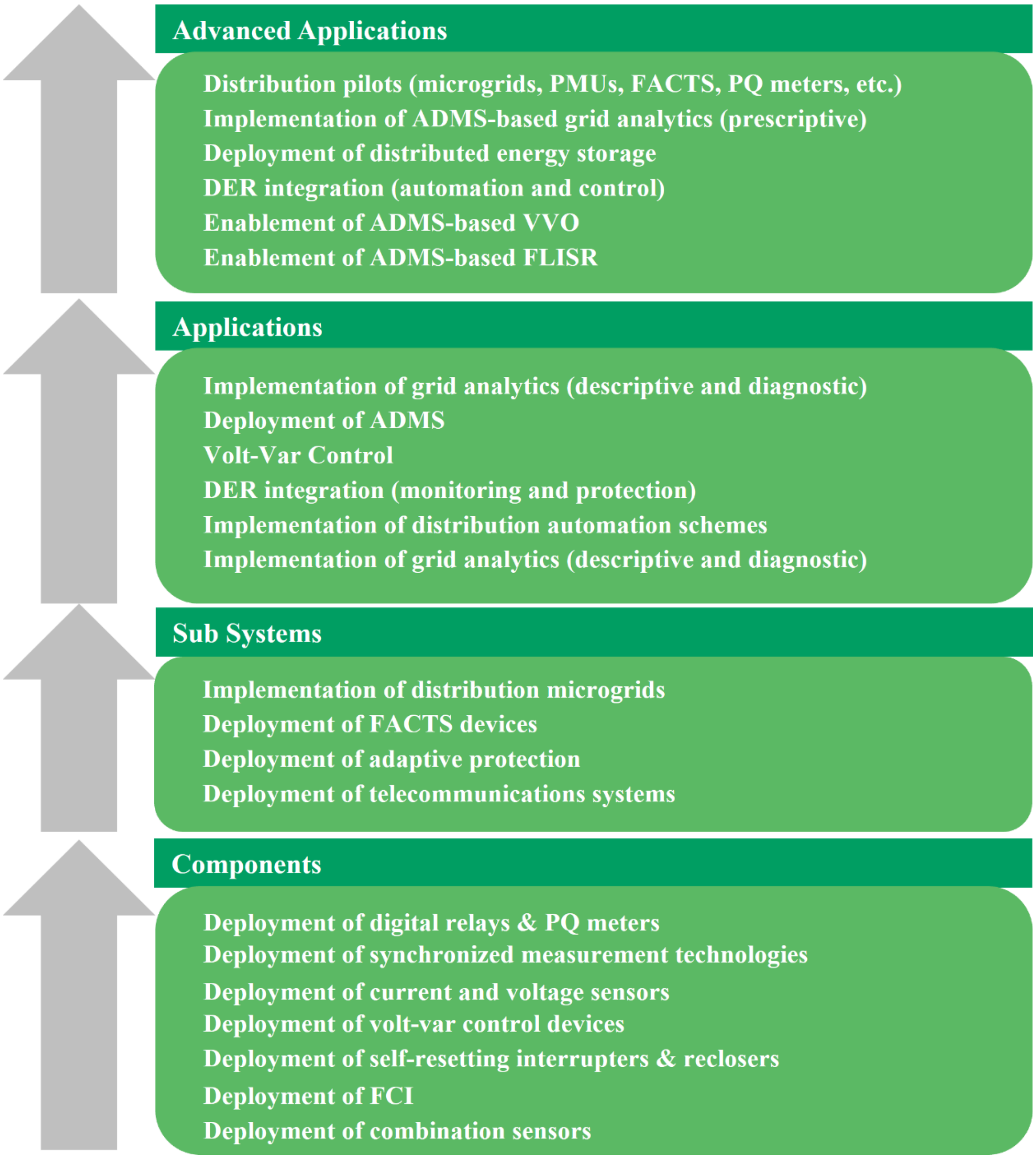

Figure 6. FoF Programs

The roadmap for the FoF is part of the overall grid modernization plan and is typically divided in timelines such as short term (zero to five years), mid-term (five to 10 years), and long term (10 to 15 years). The proposed implementation timeline is intended to balance 1) the urgency to address critical short-term distribution system needs, such as reliability improvement, 2) the need to modernize the grid to comply with industry accepted practices and prepare it for the significant changes introduced by DER adoption and climate change, and 3) the level of effort involved in the implementation of the selected components.

