FIVE YEAR WILDFIRE RISK REDUCTION ACTION PLAN FOR THE ELECTRIC POWER INDUSTRY

DOE-EPRI-2030-WRRAP-CR0000025

Abstract

The U.S. DOE and the Electric Power Research Institute convened a wildfire advisory group to bring together knowledge of ignition risks, electric utility needs, the applicability of available technology, and existing technology gaps. The outcome is a five-year action plan, containing recommendations on RD&D projects, that if completed within the next five to six years, may accelerate the power industry's ability to substantially reduce wildfire ignition risks. When reviewing this document please consider it is a snapshot in time for the years 2023 and 2024, could be obsolete by the end of the decade. The following list (from Section 7 of this report) comprises the titles and topics for the proposed follow-on demonstrations:

1. Hybrid Undergrounding RD&D
2. Live Downed Conductor Detection RD&D
3. Fault Energy Reduction RD&D
4. Advanced Inspection and Response Drone
5. Fault and PQ Event Signature Repository
6. Advanced and Intelligent Sensor Nodes
7. Fire Friendly Asset Coatings and Coverings
8. Environmental Monitoring Action Plan

Dorr, Doug
ddorr@epri.com

EPRI PREPARED THIS REPORT.

NOTE

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Contents

1 Overview

1.1 Project Objectives

Reducing wildfire ignition incidents—and therefore their impact on landscapes and customers—continues to be a key focus for electric utilities across the globe. Power delivery systems of the future must be more resilient than ever, which means being more adaptive to wildfire threats and to other weather-related impacts. Overall, the electric power system infrastructure must provide utilities with useful insights about system health, system performance, and vegetation risks. In addition, electric service providers must have unprecedented access to situational awareness technologies and to alerts that can inform emergent maintenance requirements and can dynamically adapt to fire weather threats.

Although these aspirations are well understood, the threat of wildfires impacting the power grid and the potential for wildfire ignitions - initiated by the power grid persists, even as technology developers, research organizations, and utilities dedicate significant resources to both sides of the threat.

1.2 Approach

EPRI—with its specialized test capabilities, its subject matter experts, and a worldwide network of utilities—has a unique role to play in creating an RD&D roadmap for wildfire mitigation. The model promotes greater industry visibility of ongoing RD&D projects and creates new opportunities to implement emerging technologies with documentable and measurable success criteria. EPRI has used the following approach for considering the elements of a wildfire risk reduction action plan.

1.2.1 Establish a Diverse and Comprehensive Wildfire Advisory Group (WAG)

Through focused industry workshops and surveys comprising dozens of key stakeholders and hundreds of participants, EPRI has established an industry forum that includes industry experts from utilities, national laboratories, and other relevant research and development (R&D) organizations. This group has served as the key source of information for this action plan and has provided an engagement mechanism for roadmap updates, technology discussions, and implementation projects.

1.2.2 Understand and Document the Utility Industry Wildfire Needs

EPRI has conducted four Wildfire Advisory Group workshops in regionally diverse locations. These workshops have enabled stakeholders with geographically unique wildfire risk reduction needs to participate in relevant and meaningful information exchange. By facilitating climate zone diversity these workshops reveal regional similarities and differences related to fire risk and situational awareness technology needs. The subject workshops have included structured topical sessions that walk the attendees through a progression of wildfire risk challenges. The roundtable conversations have facilitated discussions useful to inform a technology-based risk reduction roadmap with associated action plans and demonstration project recommendations.

Identification of future aspirations for wildfire risk reduction and the gaps to reaching those outcomes was achieved using a stakeholder engagement model well developed at EPRI and consisting of the following steps:

- Success Statements: What outcomes are desired from research and demonstration activities?
- Critical Gaps: What key capabilities must be created, or obstacles overcome, to achieve the Success Statements?
- Emergent Demonstrations: What demonstration projects are most appropriate to resolve the Critical Gaps and achieve the Success Statement outcomes?

Through this process, EPRI identified over seventy unique success statements, spanning seven different wildfire risk reduction-pertinent categories.

1.2.3 Catalog Existing Pilots, Approaches, and Emerging Technologies

This activity focused on cataloging technology pilots, approaches, and leading industry practices that are either emerging or in progress. EPRI subject-matter experts (SMEs), in collaboration with key industry stakeholders, have documented each application in an on-line Enabling Technologies Catalog, which describes each respective application, its role in the power system wildfire threat dynamic, and information about deployment and operational challenges and opportunities.

As of the date of this publication, EPRI has identified over fifty such emerging applications suitable for the catalog and those documented descriptions can be found at this weblink: https://distribution.epri.com/wildfire/public/wildfire-tech-database/

1.2.4 Understand Relevant Technologies and Applications from the DOE National Laboratories

A key driver of this project was to increase the exposure of national laboratory (developed or enriched) projects and technologies with the stakeholders participating in the advisory group. To that end, EPRI has engaged with four of the U.S. DOE National Laboratories to understand the RD&D projects (relevant to fire risk reduction) that are either recently completed or that are presently underway.

1.2.5 Develop a Transmission and Distribution Wildfire Risk Reduction Action Plan

As an overall outcome of the work, EPRI has developed this five-year research action plan that maps the areas of opportunity for both industry wide and for individual electric service provider wildfire threat and risk awareness improvement. The action plan includes targeting of future states, and gaps that must be overcome to achieve the future states. The plane then maps existing actions and demo needs, along with specific action plans that fill the relevant gaps for each future state. Finally, the action plan considers the technologies that are demonstrable and deployable, along with possible execution plans to vet and operationalize the successful technologies.

1.2.6 Develop Technology Demonstration Execution Plans

The action plan is consolidated in Section 7 by taking the eight highest priority wildfire risk gaps and organizing them into proposed research development and demonstrations. The proposed demos are informed by the wildfire advisory group, National Lab SMEs, and by EPRI SMEs. Using the advisory group structure, EPRI has identified utilities that are interested in applying a technology (or a selection of technologies) in the subject demonstration projects.

1.3 Summary

Overall, the input and feedback from the diverse set of stakeholders contributing to this project provide an opportunity to make advancements in the following consolidated areas that are helpful toward wildfire risk reduction:

- Fault Mitigation
- Situational Awareness
- Fire Protective Materials
- Modeling and Simulation

The action plan considers each of these opportunities for risk reduction and describes the specific vision of the future associated with each area of opportunity. The analysis of these proposed future states and the conversations with the advisory group SMEs subsequently identified multiple research gaps that need to be overcome to achieve the future vision. The following subsections summarize at a very high-level, the gap analysis and the corresponding RD&D opportunities that can best overcome those gaps.

1.3.1 Gap Review

Fault Mitigation Gaps and Research Opportunities

The two components of fault mitigation that effect wildfire risks are fault count and fault energy. Fault count is the actual number of faults per line mile per year on a given circuit. Fault energy is the amount of arc energy associated with any given fault incident. In an ideal scenario the power system of the future will have the ability to reduce fault counts by dynamically monitoring and adapting to high fire risk conditions with minimal need for PSPS (public safety power shutoffs). The system would additionally have features and capabilities to minimize the amount of energy injected into the local vegetation when unavoidable faults and arcing does occur.

While the industry has at its disposal several different hardening options that can reduce fault counts, there remain gaps. The primary gaps are associated with:

- First quantifying exactly how many faults occur on each circuit, under what conditions they occur, and knowing what the exact causes of those faults were.
- Secondly, having consistent methodology to evaluate the different hardening and fault count reduction options against vegetation ignition risk criteria.
- Finally, having criteria for verifying that a reduced fault energy objective will effectively minimize fire start and spread, based on local vegetation species and its condition.

The advisory group vetted these gaps and proposed more than a dozen future states in the fault mitigation space. After consolidating similar requirements, the following future states were identified:

- A comprehensive selection of hybrid underground construction options
- A comprehensive selection of fault energy limiting technologies
- Smart monitoring hardware capable of risk aware decision support for protective devices
- Signal injection and monitoring hardware capable of interface with protective devices
- A unified fault event and power event signature repository
- Materials that enable overhead coverings and connection hardware to be more fire friendly, lifecycle robust, and animal/weather impervious
- Full understanding of vegetation ignition probability as fault energy is reduced

The bulleted list of requirements and capabilities focuses mostly on system hardening and the ability to evaluate fault reduction options against ignition criteria. The gaps associated with knowing exactly how many faults occur on each circuit and their causes will be covered within the situational awareness discussion in the next section.

Situational Awareness Gaps and Research Opportunities

Monitoring of assets, power flows, weather, and vegetation conditions each contribute to enhanced awareness of ignition risk, and to faster emergency response. In an ideal scenario the power system of the future will be visible to decision makers at a level that supplies near-real-time understanding of any ignition risks, and any fire spread likelihood, associated with the electric power system, the surrounding vegetation, and the local weather. The industry has made significant strides with smart grid technologies over the past few decades, but there is a wide gap between todays state-of-the-art and the near-real-time awareness objectives for fire risk reduction.

For today's power line sensors, it is not just the challenge of getting accurate historical fault counts per circuit. It becomes even more challenging to accomplish data fusion activities where a single platform can ingest data streams from weather stations, and from the range of power monitors at the substation, mid circuit, and from the smart meters at the edge. It is unlikely that data fusion challenges can be resolved in the next decade, but the non-real time gaps associated with simultaneous access to weather, vegetation condition and individual fault detection may be accomplished. The advisory group vetted the gaps and the opportunities and proposed five consolidated future states in the situational awareness space as follows:

- Unified regional and North American wide fuelscape layers that are (nearer to real time) accurate.
- Consistent and replicable methodology to integrate wind, climate, and weather data into fire risk and spread modeling tools
- A unified national fire weather forecasting service
- Training and education on publicly available modeling and simulation tools that support fire analytics metrics and use cases
- Full fault count/cause visibility and history for individual power circuits
- AI enhanced monitoring/sensing at relevant circuit locations with no need for data movement.

Fire Protective Materials Gaps and Research Opportunities

Many commonly used materials in overhead distribution systems are not inherently flame resistant, such as wood poles, pole top insulators, wildlife guards and insulative coverings. While, avoiding fire starts is a core priority of utilities in high-fire-threat areas, an equally important objective is to have electric infrastructure that is less susceptible to fire damage and that is less prone to combustion or to failure in ways that might promote ignitions.

Despite the commercial availability of products that have demonstrated adequate wildfire protection, there are many questions left to be answered. Uncertainties remain regarding long-term performance, long-term resistance to weathering, environmental impacts, and end-of-life considerations, how application of protective materials interfere with inspection activities, how protective materials affect the degradation rate of the material to which it is applied, and if repeat application or renewal is needed following exposure to a single wildfire event.