While it is difficult to "future proof" the distribution grid given the uncertainties associated with transformational and disruptive technologies, clean energy adoption, and the impact of severe weather events, the FoF concept provides a strong foundation and proactive approach that will ensure a utility is ready to prevent or address expected challenges. It is important to highlight that the intention of the roadmap is not to "goldplate" the grid, but to proactively identify investments that will be needed as the grid evolves, and to schedule their implementation accordingly.

DISTRIBUTION SUBSTATION of the FUTURE (DSoF)
Another key component of a grid modernization plan is the Distribution Substation of the Future (DSoF). There is an urgent need for substation modernization given the increasing importance of the interaction effects between transmission and distribution systems, such as reverse power flow through substation transformers as well as voltage fluctuations and protection coordination challenges caused by DER proliferation. Additionally, transportation electrification integration is creating a growing need to monitor substation assets in real-time to understand how charging infrastructure impacts asset loading (e.g., substation transformers), power quality, and equipment operation (e.g., load tap changers). Similarly, complying with energy storage mandates and targets require advanced substation monitoring, automation, and control capabilities. Additional drivers for substation modernization are shown in Figure 7 and include reliability, resilience, and power quality improvement. Technology evolution, such as the proliferation of intelligent electronic devices (IED), including microprocessor-based relays and power quality meters, can enable key new capabilities to plan and operate modern power delivery systems that were not available in traditional equipment (e.g., electromechanical relays). This can also allow implementing new concepts, such as substation-level microgrids and Virtual Power Plants (VPP) and intentionally islanding.

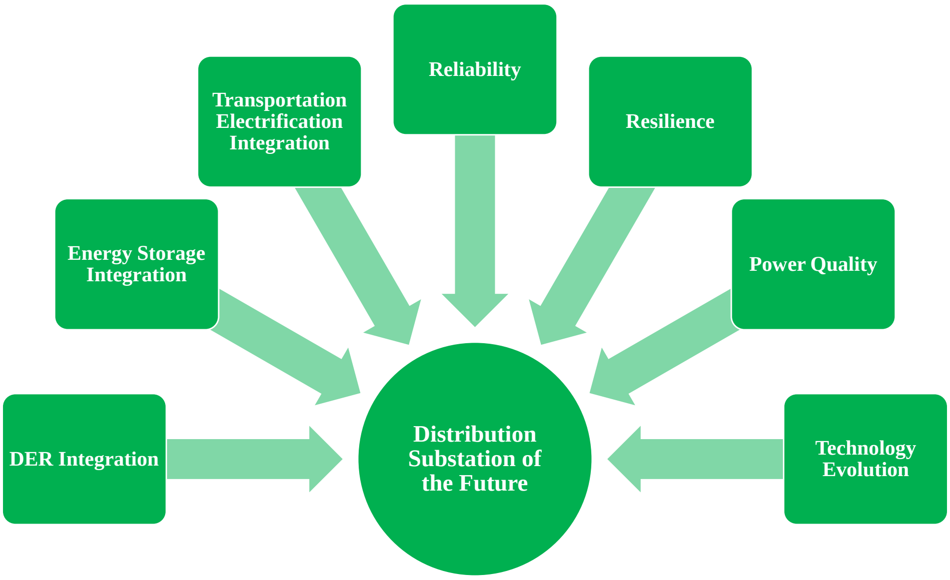

Figure 7. Substation Modernization Drivers

DSoF entails the deployment of key monitoring, protection, automation, and control technologies along with data analytics solutions to replace existing equipment and enable new capabilities and functionalities.

1. Real-time monitoring and control: This includes the deployment of sensors and communications systems and SCADA to collect and transmit key substation data in real-time to control centers (e.g., voltages, currents, power flows, equipment status, temperature, etc.) and enable the implementation of real-time operation of the distribution grid and advanced analytics.
2. Advanced protection, automation, and control: This comprises the deployment of modern microprocessor-based relays with advanced functionalities to replace electromechanical relay technology (e.g., to provide the ability to implement adaptive protection settings). This also includes ensuring that suitable protection functions are in place for reliable and safe

operation under bidirectional power flow conditions through distribution feeders and substation transformers. This component also consists of implementing the IEC 61850 communications standard to enhance protection, automation, and control capabilities and enable further integration of DER and electric transportation while maintaining or improving reliability performance.

3. Voltage regulation and control: This includes the deployment of voltage regulation and control equipment (Load Tap Changers, voltage regulators, capacitor banks, and respective controllers) with the ability to regulate and control voltage under bidirectional power flow conditions and fluctuating power flows. This includes the integration or coordination of these devices with the Volt-Var Optimization (VVO) implementation envisioned by the FoF initiative.
4. Power quality monitoring: This includes the deployment of power quality meters to monitor and evaluate electric power waveforms at substations and key distribution feeder locations (e.g., sensitive customer sites) and proactively assess and identify solutions to prevent or mitigate DER impacts (e.g., voltage fluctuations, harmonics, etc.).
5. Synchronized measurement technology: This includes the deployment of phasor measurement units (PMUs to collect high-resolution time-synchronized data (magnitude and phase angles of voltages and currents), improve wide-area situational awareness of the power delivery system and DERs, and understand and improve overall system performance.
6. Data analytics: This includes the collection, processing and analysis of real-time data provided by Intelligent Electronic Devices (IED) such as digital relays, power quality meters, PMUs and sensors for substation and wide area situational awareness and implementation of other applications such as asset condition assessment and predictive analytics.

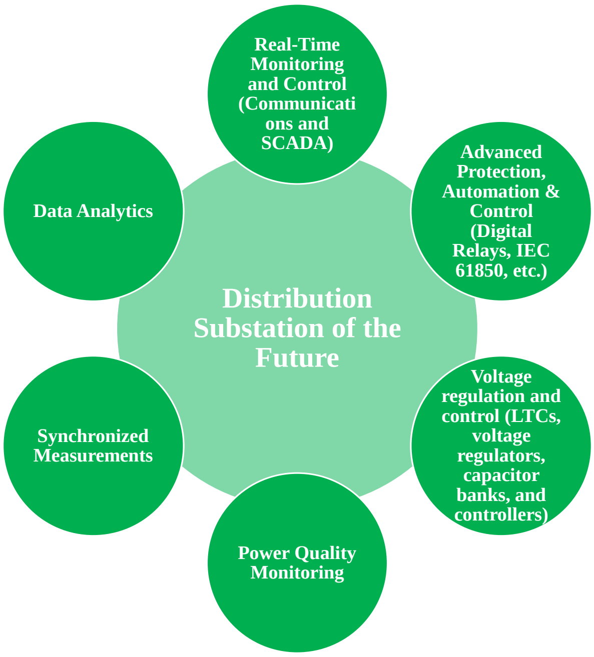

Figure 8. Components of Substation Modernization

DSoF will increase real-time awareness of the overall power delivery system and help understand, prevent, and mitigate DER and transportation electrification impacts. Substation modernization can enable the further adoption of DER, battery energy storage systems, and transportation electrification; improve reliability, power quality, and resilience of the power delivery system; and enhance asset health, maintenance, and overall safety.