In the fire protective applications space there is a need for a more versatile selection of sprays, coatings and sacrificial wraps for transmission and distribution assets. The advisory group vetted specific examples where some new materials science R&D may be appropriate and generalized the following 2030 future state aspirations:

- *Coatings for insulators and electrical hardware that do not retain contaminants after smoke or fire exposure*
- *Materials science mixtures that enable overhead coverings and connection hardware to be more fire friendly, lifecycle robust, and animal/weather impervious*

The advisory group consensus was that it would be preferred and beneficial to work with the National Labs to develop a selection of suitable product and materials specifications, based on some utility SME field experience regarding asset specific needs and subsequent performance criteria.

Modeling and Simulation Gaps and Research Opportunities

Advanced tools that enable scenario analysis, such as impinging weather projections, fire-spread forecasting, and spatially relevant fire threat indices, are important innovations that can help the industry more comprehensively understand and reduce wildfire risks. Foresters, fire emergency responders, communities, and electric utilities alike have similar needs for advanced tools that enable fire scenario analysis. The advisory group vetted this topic and the consensus for the 2030 future state was to have consistent and up to date information layers that are readily available and are largely developed with open-source approaches, such that the layers can be adapted to all modeling and simulation tools. Some specific capabilities that could be improved by 2030 include:

- Regional and National Fuel Layers that are (nearer to real time) accurate
- Regional and National Fuel Layer archives for improved analysis and forecasting
- A National Fire Weather Data Service
- Training and Education on Fire Analytics Modeling and Simulation

1.4 Wildfire Advisory Group Endorsed RD&D

One of the final outcomes of the five-year risk reduction action plan is a high-level summary of important RD&D projects that if successful within the next five to six years, could accelerate the power industry's ability to reduce wildfire ignition risks.

Using the Wildfire Advisory Group to vet the demonstration concepts, EPRI has identified the most relevant and high interest projects to fill industry gaps. To summarize the recommendations, the following list comprises the individual Research, Development and Demonstration or RD&D activities:

1. Hybrid Undergrounding RD&D
2. Live Downed Conductor Detection RD&D
3. Fault Energy Reduction RD&D
4. Advanced Inspection and Response Drone
5. Fault and PQ Event Signature Repository
6. Advanced and Intelligent Sensor Nodes
7. Fire Friendly Asset Coatings and Coverings
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2 Fault Mitigation

2.1 Overview

Power system faults happen for numerous reasons including vegetation contacts, animal contacts, equipment failures, lightning, and wind. Most faults can create electrical arcing and sparks and in high-risk wildfire areas and these faults can act as an ignition source. The operation of protective equipment, such as fuse cutouts generate high-temperature debris when they operate, and this raises questions about potential ignition of ground fuels below.

Identifying methods and technologies to reduce the number of electrical line faults is an effective means of reducing both ignition incidents and subsequent fires. For more extensive background on fault causes and characteristics, Appendix A provides that detail.

To be concise on the relevant challenges, this section summarizes the present state of the art, the 2030 future state aspirations and the research needed to achieve the future vision. That future vision is as follows: In an ideal scenario the power system of the future will have the ability to dynamically monitor and adapt to high fire risk conditions with minimal need for public safety power shutoffs or (PSPS). The system would additionally have features and capabilities to minimize the amount of energy injected into the local vegetation when unavoidable faults and electric arcing does happen.

The wildfire advisory group has considered the two components of fault mitigation that effect wildfire risks. These two components are the number of faults per line mile per year (**fault count**) and the amount of electric arc energy or (**fault energy**) associated with any given incident. Because trees, animals, and unintended power-line contacts result in arcing faults and those arcs create the energy that may ignite vegetation, any methods to reduce the total (fault count) will reduce the total number of actual ignition and fire incidents. Further, any approach that can reduce the amount of time the arc energy is present will reduce the likelihood of igniting combustible materials around the power lines.

2.1.1 Fault Count

Fault count awareness/quantification – The most prominent industry gap for actual fault count and cause understanding is a lack of awareness on the total number of external physical contacts with the power lines that result in temporary line faults. If the fault results in an outage requiring a line crew action, those events have a data record, but for minor incidents like a tree or an animal contact where the contact is proceeded automatic restoration of power, it is difficult to develop accurate statistics unless a utility has been progressive with smart meter data and other power quality monitoring technologies. While continuous electrical monitoring is discussed in greater detail in Section 3, it is useful here to tie the existing gap in quantifying total fault count awareness to the gaps in how to reduce fault counts.

The specific future states identified by the WAG for ***fault count awareness/quantification*** were:

By 2030 the industry will have:

- <u>*Full fault count/cause visibility and history for all power lines of interest*</u>
- <u>*A Unified fault and power quality (anomaly event) signature repository*</u>
- <u>*Intelligent monitoring and sensors at all relevant protective and transition nodes of interest with no need for data transfer*</u>

To summarize the WAG discussions, it is recognized that there are several existing and emerging power monitoring and diagnostic technologies that can help with situational awareness for faults and incipient failure analysis. These existing sensors and approaches have been detailed in the EPRI DOE technology catalog and the monitoring capabilities for improved fault count awareness and visibility do exist today. While the sensors are readily available, a significant industry gap is a lack of a single platform capable of ingesting all the monitor/sensor data feeds in parallel and subsequently turning that data into either, immediately actionable recommendations, or into fault count statistics, or into a data repository with labeled event data. Therefore, the demonstrations proposed by the advisory group, and described in Section 7, focus on developing innovative ways to leverage relevant fault cause insights, without the need to move large amounts of data, and secondly on continuing to support and enhance a fault event signature library. The recommended path forward will involve collaboration amongst electric utilities and their data repositories, vendors with data repositories, and the U.S. National Labs.

Fault Count Reduction – Once a clear understanding of fault numbers (at the circuit level) is available, it is then possible to spatially layer fire weather, ground fuel, terrain, and other enrichment data together and to quantify the expected reduction in ignition risk, based on the technology or the hardening approaches to under consideration. The Wildfire Advisors considered the existing options for system hardening/fault count reduction and consolidated the discussion within the following three future states:

By 2030 the industry will have:

- *Access to comprehensive selection of hybrid underground construction options*
- *Coatings for insulators and electrical hardware that do not retain contaminants after smoke or fire exposure*
- *Materials science mixtures that enable overhead coverings and connection hardware to be more fire friendly, lifecycle robust, and animal/weather impervious*

Each of these aspirational objectives is unique in terms of the research and the project work needed to bridge today's gaps, but all are equally useful capabilities, that can avoid faults and fire starts. After discussion and vetting with the advisory group, the consensus opinion was to:

a.) Focus the proposed utility industry collaborative research on hybrid underground construction options that are not available to utilities today. This primarily involves research, development, and demonstration (RD&D) on technologies such as the GLDS or Ground Level Distribution System described in Section 7.1.

b.) Propose that the U.S National labs participate in some ideation sessions and then lead any R&D toward more contaminant resistant insulators and more fire and animal friendly coverings. More detail on follow-on activities for this topic can be found in Section 7.8.

2.1.2 Fault Energy

Fault Energy Reduction – When a power system fault occurs, any technology or strategy that reduces the amount of current that flows into the fault path reduces the likelihood that local vegetation will ignite. Similarly, any technology or strategy that can speed up the opening of the circuit protective device reduces the risk of vegetation ignition. Under the topic of fault energy reduction, the advisory group identified the following future states:

By 2030 the industry will have:

- *A comprehensive selection of fault energy limiting technologies*
- *Smart and risk aware interface and decision support for protective and sectionalizing devices such as AI-driven adaptive protection (i.e. one-shot reclose vs PSPS)*
- *Signal injection and monitoring hardware capable of interface with protective devices for live downed conductor detection*
- *Full understanding of vegetation ignition probability as fault energy is reduced*

When combined, these future states require power system protective devices that are more intelligent, more adaptive to fire weather and more tightly coordinated and the advisory group is interested in demonstration of technology that can begin to fulfill these requirements. The major research challenge that can be supported by both EPRI and National Laboratory research and development is associated with faster protective device operation innovations and demonstrations with protective devices that have adaptive settings based on their understanding of the localized fire risks.

Understanding the localized fire risks requires ignition testing on different vegetation types under different wetness/dryness conditions and with varying levels and durations of arc energy. This is a significant undertaking and will require collaborative research between the power industry, other interested parties, and the U.S. National Labs. Ideally the outputs will be ignition risk curves that can be applied to fire threat analytics to understand if it is safer to operate and trip the circuit or if it is necessary to transition into a proactive public safety power shutoff event. More detail on the proposed work moving forward can be found in Section 7.3.

2.2 Circuit Hardening to Reduce Fault Count

Circuit Hardening to reduce outage durations and damage during storm events is not new. What is new is the idea of hardening to reduce ignition incidents. Therefore, the focus of the advisory group considered the following ignition-mitigation and fire-hardening areas:

- Improved insulating coverings, such as asset covers, connectors, and the coverings used on the wires
- Flame-inhibiting applications, such as intumescent pole wraps, sprays, and applicants that reduce soot and particle deposition on electrified assets.

The Advisory Group is aware that some of the listed items (intumescent pole wraps for example) don't really belong in a section describing ways to reduce fault counts, but the consensus was that specialized coverings, sprays, wraps and so on should ultimately be considered in a single U.S. National Lab recommendation for proposed new RD&D. Therefore, it is included here to ensure that there is documentation of the existing gap, and to express the need for new applications of protective coatings when a utility is endeavoring to harden an overhead power system.

2.2.1 Coverings that Reduce Ignition Opportunities

Many utilities have experienced significant reduction in fault counts by hardening their overhead distribution lines. Such hardening can include stronger poles, covered conductors, covered connectors, and specialized coverings and tapes for other exposed and electrified hardware. This is a mature area of application in the grid resilience space. The gap identified by the advisory group is that when energized equipment fails, the failure mode may ignite portions of the equipment, such as synthetic components and coverings like animal guards, tapes, and wraps. Some of the flame test examples are shown in **Figure 2.1**. While most equipment has protective fuses to quickly isolate the equipment, the fault energy may still be great enough to provide an ignition source to ground vegetation.

Figure 2.1
Examples of combustible power system component coverings. The animal guard on the left drips flaming material while the guard on the right flames, chars, and smokes but doesn't ignite vegetation.

As a peripheral concern with equipment failure, EPRI testing on different brands of animal guards, insulating tape, conductor coverings, and other insulating hardware reveal materials and design challenges that warrant new research and development moving forward:

- First, the materials that the guards, and other insulating electrical coverings are made from is not being consistently specified and designed to be either flame friendly, or moisture ingress proof.
- Secondly, the same insulative mixtures used for tapes, wraps, and other electric asset coverings have unique combustion concerns whereby the materials can either easily burn or can exacerbate the situation by dripping flaming liquid materials onto the vegetation beneath the coverings.

While these issues don't apply to every insulating material, testing is advised to better understand how different products and mixtures perform under a flame test. Ideally it would be beneficial to work with one or more of the National Laboratories to develop a selection of improved insulating mixtures that are flame friendly, UV resistant, and weather impervious and provide the criteria to vendors for future products. More discussion on this topic can be found in Section 7.8.

2.2.2 Fire-Protective Materials

One approach to reducing wildfire risk to the power grid is to integrate fire-protective materials into overhead distribution infrastructure. Application of fire-protective materials would be expected to reduce wildfire risk by improving the fire resistance of overhead components exposed to a wildfire, thereby reducing the need for infrastructure replacement after wildfire exposure.

Fire-protective materials include a wide range of mixtures that inherently withstand high temperatures, react when exposed to high temperatures to create a protective barrier, react to locally inhibit the oxidation process by consuming energy, release moisture or an oxygen-depleting reactive compound, or a combination of any of these. Materials such as concrete and brick are inherently flame resistant. However, many commonly used materials in overhead distribution systems are not inherently flame resistant, such as wood poles, pole top insulators, wildlife guards, and others. One example of a good success case here are the intumescent fire protection wraps that prevent wood pole combustion in the event of wildfire.

Despite the commercial availability of products that have demonstrated adequate wildfire protection, there are many questions left to be answered. Uncertainties remain regarding long-term performance, long-term resistance to weathering, environmental impacts, and end-of-life considerations, how application of protective materials interfere with inspection activities, how protective materials affect the degradation rate of the material to which it is applied (e.g., wood poles), and if repeat application or renewal is needed following exposure to a single wildfire event.

Testing is advised to better understand how different coatings, products, and mixtures perform under simulated wildfires. Like the recommendations for the coverings section 2.2.1, it would be beneficial in this space to work with one or more of the National Laboratories to develop a selection of improved fire protection products that are lifecycle optimized. More discussion may be found in Section 7.8.

2.3 Summary

Because line faults are the leading cause of electric power–related ignition incidents it is necessary to have in place the appropriate monitoring and diagnostics capabilities to quantify both the numbers of faults per circuit and the leading causes of those faults. Further, any technology or protective strategy that reduces the likelihood of vegetation fires is an essential risk mitigation strategy. Toward these aspirations, the wildfire advisory group has recommended pursuit of the projects identified in Table 2-1.

Table 2-1.
Proposed Projects and Future States Addressed

Category	Project Title	Proposed Lead	Future States Addressed
Fault Count Awareness	1. Fault Event Repository and Algorithm R&D	EPRI and National Lab Joint	• *Full fault count/cause visibility and history for all power lines of interest* • *A Unified fault and power quality (anomaly event) signature repository* • *Intelligent monitors and sensors at protective and transition nodes*
Fault Count Reduction	2. Hybrid Underground Demo 3. Improved Coverings and Coatings for Electrical Assets	EPRI and National Lab Joint	• *Access to comprehensive selection of hybrid underground construction options* • *Coatings for insulators and electrical hardware that do not retain contaminants* • *Fire, and weather friendly, coverings for electrical assets*
Fault Energy Reduction	4. Fault Current Limiting R&D 5. Live Downed Wires R&D 6 Smart Protection R&D	EPRI and National Lab Joint	• *A comprehensive selection of fault energy limiting technologies* • *Signal injection and monitoring for live downed conductor detection* • *Full understanding of vegetation ignition probability as fault energy is reduced* • *Smart and risk aware interface and decision support for distribution automation devices and AI-driven adaptive protection (i.e. one-shot reclose vs PSPS)*

3 Situational Awareness via Continuous Monitoring

3.1 Overview

Continuous monitoring describes activities and technologies that enable electric service providers to measure and monitor changes over time or to monitor for abnormalities against a normal baseline. Both activities are important fire and ignition risk-monitoring and risk-reduction objectives.

The wildfire advisory group has considered three separate activities in the continuous monitoring space that can affect wildfire risk and reduction of that risk. These three activities are:

- **Grid Monitoring** – Observing the electrical performance of each power circuit to understand when abnormal conditions, and power quality variations, such as line faults, occur.
- **Asset Monitoring** – Periodic physical inspections and observations of the power system assets over their lifecycle to understand when maintenance or replacement is needed
- **Environmental Monitoring –** Continuous monitoring of the local weather to prepare for storms, and periodic physical inspections and observations of the power system right-of-way vegetation, to understand when remediation actions are needed.

3.2 Grid Monitoring

Grid Monitoring has been part of electric power delivery for over 100 years, but the ability to analyze power quality parameters such as voltage and current waveforms, power factor dynamics, and phasor relationships, and to do so with micro-second resolution is emergent over the past few decades.

For the wildfire risk mitigation topic, the primary use case is understanding faults. More specifically to gain insights into fault causes, fault signature analysis, fault location, and subsequently how to reduce fault counts with various hardening approaches.

Toward these fault related use cases and objectives, the monitoring technologies applied to the system should provide specific detail on (what just happened electrically) and (why did it happen) and to start to use that data to populate industry accessible signature repositories.

The most prominent industry gap for grid monitoring is not the availability of technology but rather, the gap is the inability to take the data from the available sensors and aggregate it with the other sensors and monitors distributed across the power system, to get useful and unified locational power quality and fault insights. Ideally the nearer to real time these insights are, the more actionable they may become. However, just having a repository of the unified data is very helpful for facilitating AI related use cases.

The specific future states identified by the wildfire advisory group for ***grid monitoring*** were:

By 2030 the industry will have:

- *Full fault count/cause visibility and history for all power lines of interest (this is also a future state from section 2)*
- *A Unified fault and power quality (anomaly event) signature repository*
- *Intelligent monitoring and sensors at all relevant protective and transition nodes of interest with no need for data transfer*

All three of these future states are focused on the topic of power line faults and electrical arcing, and they are duplicates from the previous chapter. As such, they could be considered essential and very beneficial industry needs.

To expand on how grid monitoring plays a key role in understanding faults, fault characteristics, and which types of faults may create ignition incidents, a good description of some different fault use cases that could be curated in a fault event signature repository is helpful. Four such fault types that are common to all utilities and that have potential to result in an ignition incident are:

- Conductor Slap
- Live Downed Conductors
- Hotline Clamp Arcing
- Capacitor Bank Contact Pre-failure

Conductor Slap – To narrate a simple example from the conductor slap use case, one phenomenon that is common is referred to as magnetically induced conductor slap. When the lines contact one another, they throw sparks and molten metal onto the vegetation below. Interestingly this happens quite often on bare overhead conductors and is not well understood by field crews that don't find evidence of a problem when they patrol the line, and many times record the breaker lockout incident with a cause code of "No problem found."

Even with the "no problem found" result, the following pattern of currents and voltages would be recorded by a power monitoring device. To supplement the narrative, the following **Figure 3.1** and the (lower blue trace) in the figure contains a power quality recording from a conductor slap incident and can be described with the sequence description that follows the image.

1. An initial fault occurs downstream of a protective device from some initiating event such as a tree branch, or a ballon, or an animal. When the initial fault occurs, the wires have equal and opposite fault currents, and this causes the wires to magnetically oppose on another and to swing apart in a pendulum motion. For a typical power system, the upstream protection senses the fault current and opens to clear the fault - leaving the wires heated up, stretched out a foot or more from the heat, and still swinging. In the figure (bottom blue trace) the first current increase on the left side shows this initial fault followed by zero current once the protective device opens.
2. When the protective device re-closes back in (a few seconds or so later) the upstream conductors swing together and cause a new fault, this time with even higher currents than the previous event. This can be seen as the second current increase in the blue trace and again a protective device opens and the currents go to zero again
3. After the protection recloses, the conductors slap together for a third time. At this point the main breaker opens – locking out the circuit and the currents and voltage go to zero.

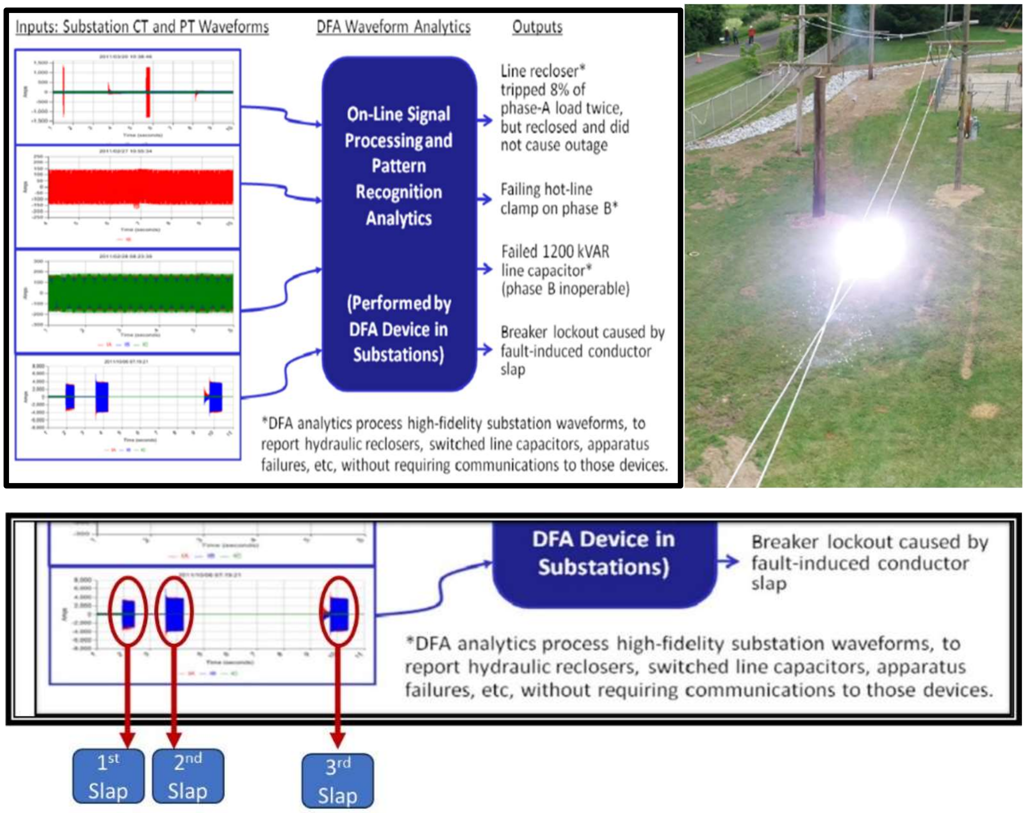

Figure 3.1
Waveforms and Trained Insights from the EPRI/Texas A&M Developed Distribution Fault Anticipator

There are several different variations and combinations of fault – reclose – fault – reclose – lockout that can and do happen, but the key takeaway here is that this sequence of events, and the current magnitudes and the patterns are detectable, predictable and can be turned into recognition algorithms. In fact, not only can the power signatures for conductor slap be patterned, but the same patterning and algorithm development approach works for another dozen different kinds of fault incidents and fault causes. Further, taking the time synchronized voltage and current data from some of the other line sensors, either upstream or downstream of the fault location, make the algorithms even more accurate and insightful and even more useful for fault and ignition risk analytics.