OVERVIEW OF ADVANCED METERING INFRASTRUCTURE (AMI)

An AMI program implements a two-way remote meter reading capability that includes the smart meters, field area network (FAN) communications to the meters and other grid edge devices, a wide area network (WAN) to the system access points, and the system head-end applications that interface to systems such as billing, outage management, etc. (Figure 9 presents a functional overview of an AMI system.) Smart meters have functionality such as load, demand, and voltage profiling that was previously only available for large commercial and industrial (C&I) customers but is now available at every metering point. With two-way communications, an AMI system can provide additional information such more granular consumption data and power quality information, as well as outage notification, water leak detection, and remote connect/disconnect.

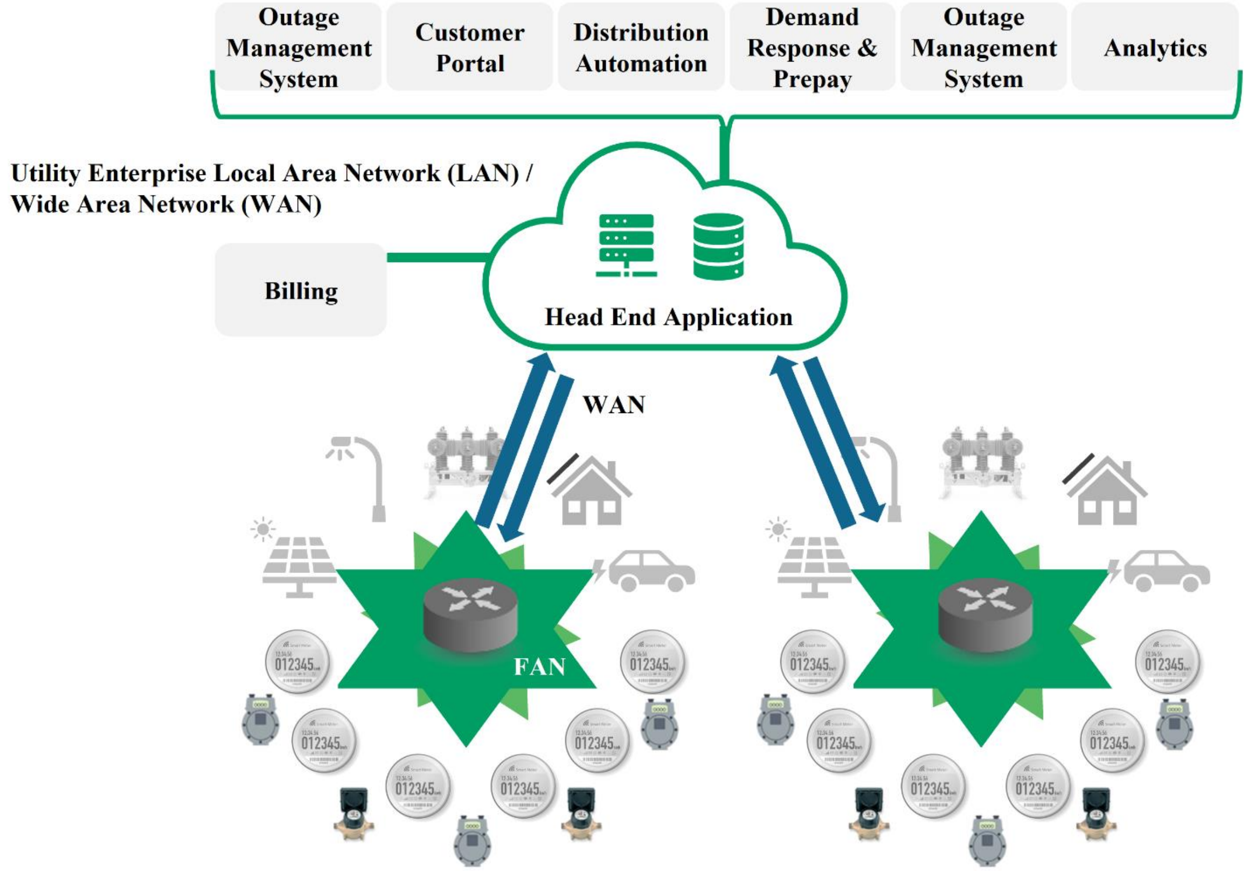

Figure 9. AMI System Overview

There are many different communications architectures in AMI systems, and while these include some very expensive implementations like “fiber-to-the-meter”, the two dominant architectures typically utilized are the “star” (a.k.a. point-to-multipoint) and “mesh” (a.k.a. peer-to-peer) architectures (see Figure 10). The star implementation generally has multiple elevated base stations that communicate directly