Live Downed Conductors – This use case and its variations are described comprehensively in Section 7.2.1. Having a signature library with dozens of examples of each variation in downed conductors will help the industry identify new algorithms and enhance existing ones.

Hotline Clamp Arcing – Referring again to Figure 7.5.1 the red trace on the (middle left) is a classic example of the intermittent high frequency arcing pattern common with failing line clamps on distribution lines. These clamps can be proactively located and replaced before they become an ignition risk.

Capacitor Bank Contact Pre-failure – The capacitor bank switch failure is very easy to detect with power line monitoring and many examples exist where the associated switching transients may exceed three or four per unit of the line voltage amplitude – typically due to system resonances. Detecting these incidents and acting quickly can avoid failures of lightning arrestors and other power line assets before they become an ignition risk.

In short, if enough field samples for different fault incidents and for different fault types are curated in an industry fault signature repository, then researchers, vendors, and subject matter experts can all work on new algorithms and test them with a common fault signature library – hopefully to identify ignition incident causes and to understand how to avoid them.

3.3 Asset Monitoring

Asset monitoring involves periodic inspection of the power system infrastructure and the power elements over their lifecycle with the intent to either extend the life of the assets or to replace them more efficiently – either right after a failure or just prior to failure. In the context of wildfire risk awareness, the inspections are performed more frequently and with exceptional detail. Clearly any technologies or approaches that can make asset monitoring more time efficient and more predictive of failure can reduce wildfire risk.

Electric utility infrastructure is designed to operate outdoors in the elements for several decades. However, these assets will fail eventually. Utilities try to optimize the inspection cycles to manage failures and avoid extended outages. This is a logical approach considering the cost of inspections, the amount of infrastructure, and the robust design of the assets.

An additional complication is the challenge with post wildfire inspections whereby a wildfire passes through an area where power lines presently exist and the task is to do the post-fire inspection of each asset to understand the degradation, and whether the individual elements need to be replaced or can remain in service.

Overall, utilities need new tools and new methods that enable more frequent and efficient inspection and monitoring of their infrastructure. A combination of fixed monitors and remote sensing may be the solution. The goal is improved situational awareness that allows utilities to act before issues occur and to improve their response. The advisory group was tasked with defining what the future might hold in this space and what gaps will need to be overcome. The specific future states identified for asset monitoring were:

- Ability to know what asset end-of-life looks like and adequate models to predict it.
- Ability to model degradation of assets based on existing and past conditions including both electrical and physical assets such as crossarms and bolts
- AI and technology supported inspections of utility assets including crossarms, insulators, and connectors
- Clearer understanding of the role and opportunity of advanced inspection technologies such as spectral imagery
- Ability to evaluate the health of de-energized systems before re-energizing after PSPS
- Ability to do post fire damage assessments more accurately and efficiently

Most of these future states are moving toward fruition without the need for new research and development, however the quick inspection of systems after a power shutoff – prior to re-energization is challenging and has significant opportunity for new concepts. To this objective, the advisory group converged on the consensus that Drone Inspection Technology as described in Section 7.4 could provide the best opportunities to advance the state of the art.

3.4 Environmental Monitoring

From an electric power system and wildfire interaction perspective, environmental monitoring has three key objectives.

- The first objective is to accomplish periodic physical inspections and observations of the power system right of way and its vegetation to better understand when remediation actions are needed to avoid faults, avoid tree fall-ins, or to avoid igniting ground fuels.
- The second objective is to have near real time visibility on the regional and local weather conditions to better prepare for storms and to respond to weather related outages.
- The third objective is having visual monitoring in place and to be able to detect smoke and fire starts and respond, before the incident becomes an uncontrolled wildfire

The advisory group vetted these objectives and identified the following future states for environmental monitoring:

- A nationwide high fire threat aerial imagery and sensor network
- Regional and National Fuel Layers that are (nearer to real time) accurate
- Wildfire threat zones will have adaptive reclosers with integrated micro weather stations that support risk informed settings

3.4.1 Nationwide Fire Threat Aerial Imagery

Present day, aerial imagery to understand vegetation condition and fire starts is accomplished with disparate stakeholders and many vendor platforms. For micro weather stations, smoke detecting cameras and satellite analytics there are few ownership consistencies, and the advisory group consensus was that all vegetation condition use cases would be better served by conducting focused U.S. National Laboratory research instead of proposing electric utility demos, because the research could equally benefit fire response organizations, foresters, communities, and other interested stakeholders.

3.4.2 Nearer to Real-Time Fuel Layers

Because this topic and the data comprising a fuel layer is a subset of an aerial imagery and sensor network the same recommendations hold true whereas the acquisition and curation of the data would be best served through focused U.S. National Laboratory research instead of through electric utility demos. The key takeaway from the discussions with the advisory group were that it is important to have every stakeholder using the same fuel layers for modeling and simulation so that the risk answers are always the same. Whether the use case is simply understanding which risk reduction technologies should be applied in a specific area or whether the use case is establishing the wind speed and vegetation fire risk thresholds for when to moving from a monitoring posture and into an actual power shutoff, there should be one single source of the truth – derived from the most up to date fuel data.

3.4.3 Adaptive Reclosers that Support Risk Informed Settings

One of the demos described in Section 7.6 describes a future state where protective devices would combine all three continuous monitoring categories including, grid power parameters, asset health indicators and environmental attributes in a single remote computing platform. This intelligent sensor node could reside at any protective device and would have access to local weather, fuel moisture conditions, power quality parameters, and would subsequently be capable of dynamically adapting the protection settings based on the real time fire weather on that day. The concept does not have to be just for distribution automation, however that use case is an important example to highlight within the continuous monitoring space.

3.4.4 Post Fire Damage Inspections

For post fire damage inspection, no specific demo was identified, but it would be useful for some combined ideation between the U.S. National Labs and some of the advisory group members to discuss the idea of developing asset customized test coupons. The test coupons would need to be designed to be attached to lines, towers, poles, and critical assets and then removed later for inspection of heat degradation from a passing wildfire.

3.5 Continuous Monitoring Summary

Monitoring of assets, power flows, weather, and vegetation conditions each contribute to enhanced awareness of ignition risk, and to faster emergency response. In an ideal scenario the power system of the future will be visible to decision makers at a level that supplies near-real-time understanding of any ignition risks, and any fire spread likelihood, associated with the electric power system, the surrounding vegetation, and the local weather. The industry has made significant strides with smart grid technologies over the past few decades, but there is a wide gap between todays state-of-the-art and the near-real-time awareness objectives for fire risk reduction.

For today's power line sensors, it is not just the challenge of getting accurate historical fault counts per circuit. It becomes even more challenging to accomplish data fusion activities where a single platform can ingest data streams from weather stations, and from the range of power monitors at the substation, mid circuit, and from the smart meters at the edge. It is unlikely that data fusion challenges can be resolved in the next decade, but the non-real time gaps associated with simultaneous access to weather, vegetation condition and individual fault detection may be accomplished. The advisory group vetted the gaps and the opportunities and proposed that the most useful electromagnetic monitoring activity would focus on an updated fault signature repository. In short, if enough field samples for different fault incidents and for different fault types are curated in an industry fault signature repository, then researchers, vendors, and subject matter experts can all work on new algorithms and test them, hopefully to identify ignition incident causes and to understand how to avoid them.

In the Environmental Monitoring section, the consensus from the wildfire advisory group was that there are many important use cases for weather, vegetation health, and fire detection, but those use cases would all be best served by conducting focused U.S. National Lab research instead of proposing electric utility demos, because the outcomes could equally benefit fire response organizations, foresters, communities and other interested stakeholders beyond just the electric power industry.

In the Asset Monitoring section, a research opportunity, that did have a specific electric utility related focus was the Substation Inspection Drone. More detail is contained in Section 7.4 and the drone demo would crosscut all three continuous monitoring objectives by flying both planned and unplanned missions to monitor vegetation health, vegetation risk to power lines, to conduct electromagnetic sensing of incipient failure conditions, and to respond to electric fault detections by flying (on-demand) inspection missions, to the fault location to look and report back on smoke detection or on identified power system damage.

Overall, continuous monitoring of the environment, electrified assets and electric power flows can help minimize the risk of ignitions. As such, the wildfire advisory group has recommended pursuit of the projects identified in **Table 3-1**.

Table 3-1.
Proposed Projects and Future States Addressed

Category	**Project Title**	**Proposed Lead**	**Future States Addressed**
Fault Count Awareness	1. Fault Event Repository and Algorithm R&D	EPRI and National Lab Joint	• *Full fault count/cause visibility and history for all power lines of interest* • *A Unified fault and power quality (anomaly event) signature repository* • *Intelligent monitors and sensors at protective and transition nodes*
Asset Awareness	2. Substation Inspection Drone RD&D 3. Signal Injection use case RD&D	EPRI and National Lab Joint	• *Ability to evaluate the health of de-energized systems before re-energizing after PSPS (e.g. injecting non-60 Hz signal or gradual V increase etc.)* • *AI and technology supported inspections of utility assets including crossarms, insulators, and connectors*
Environmental Monitoring	4. Nationwide imagery and fuel layers to support ignition risk awareness use cases	National Labs	• *A nationwide high fire threat aerial imagery and sensor network* • *Regional and National Fuel Layers that are (nearer to real time) accurate*
Post Fire Inspection	5. Development of test coupons to assess heat damage per asset post-wildfire	EPRI and National Lab Joint	• *Ability to evaluate the health of de-energized systems before re-energizing*

4 Modeling and Simulation

4.1 Overview and Relevance to Wildfire Risk Reduction

A good fire spread model can project the direction and speed of travel of a wildfire based on factors such as fuel condition, wind speed, and humidity. Foresters, fire emergency responders, communities, insurance actuaries, and electric utilities alike have different interests and needs for advanced tools that enable fire risk scenario analysis, such as impinging weather predictions, fire-spread forecasting, and other spatially relevant fire threat indices.

Utilities can benefit from many different fire spread use cases, for example, using a fire spread model to predict when and where critical infrastructure may become threatened. Insurance companies on the other hand, might use the same outputs to understand how many of their insured properties are in a high-risk area. Individual models are available for purchase by stakeholders for fire spread analysis and many of the larger organizations invest significantly into the modeling software. Smaller organizations and communities can be challenged with the costs for these commercial products therefore, a key focus of the National Laboratories has recently been around development for the open-source community.

Along with near-term fuel layers, the simulation tools can benefit from a long-term analytics perspective because the climate and the fuelscape is dynamic and can change over time. The models need up-to-date information layers, that are readily and publicly available, and are largely developed with open-source approaches and available exports that support any organization's simulation package. Toward these objectives the advisory group identified the following 2030 future states that support more consistent and replicable modeling and simulation:

- *Unified regional and North American wide fuelscape layers that are (nearer to real time) accurate.*
- *Consistent and replicable methodology to integrate wind and recent climate and weather data into fire risk and spread modeling tools*
- *A unified national fire weather forecasting service*
- *Training and education on publicly available modeling and simulation tools that support fire analytics metrics and use cases*

Some of these future states are cross cutting with the situational awareness objectives from section 3 and are repeated here because they do have relevance to both modeling tool development and to vegetation condition awareness.

4.2 Modeling and Simulation Gap Analysis

The existence of fire spread models is not a technical gap today but acquiring them can be cost prohibitive. Larger utilities and fire agencies, such as the California Department of Forestry and Fire Protection (CAL FIRE), along with state and federal government agencies are among the current subscribers to one commercially available product described in the on-line technology catalog. The simulation package combines multiple fire-related models to predict wildfire behavior, mitigate wildfire risk, and improve wildfire operations, response, and firefighter safety. The availability of more open-source models and datasets, such as those being developed at PNNL could alleviate the cost challenge.

One technical gap that exists today is the lack of integration of sensors. For example, some utilities manage networks with hundreds of weather stations providing data on wind speed; however, while these sensors are providing useful information, they are probably underutilized in terms of the potential benefits for fire spread modeling.

Another gap is the lack of a single source of truth for fuel density. Among the multiple sources of this data, some can be either outdated or spatially sparse. Similarly, weather data may be obtained from the National Weather Service, but more timely updates and more weather stations reporting would be helpful for predicting fire spread.

4.3 What Is Needed to Move the Industry Toward the 2030 Vision

To overcome the existing gaps toward the vision statements listed in ***Table 4-1*** *the following activities are recommended:*

- Continued support of National Lab activities associated with the development of open-source data layers and modeling tools.
- Increased collaboration from stakeholders who either curate or maintain fire weather and fuelscape data layers to create a unified source of the truth for modeling inputs
- A single organization capable of developing and providing regional fire weather forecasts for the U.S. and Canada.

Like the discussion from Section 3, the consensus from the Wildfire Advisory Group was that there are many important modeling and simulation use cases that could provide better informed outcomes by incorporating weather, vegetation health, and fuelscapes. A key theme that came up multiple times, is the need for a single source of the truth, whereby every stakeholder is using a consistent and up to date (fire risk and fire weather) data layers for their analysis. It was a consensus that focused National Lab research and publicly accessible data layers could equally benefit fire response organizations, foresters, communities, and other interested stakeholders, as well as the electric power industry. Therefore, the wildfire advisory group has recommended pursuit of the projects identified in the following Table.

Table 4-1

Proposed Projects and Future States Addressed

Category	Project Title	Proposed Lead	Future States Addressed
Modeling & Simulation	1. Open-Source Fuelscape Layer Development	National Labs	• *North American Wide Fuelscape Layers that are (nearer to real time) accurate.*
Modeling & Simulation	2. High Resolution Fire Weather Forecasting	National Labs	• *Consistent and replicable methodology to integrate wind and recent climate and weather data into fire risk and spread modeling tools*
Modeling & Simulation	3. Open-Source Data Layers to Support Fire Spread Analytics	National Labs	• *A nationwide high fire threat aerial imagery and sensor network* • *Regional and National Fuel Layers that are (nearer to real time) accurate*

5 Utility Telecommunications and Wildfire Risk Reduction

5.1 Overview

Without telecommunications, many of the wildfire risk mitigation solutions and the 2030 aspirations discussed in this document would not be possible. While the advisory group did not explicitly focus on telecommunications, this section is included to consider wildfire mitigation techniques identified in other sections that require telecom along with a projection of the likely state of utility telecom in 2030 and some suggested technologies for consideration.

The supporting Appendix D, then provides a more complete overview of the current state of utility telecom, a high-level gap analysis, some items that would help bridge the gaps, and a few things that the U.S. National Labs are doing in these areas.

5.2 Telecom Use Case Requirements

Each telecom use case has an associated set of performance requirements, with the main elements being the minimum data rate (also known as throughput or bandwidth), and latency (which is the delay or time between the transmission of the message by the sender, and its receipt at the distant terminal).

Beyond these two primary technical performance items, conclusions can be made about a common telecom solution that would simultaneously satisfy most wildfire use case performance requirements. Such a communications solution would need to have these attributes:

- Ubiquitous reach or coverage
- Rapid deployment
- Low cost
- Small terminals with low power consumption
- High data rate
- Low latency
- Highly scalable (100s to 1000s of endpoints per square mile)
- Resilient (independent from commercial networks)

5.3 2030 Future State of Utility Telecom

Utilities in 2030 should have telecommunications capabilities that can economically meet any of the combination of performance, capacity, and latency required for any of the wildfire risk mitigation techniques that are chosen for implementation. These telecom capabilities should also be easily scalable and available for rapid deployment. What is not yet apparent is whether some of the unique communications approaches and requirements for ubiquitous sensor networks requires additional field demonstration.

The specific future states defined by the wildfire advisory group where this topic may need some additional RD&D include:

- Intelligent monitoring and sensors at all relevant protective and transition nodes of interest
- Consistent and replicable methodology to integrate wind and recent climate and weather data into fire risk and spread modeling tools
- Ability to evaluate the health of de-energized systems before re-energizing after PSPS (e.g. injecting non-60 Hz signal or gradual V increase etc.)

- Signal injection and monitoring for live downed conductor detection
- Smart and risk aware interface and decision support for distribution automation devices and AI-driven adaptive protection (i.e. one-shot reclose vs PSPS)

Each of these future states will require communications and may need to be considered in any follow-on demonstrations.

5.4 Advisory Group Gap Discussions

The two key challenges where solutions are not yet available were identified by the advisory group. These challenges (presented in the form of questions) were:

1. In areas without reliable signal or bandwidth, are there approaches available that can simultaneously process data in-situ and simply send a text message or a message plus an image to the alert manager? A good example considering remote camera video is described in the Section 7.6 demos section.
2. Toward the potential requirements for signal injection and monitoring for live downed conductor detection and for system health evaluation immediately after a power shutoff event, can this injection be done with power line carrier (PLC) technology or else with a hybrid PLC and wireless? More discussion on this is included in Section 7.2 and in Appendix D.

5.5 Hybrid Power-Line Carrier and Wireless

The application of PLC technology to many of the wildfire mitigation communications use cases appears to be a good fit. The hybrid solution offered by the PRIME Alliance (see Appendix D.) would enable not only an ability to reach devices attached to the power line, such as grid monitoring sensors and reclosers, but the wireless component could reach environmental sensor solutions such as smoke-detecting cameras, gas-sensing detectors, and micro weather stations.

A 2030 vision for PLC is leveraging the decades of experience of PLC protective relaying in the bulk electric system and applying this to high-speed protection of distribution lines in high-risk wildfire areas. Also, PLC could be used to perform widespread change settings on remote protective devices that presently require a field visit. Finally, because PLC rides on the power conductors, it has an inherent ability to detect broken or downed conductors. This can be combined with protective devices for rapid response to interrupt the fault current.

6 Database of Technologies

6.1 Overview

The work to catalog existing and emerging wildfire risk-reduction support technologies focused on cataloging either hardware, pilot projects, approaches, or leading industry practices that are either emerging or in progress. EPRI SMEs, in collaboration with key industry stakeholders, have documented each application in an on-line Wildfire Mitigation Technologies Catalog, which describes each respective application, spells out its role in the power system wildfire threat dynamic, and informs understanding for deployment and operational challenges and opportunities. The catalog may be accessed at this link. As of the date of this publication, EPRI has identified over fifty such emerging applications and technologies suitable for description in the catalog.

When reviewing the materials on this website, keep in mind the material posted represent 2023 vintage technology and anticipated advancements and developments over time may obsolete the posted information and the weblinks. There is presently no plan in place to update the website or the content.

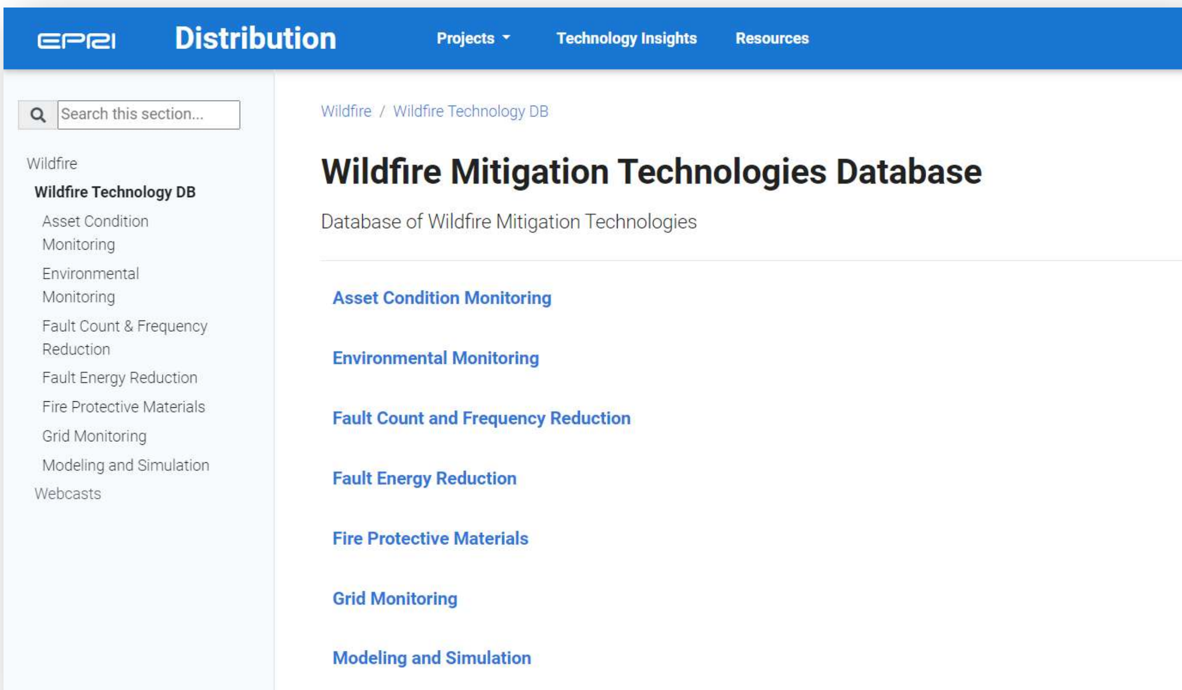

Figure 6.1
Screen Capture from the Fire Mitigation Technology On-Line Catalog

The following set of tables organizes the catalog into the common wildfire risk reduction topics and describes the purpose of the technology as well as its technology maturity level.