to field devices. In some cases, battery-powered devices such as gas and water meters communicate through an adjacent electric meter, but direct communications to and from these devices and the base station are usually possible. In a mesh architecture, electric meters register to the access points – either directly if they have a strong enough radio frequency (RF) signal or through a peer electric meter that has a good signal. These systems usually require that battery-powered devices communicate through an electric meter or a repeater installed specifically for this purpose.

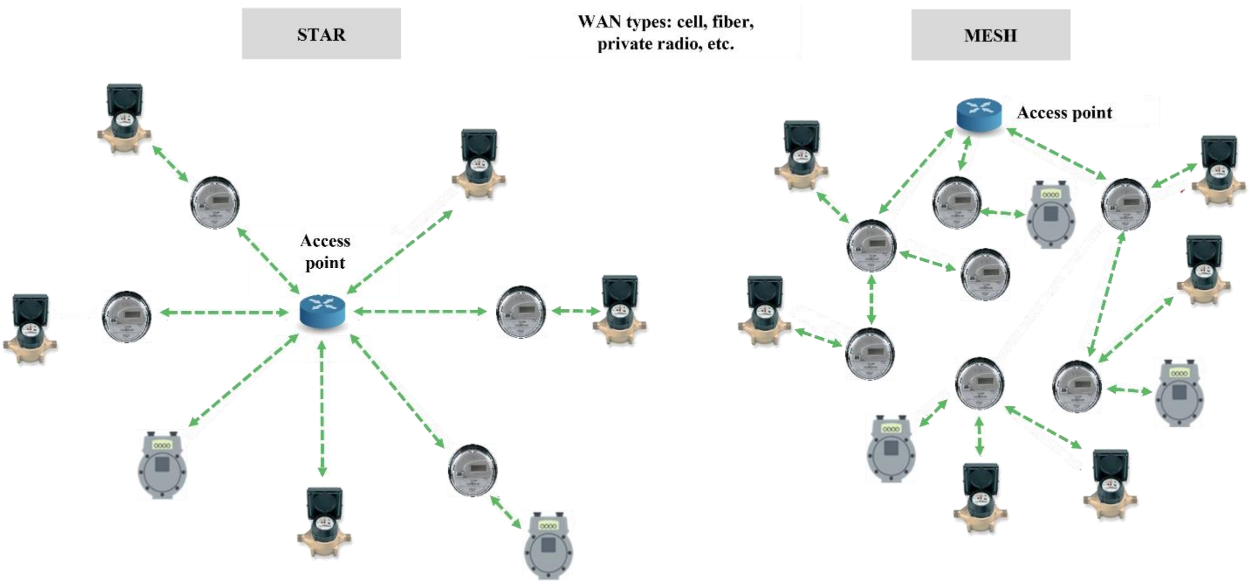

Figure 10. Dominant AMI Architectures

There are advantages to each type of architecture. For dense deployments where the electric, gas, and water service areas almost completely overlap, mesh implementations can lead to lower deployment costs since there might be little-to-no network-specific equipment other than meters. For low-density deployments or deployments with significant gas and/or water-only service territory, the star approach can be more attractive as it tends to be simpler to implement and operate. Of course, these are very general distinctions, and many other considerations can influence architecture selection. Ultimately, the physical constraints and desired functionality must be considered when selecting an AMI system.

GRID MODERNIZATION WITH AMI AS A FOUNDATIONAL PROGRAM

AMI has greatly improved the quantity and value of information provided by meters. In addition to electrical revenue metering to support the meter-to-cash process, modern smart meters provide additional information such as bi-directional metering needed for residential renewables, interval energy consumption to customer portals to allow consumer monitoring, prepay options to reduce barriers to electric service, and voltage monitoring for system analysis. In case utilities provide water and electricity, AMI-equipped water meters enable remote meter reading, but also provide leak detection to consumers and loss analysis to utilities.

While AMI systems have provided a major step forward over earlier manual or drive by meter read processes, AMI is typically not fully utilized for additional applications as part of a grid modernization plan. For example, AMI can be utilized for:

- Feeder automation including communications to reclosers, switches, Fault Current Indicators (FCIs), capacitor banks, etc.
- Demand response systems
- Smart streetlights
- Validation of the distribution model including mapping of meters to transformers, transformers to phases to support re-configuration schemes, load balancing, or planning
- PEV or EV detection and/or submetering
- Water loss detection.

Some of the applications typically implemented today are shown in the lower half of the two figures below. By taking a more holistic approach, AMI can support additional functions shown in the upper half of the figures.

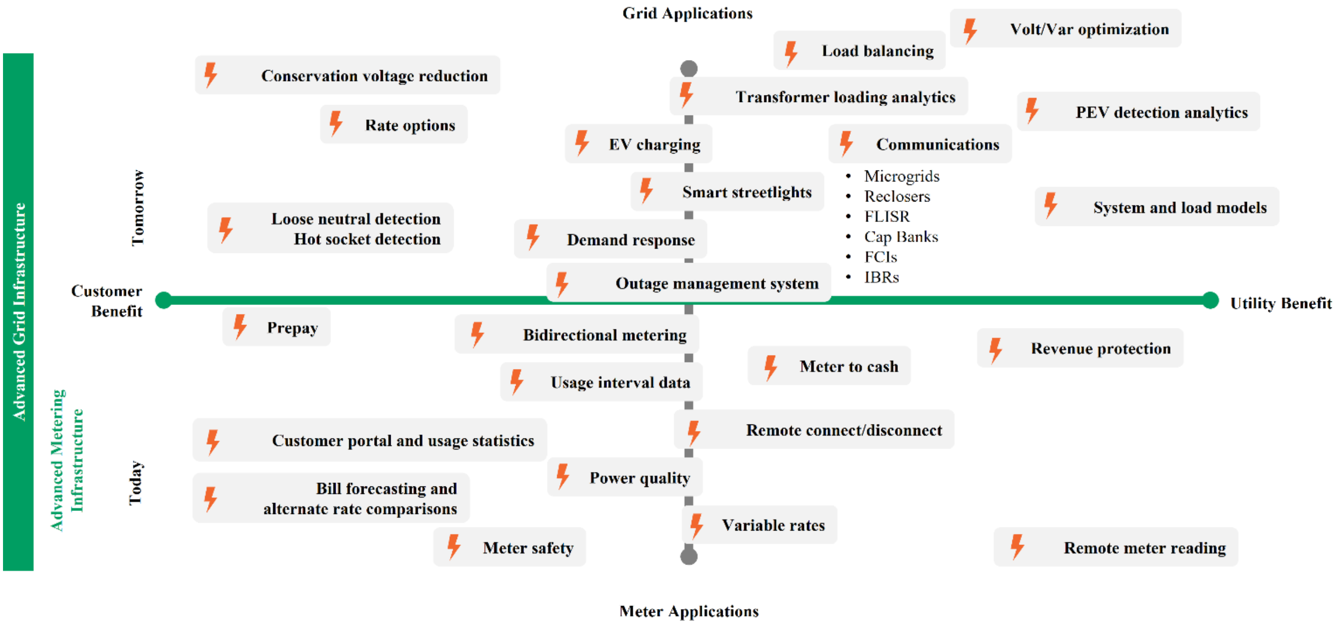