Table 6.1
Fire Protective Materials

Technology or Use Case	Purpose	Maturity
Pole wraps	Fire protection for wood poles	O, P, E
Fire-inhibiting sprays	Flame inhibitors for vegetation and wood poles	O, P, E
Smoke/soot inhibitors	Avoid conductive soot buildup on insulating assets	E
Flame-inhibiting coverings	Flame-inhibiting coverings for assets	E
Vegetation clearing and brushing	Fire barriers around poles, substations, and critical assets	O

O = Operational P = Pilot Stage E = Emerging Tech

Table 6.2
Modeling and Simulation Tools

Technology or Use Case	Purpose	Maturity
High resolution weather forecast	Optimized PSPS, focused line hardening, outage analytics	O,P
Fire risk layer fusion (DOE.)	Near-real-time fire risk and spread awareness	P,E
Event response	Active fire emergency management	O,P,E
Evacuation route analytics	Community risk awareness services	O,P,E
Vegetation management data sandbox	Efficacy of different vegetation management strategies	E
Fire spread forecasts (DOE.)		
◊ Active spread front	Near-real-time fire risk and spread awareness	O,P
◊ Weather-based spread risk	Real-time fire risk and spread awareness	P,E
◊ Fuel-based spread risk	Near-real-time fire risk and spread awareness	P,E

O = Operational P = Pilot Stage E = Emerging Tech

Table 6.3
Environmental Monitoring

Technology or Use Case	Purpose	Maturity
Micro weather stations	Awareness on soil moisture, humidity, wind speed, and direction	O,P
Fixed and 360 cameras	Fire detection through imagery	O,P
Gas/air quality sensors	Remote smoke detectors (sniffers)	P,E
Imagery	Vegetation condition assessment	
◊ Visible		O
◊ Multispectral		P
◊ LiDAR		O
◊ Infrared		E
◊ Synthetic Radar		E

O = Operational P = Pilot Stage E = Emerging Tech

Table 6.4
Grid Monitoring

Technology or Use Case	Purpose	Maturity
Substation 60Hz PQ monitors	Baseline for fault counts and location	O
Fault recorders	Relay-based high-impedance fault detection	O
Substation synchro phasors	Live broken conductor detection and trip	P
Substation fault anticipators (DFA)	Incipient asset failure detection	P
Substation PQ and RF indicators (DOE)	Populate fault signature repository and train new algorithms	E
Distributed RF Sensors (IND)	Incipient asset failure detection	P
Line fault indicators	Faster fault locating	O,P
Smart meters	Fault counts and downed conductor detection	O,P

O = Operational P = Pilot Stage E = Emerging Tech

Table 6.5
Asset Condition Monitoring

Technology or Use Case	Purpose	Maturity
Charred pole integrity	Fire damage inspection	E
Line splice sensor (DOE)	Detection of out-of-spec condition	P,E
Imagery	Aerial asset inspections	
◊ Visible		O,P
◊ Multispectral		E
◊ Electrical arcing		E

O = Operational P = Pilot Stage E = Emerging Tech

Table 6.6
Fault Energy Limiting

Technology or Use Case	Purpose	Maturity
Reclose blocking, manual	Avoid additional arc energy	O
Reclose blocking, adaptive	Avoid additional arc energy	O
Pulse recloser (S&C)	Avoid additional arc energy	O
Protective device communication	Increased trip speed	E
Rapid earth fault current limiter	Fault current limiting	O,P
Non-expulsion fuse designs	Avoiding hot molten particles	O
Current limiting fuse with bypass	Delay in moving to PSPS	E
Power-line carrier signaling	Fast broken conductor de-energization	E
Public safety power shutoff (PSPS)	Avoid faults under high risk conditions	O

O = Operational P = Pilot Stage E = Emerging Tech

Table 6.7
Fault Count Reduction

Technology or Use Case	Purpose	Maturity
Covered overhead conductors	Reduced faults from animal, vegetation, and balloon contacts	O,P
Strategic undergrounding	Reduced fault counts in highest risk locations	O
Hybrid undergrounding	Decreased fault counts in publicly inaccessible areas	E
Optimized construction practices		
◊ Resilient wire	Reduced broken and damaged conductors	O
◊ Resilient poles	Decreased fault counts from weather events	O
◊ Span distance, crossarm length, physical spacers	Avoiding conductor slap and galloping	P

O = Operational P = Pilot Stage E = Emerging Tech

7 Proposed Demonstration Projects that Bridge Industry Gaps toward the 2030 Wildfire Risk Reduction Vision

One of the final outcomes of the five-year risk reduction action plan is a high-level summary of important RD&D projects that if completed within the next five-to-six years accelerate the power industry's ability to reduce wildfire ignition risks and achieve the 2030 vision statements described throughout this document.

Using the Wildfire Advisory Group (WAG) to vet the demonstration concepts, EPRI has identified both the most relevant projects to fill industry gaps and the electric utilities that are interested in applying the proposed technology(s) in demonstration projects. The following list comprises the individual Research, Development and Demonstration or RD&D activities proposed to address present-day ignition risk reduction gaps:

1. Hybrid Undergrounding RD&D
2. Live Downed Conductor RD&D
3. Fault Energy Reduction RD&D
4. Advanced Inspection and Response Drone
5. Fault and PQ Event Signature Repository
6. Advanced and Intelligent Sensor Nodes
7. Fire Friendly Asset Coatings and Coverings
8. Environmental Monitoring Action Plan

Each topic is presented in a format that considers, the overall objective of future RD&D, what is required to accelerate the industry toward 2030 risk reduction vision, and the listing of future states that are addressed by each demonstration.

7.1 Hybrid Undergrounding RD&D

7.1.1 Background and Objectives

Undergrounding power lines to avoid wind, ice, tree, and airborne ignition incidents is an expensive but well accepted approach that has been documented to improve reliability, decrease fault counts and minimize ignition risks. Traditional excavation methods continue to present many challenges including:

- Rocky geologies that increase the time and cost of excavation
- Time consuming permitting for archeological and religiously sensitive areas
- Removal or treatment of excavated soil adds cost and time
- Presence, of contaminants extends project timelines or may require re-routing

Hybrid undergrounding where the lines are neither left in the air nor trenched and buried underground is a compelling concept.

The objective of this proposed work is to demonstrate hybrid undergrounding solutions that require minimal or no excavation and to simultaneously eliminate weather and tree exposure. Virtually any approaches that provide physical protection to the cables and the public, without excavation of the subsoil, could provide additional options in the undergrounding toolbox for utilities.

One such system referred to as GLDS or Ground Level Distribution System is being demonstrated in the field at one utility. The system is additionally being evaluated in a laboratory environment at the EPRI Lenox, Massachusetts test facility to begin to answer some key resilience questions including:

- How does the encasement on the cable impact its current carrying capacity (ampacity)?
- How well do the GLDS protective structures protect the cable system from vertical impacts, such as tree impacts, and crush events, such as vehicles driving over it?
- What is the longevity and survivability of GLDS structures?
- What effect do repairs to the top cap and geopolymer concrete have on the strength of the structure?
- How may the cable system be maintained over its life?

Overall, the 2024 testing is designed to provide early insights into questions associated with safety, robustness, fire immunity, ampacity, thermal performance, and fault protection. This leads to a compelling opportunity for EPRI, DOE and the power industry to accelerate the use of GLDS and similar hybrid undergrounding approaches that can serve to meet industry objectives to reduce ignition incidents exponentially.

7.1.2 What is needed to accelerate the industry toward the 2030 Vision?

The proposed RD&D moving forward is to collaborate with ten or more electric service providers to install either GLDS or a similar hybrid undergrounding variation in their service territories and to monitor these systems over at least one full vegetation management cycle of four-to-five years.

The Task set would focus on documenting the full process required at each utility to first identify the candidate high risk areas, attain the permits and right of ways as needed, document the full project procurement and construction process, and to then document the before and after fault count and ignition incident statistics.

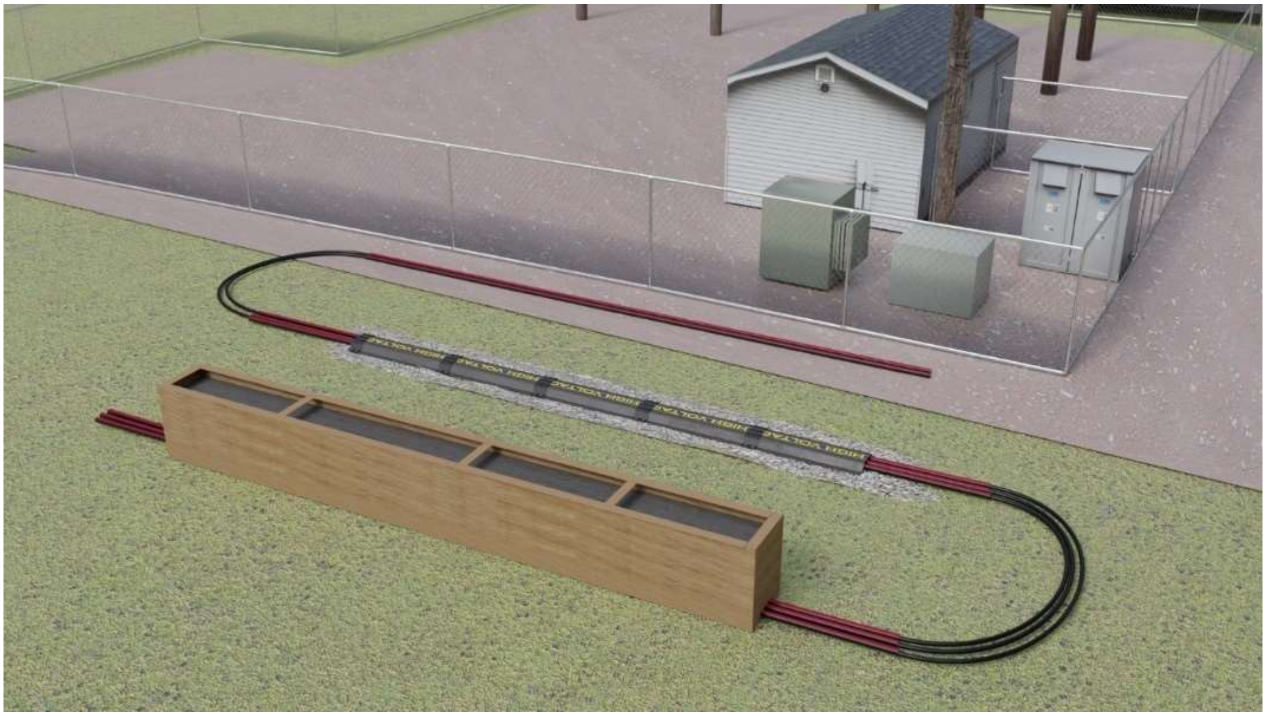

Figure 7.1
Artists Rendering of the Test Structure in Place at the EPRI Lenox, MA Test Facility

The WAG has additionally emphasized that the field demonstrations should consider unique application challenges to answer basis questions around how feasible it is to use the technology in different terrain and geological scenarios. For example, suitability for:

- Granite, rocky, and mountainous terrain
- Areas where the soil should not be disturbed
- Wet (swampy) areas
- Across ravines and small streams
- Culturally sensitive locations
- ROW restricted locations
- Understanding vandalism challenges and accidental public issue
- Road crossings
- In or beneath sidewalks

Concurrently, EPRI and at least one of the National Labs could perform accelerated lifecycle testing and work with the WAG to ideate on splicing and protection strategies that have not yet been conceptualized or vetted. The following Table summarizes these follow-on recommendations.

Table 7.1
Hybrid Undergrounding Demonstration Projects Summary

Project Title	Development Required? Y/N	Field Demos Recommended? Y/N	Estimated Period of Performance
Laboratory Lifecycle Testing on Samples and Small-Scale Installations	No	N/A	3 Years
Field Installations of Hybrid Underground	No	Yes	4-5 Years

7.1.2 Which 2030 Future States are Impacted by this Work?

This work addresses the following 2030 future states:

- *Access to comprehensive selection of hybrid underground construction options*
- *Flame immune power system hardware*

The work additionally supports and resolves the challenges associated with other overhead hardening options that don't achieve high 90's percentile ignition risk reduction.

7.2 Live Downed Conductor Detection RD&D

7.2.1 Background and Objectives

One of the most difficult and challenging wildfire ignition risks (to confidently detect, locate and to protect against) is a broken conductor that falls to the ground and then becomes an energized live electric shock and fire hazard. Live downed conductors have been a public-safety issue on utility distribution systems since they were first built, and they can remain energized on the ground for long periods of time because the current is often much lower than needed to operate relay or a fuse. The fault currents are often below 50 amps and sometimes as low as a few hundred milliamps. Backfeed from distributed energy resources into downed conductors are yet another area of interest because customer side generation can energize downed conductors during storms even if the main feeder protective device is open.

Even though the power industry has been conducting research on detecting and preventing live, downed conductors for decades, today's gap in the distribution systems space, is the lack of automatic detection and de-energization of the affected circuit segment. Avoidance and detection are possible, but getting to a point where true detections without nuisance false tripping is challenging. The key challenge being that voltage and current signatures of arcing downed conductors can be intermittent, sporadic, and generally difficult to detect with high confidence.

Information from smart meters or from SCADA can help identify some downed-conductor scenarios and modern operations centers are becoming equipped to process data to detect these scenarios with what is referred to commonly as multi-sensor fusion.

Figure 7.2
Arcing to Ground Vegetation from a Live Downed Conductor Test

7.2.2 Unique Research Pathways

There are four unique opportunities for (detecting live downed conductors) identified by the Wildfire Advisory Group that warrant further research including:

- An active signal injection technology or (power line carrier) which may prove to be the essential supplement to minimize false positive detections and to optimize true positive detections
- Lab test data – and new contributions to an industry accessible Fault Signature Repository
- Evaluation of detection algorithms – to support in intelligent sensors integrated with distribution automation DA devices
- Proof of concepts with innovative new sensors and detection approaches

Active Signal Injection – Power line carrier systems are presently leveraged on transmission lines, but they are challenging to implement on multi-grounded distribution lines. However, one such system, leveraging a power line carrier pulse in a smart meter is being piloted at the EPRI Lenox MA test facility to begin to answer several key research questions including:

- How much attenuation might be expected across different length of distribution lines?
- How many pulses per second are needed for optimal signal detection?
- What is the longevity and survivability of the injection hardware?

The follow-on opportunity (assuming success for the proof of concept) would be to develop expanded field demonstrations on utility feeders while documenting the detection success rates.

Hybrid Power-Line Carrier and Wireless – A 2030 vision for PLC is leveraging the decades of experience of PLC protective relaying in the BES and applying this to high-speed protection of distribution lines in high-risk wildfire areas. Because PLC rides on the power conductors, it has an inherent ability to detect broken or downed conductors. This can be combined with protective devices for rapid response to interrupt the fault current. The application of PLC technology to many of the wildfire mitigation communications use cases appears to be a good fit. The PRIME Alliance hybrid solution (described in Appendix D of this document) would enable not only an ability to reach devices attached to the power line, such as grid monitoring sensors and reclosers, but the wireless component could reach environmental sensor solutions such as smoke-detecting cameras, gas-sensing detectors, and micro weather stations.

Laboratory Testing – EPRI has conducted many downed conductor tests with high resolution voltage and current sensors on the circuit, or with protective relays connected, while running their detection algorithms. The collected historical data would be useful to all researchers as a shared element in the fault signature repository. Further, Texas A&M and one or more of the U.S. National Labs have similar downed wire data sets that could be curated in the repository.

The follow-on opportunity is for the industry to have a funding mechanism available to ensure that relevant previous tests and all future tests on live downed conductors result in an entry into the *industry fault signature repository*.

Evaluation with DA Hardware – A separate use case described in this shovel ready demos section is titled intelligent sensor nodes and there is some overlapping nature to detecting live downed wires and using the smarter DA controllers to support downed conductor detection and protective objectives. While DA hardware is not necessarily the key criteria for an AI based monitoring system, the DA happens to be a convenient location to place the smart analysis node, and to the do sectionalizing, protection, and power shutoffs as deemed necessary.

As a follow-on opportunity, there is a need for some proof-of-concept development work at EPRI and the National Labs over the near term or next 18 months, and assuming the results are successful, this work could be expandable to utility field demonstrations over time either within the downed conductor detection area of research or in the Smart DA are of research.

Innovative New Sensors and Approaches – Several novel concepts have been vetted with the wildfire advisory group and each show promise for specific field demonstrations. These include:

- **IND's Early Fire Detection (EFD) System –** Which demonstrates the well understood power quality monitoring principle that if at least one sensor upstream of a line break and at least one sensor downstream of the line break are used together, they provide nearly 100 percent effective detection capability for downed wires use cases.
- **GridWare's Gridscope –** Multi-Dimensional Sensor Network, that demonstrates similar detection capabilities to the EFD system, but adds several additional physical parameters to their data fusion and analyses.
- **Sandia's Traveling Wave Detection R&D –** Traveling wave protection schemes are based on high-frequency measurements and determining the arrival time of the fault wave signature. The high frequency electromagnetic transient propagates through the system at roughly the speed of light, allowing the protection equipment to detect the wave in less than 1ms after the fault. This ultimately could avoid some of the use cases such as line burndowns which result in a live downed conductor.

As a follow-on opportunity, there is a need for some proof-of-concept development work at EPRI and the National Labs over the near term or next 12-18 months, and assuming the results are successful, this work could be expandable to utility field demonstrations.

7.2.2 What is needed to accelerate the industry toward the 2030 Vision?

Today's gap in the distribution systems space, is the lack of automatic detection, locating, and de-energization of the affected circuit segment where the live conductor is on the ground. This research area has four separate pathways forward as described in the follow-on opportunity discussions in the preceding sections. The following Table summarizes those follow-on recommendations.

Table 7.2
Live Downed Conductor Demonstration Projects Summary

Project Title	Development Required? Y/N	Field Demos Recommended? Y/N	Estimated Period of Performance
Active Signal Injection RD&D	Yes	Yes	3-5 Years
Lab Testing (to feed a fault signature repository)	No	No	2-3 Years
Evaluation with DA Hardware RD&D	Yes	Yes	3 Years
Innovative New Sensors and Approaches RD&D	Yes	Yes	3-5 Years

The next step is to craft more specific proposals and timelines to move the work forward in the four areas listed.

7.2.3 Which 2030 Future States are Impacted by this Work?

- *Smart and risk aware interface and decision support for protective and sectionalizing devices such as AI-driven adaptive protection (i.e. one-shot reclose vs PSPS)*
- *Signal injection and monitoring hardware capable of interface with protective devices for live downed conductor detection*

7.3 Fault Energy Reduction Technology and Enhanced Protection RD&D

7.3.1 Background and Objectives

To reduce ignition and fire risks, power system protective devices need to be more intelligent, more adaptive to fire weather and more tightly coordinated and the Wildfire Advisory Group has expressed interest in demonstration of technology that can begin to fulfill these requirements. Toward these interests, when a power system fault occurs any technology or strategy that reduces the amount of current that flows into the fault path can subsequently reduce the likelihood that local vegetation will ignite. Similarly, any technology or strategy that can speed up the opening of the circuit protective device would reduce the risks of vegetation ignition. These concepts are generically referred to as enhanced protection settings and approaches.

The major research challenge for enhanced protection settings - that can be supported by both EPRI, and U.S. National Laboratory research and development is associated with:

- Faster protective device innovations
- Understanding the localized vegetation ignition risks based on testing of (different vegetation types and wetness/dryness conditions) under varying amplitudes and durations of arc (fault) energy

These research gaps are significant undertakings and likely require collaborative activities across the electric power industry, vendors, and the U.S. National Labs.

Faster Protective Devices – EPRI Previously tested and demonstrated a fault current reduction technology that operates about ten times faster than a traditional protective device. The technology can react to clear a fault in less than ten milliseconds, which is significantly faster than the typical 100 millisecond clearing time for most protective reclosers and sectionalizers. The early testing demonstrated the ability to SCADA control the unit and can bypass the fast protection with a standard recloser when fire weather was not a threat. It is believed the technology can be optimized to provide less than five millisecond response time and can be customized for different current levels with additional RD&D.