Figure 11. Advanced Grid Infrastructure – Electric

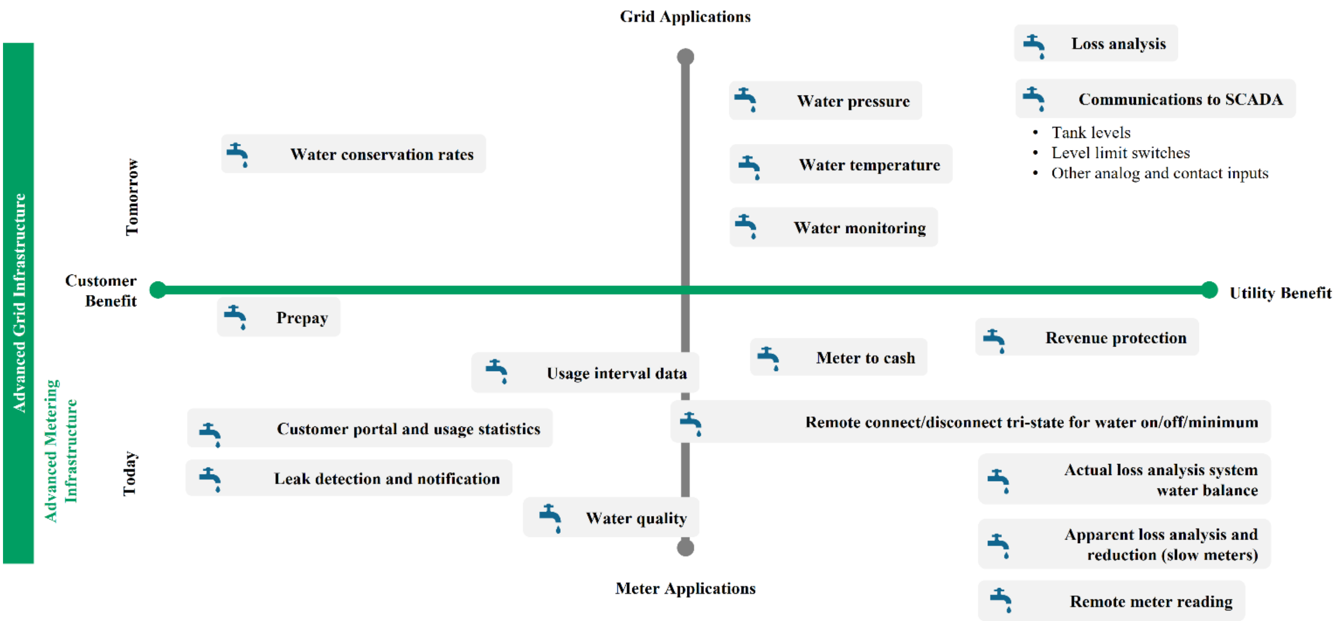

Figure 12. Advanced Grid Infrastructure - Water

SUMMARY

The electric utility industry is actively working on: (i) improving grid reliability and resilience to address severe weather impacts, (ii) increasing deployment of renewable generation and DER to meet clean energy targets, and (iii) enabling the adoption of transportation electrification on the distribution grid. Key to support the deployment of new solutions to meet these challenges is the use of a communications network across the distribution grid. However, most AMI systems today are still providing primarily metering functionality.

Most engineers involved with protection and control applications are used to dedicated high-speed communications networks such as fiber. While fiber is an optimal example of a communications medium, it is not practical for all distribution applications. AMI systems offer two-way communications that can be used to support a wide variety of applications. It is important for engineers to understand the capabilities of the AMI system and how to leverage the system to support the applications. In order to do this, it is important to have use cases and applications such as system model support, feeder restoration schemes, or electric-vehicle monitoring defined beforehand. Conversations need to shift beyond the meter as a metering device to a component of an Advanced Grid Infrastructure (AGI) that addresses the needs of a modern grid as highlighted in the figures above.

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