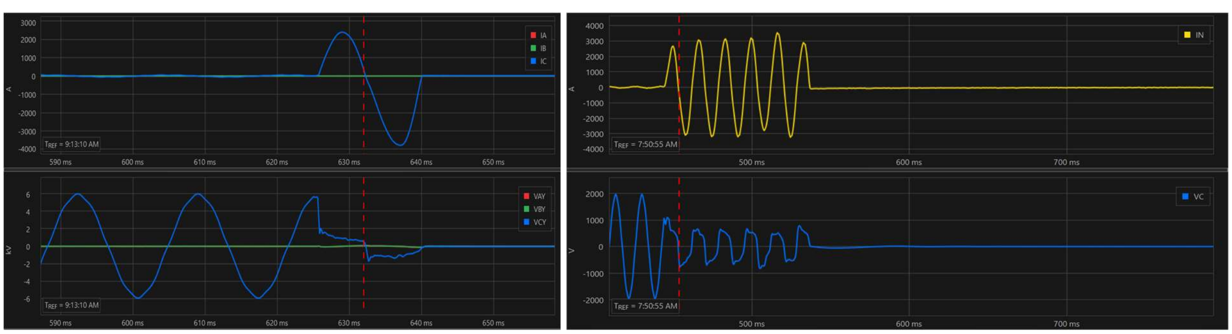

Figure 7.3
Left Trace: Current and Voltage During Fault with Fast Fuse ~ 10ms Clearing Time
Right Trace: Current and Voltage During Fault with Recloser ~ 100ms Clearing Time

Vegetation Ignition Curves – Different kinds of vegetation under different levels of wetness/dryness exhibit ignition propensities that are not easy to calculate or compare. There is a need for a consistent and replicable method of using variable arc currents to understand the complete ignition and sustained flame profile.

Figure 7.4
Different Ignition Sources from Contact with Vegetation

By leveraging spectral imagery to characterize the wetness/dryness of different vegetation samples and then applying different current and durations to the samples, the expected outcomes are ignition risk curves for different vegetation types. The curves may then be applied to smart distribution automation equipment along with customized fire threat modeling. The model outputs would then provide understanding of whether it is safer to operate and trip the circuit or if it is necessary to transition into a proactive PSPS (public safety power shutoff) event.

7.3.2 What is needed to accelerate the industry toward the 2030 Vision?

Research in this space could have a two-fold benefit as it would address the need for faster fault clearing and would simultaneously help understand vegetation/ground fuel ignition risk, based on the existing fault clearing capabilities of the protective hardware in place. Most significantly there is an opportunity with this research to reduce both the need for Public Safety Power Shutoff (PSPS) and could reduce the amount of time a circuit needed to be in the PSPS outage condition.

The following Table summarizes those follow-on recommendations.

Table 7.3
Fault Energy Reduction Demonstration Projects Summary

Project Title	Development Required? Y/N	Field Demos Recommended? Y/N	Estimated Period of Performance
Faster Protection Hardware RD&D	Yes	Yes	3-5 Years
Vegetation Ignition Profile Testing	No	No	2-3 Years

7.3.3 Which 2030 Future States are Impacted by this Work?

- *A comprehensive selection of fault energy limiting technologies*
- *Full understanding of vegetation ignition probability as fault energy is reduced*

7.4 Advanced Inspection and Diagnostics R&D Drone

7.4.1 Background and Objectives

An innovative way to make visible and spectral imagery, and electromagnetic inspections of power circuits, assets, and vegetation the substation drone dock could be a useful dispatchable asset. The consensus from the Wildfire Advisory Group and EPRI SMEs is that electric utilities will continue to expand their use of drones in the future. To date, documented case studies show that inspectors using drones can work safer, faster, and with higher-quality results as compared to traditional ground based, and manual inspection methods. This is true for most local inspections regardless of the environment (distribution, substations, transmission, generation, or forestry). Two key use cases in the wildfire awareness space include:

- Planned cyclic inspections on a set schedule and
- On demand flights to accommodate “what just happened” missions

While there remain a few regulatory and technical limitations, commercial drone solutions are emerging for (drone-in-a-box, or drone “dock”) systems that would always reside at a substation and could be remotely outfitted with specific sensors for specific missions. that would be dispatched for one or more objectives either daily, weekly or on demand. The prototype systems combine a drone with a protective housing, embedded charging, wireless connectivity, and remote or automated command and control of the aircraft. Conceptually, these systems promise hardware that utilities install and leave in place for remote and autonomous operations. This may improve the drone business case for long-distance, very remote, or high-priority situational awareness needs. As with most new and rapidly developing applications, the electric utility industry could benefit by collaborative research, testing, and deployment with drone dock technology.

While the primary use cases expand well beyond just the wildfire cases, wildfire does have a significant priority, and those applications of the drone dock are foundational to the proposed demo ideation.

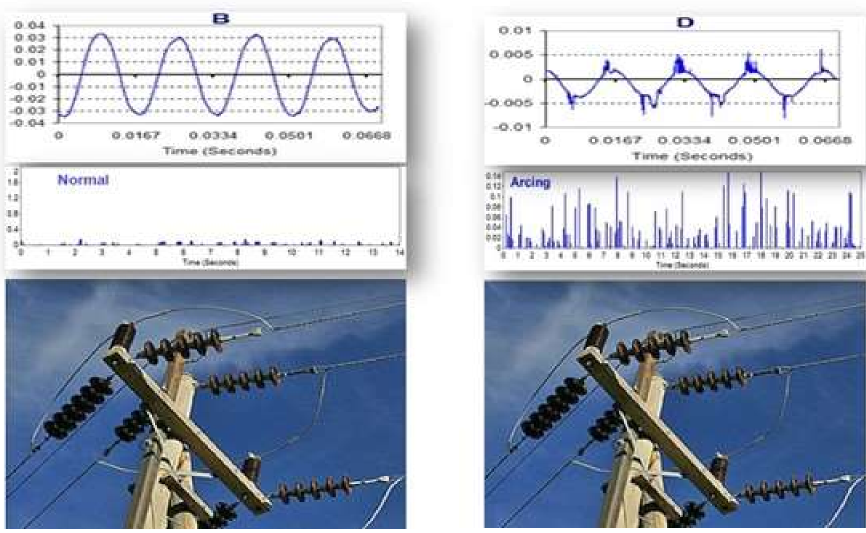

Figure 7.4

Drone Mounted Sensors can Detect Normal (Left) vs Pre-failing Equipment (Right)

7.4.2 New Learning from a wildfire focused demo

If a utility managed a network of drone docks for wildfire risk reduction, how could they routinely and reactively manage their utility's rights-of-way and infrastructure? This research would offer new learnings by deploying state-of-the-art drone technologies over a large area for utility situational awareness of the vegetation conditions, frequent asset inspections, investigation of line faults and monitoring of the right of way to detect smoke from any fire initiations. While all this seems possible, drone operations must ensure airspace safety, and privacy for the public should be considered. Field demonstrations at scale have not exposed the value and limitations of this approach. It is likely there are scenarios where the approach fails due to environmental limitations, and others where the pipeline adds significant value compared to traditional methods. Lessons learned from these experiments can direct utilities to a new way of managing their rights-of-way and infrastructure for all kinds of implementations and objectives.

As a partnership opportunity, Oak Ridge National Laboratory could be a partner with this research with the related UAS Edge Computing of Energy Infrastructure Damage Assessment.

7.4.3 What is needed to accelerate the industry toward the 2030 Vision?

The drone demo would crosscut all three continuous monitoring objectives by flying both planned and unplanned missions to monitor vegetation health, vegetation risk to power lines, to conduct electromagnetic sensing of incipient failure conditions, and to respond to electric fault detections by flying (on-demand) inspection missions, to the fault location to look and report back on smoke detection or on identified power system damage. Research in this space could have multiple benefits as it would:

- Firstly, enable a utility to get reasonably high-resolution data on the local vegetation to help inform vegetation/ground fuel ignition risk and to make the modeling tools more certain in their projections.
- Secondly enable an immediate response to a fault to identify its cause, the hazard level for the system or the public and a quick assessment of whether a fire start response is warranted
- Finally, the inspection drone would be able to support damage assessment immediately after the winds have died down and the lines need to be inspected - post PSPS

The following Table summarizes the follow-on recommendations.

Table 7.4

Substation Drone Demonstration Projects Summary

Project Title	Development Required? Y/N	Field Demos Recommended? Y/N	Estimated Period of Performance
Substation Drone Demonstration	Yes	Yes	3-5 Years
Fulfillment of Drone Demo Use Cases	No	Yes	2-3 Years

7.4.4 Which 2030 Future States are Impacted by this Work?

- *Full fault count/cause visibility and history for all power lines of interest*
- *A Unified fault and power quality (anomaly event) signature repository*
- *Full understanding of vegetation ignition probability as fault energy is reduced*

7.5 Fault and PQ Event Signature Repository

7.5.1 Background and Objectives

The DOE-EPRI Fault Signature Database started out as a collaborative activity, initiated in the 2010 timeframe, and aimed at improving the understanding and management of electrical faults in power systems. The original database and some of the other (event signature libraries) are designed to collect, analyze, and share data on various types of faults and disturbances that occur across electric power systems. By sharing data and insights, participants can collectively improve the reliability and performance of the electric grid. Such repositories provide utilities, researchers, and other stakeholders with detailed information on fault signatures and assist in identifying the characteristics and patterns of different types of faults. The signatures and the actual cause detail can be used to improve fault detection, diagnosis, and response strategies. The original Fault Signature Database contains:

- Real field incidents as recorded by electric service provider power analyzers
- Tests performed in a controlled laboratory setting to replicate real field incidents
- Vendor sensor platforms where the vendor curates the incident data from the power system and then utility field crews are enlisted to identify the actual cause

Data types include waveforms, event logs, and other relevant information captured during fault events. The database includes information on various fault types, such as phase-to-phase contacts (conductor slap), line to ground faults, equipment failures, and fault types. Each fault type is characterized by specific signatures, which are patterns or features in the data that indicate the presence and nature of the fault. To date it is unlikely the signature database has been used for any wildfire analysis, but this is an area of low hanging fruit.

7.5.2 How can wildfire ignition incidents be leveraged?

To expand on how grid monitoring plays a key role in understanding faults, fault characteristics, and which types of faults may create ignition incidents, a good description of some different fault use cases is helpful. Four such fault types that are common to all utilities and have potential to result in an ignition incident are:

- Conductor Slap
- Live Downed Conductors
- Hotline Clamp Arcing
- Capacitor Bank Contact Pre-failure

Conductor Slap – To narrate a simple example from the conductor slap use case, one phenomenon that is common is referred to as magnetically induced conductor slap. When the lines contact one another they throw sparks and molten metal onto the vegetation below. Interestingly this happens quite often on bare overhead conductors and is not well understood by field crews that don't find evidence of a problem when they patrol the line and many times record the breaker lockout incident with a cause code of "No problem found."

Even with the "no problem found" result, the following pattern of currents and voltages would be recorded by a power monitoring device. To supplement the narrative, the following figure and the (lower blue trace) in **Figure 7.5** contains a power quality recording from a conductor slap incident and can be described with the sequence description that follows the image.

4. An initial fault occurs downstream of a protective device from some initiating event such as a tree branch, or a ballon, or an animal. When the initial fault occurs, the wires have equal and opposite fault currents, and this causes the wires to magnetically oppose on another and to swing apart in a pendulum motion. For a typical power system, the upstream protection senses the fault current and opens to clear the fault - leaving the wires heated up, stretched out a foot or more from the heat, and still swinging. In the figure (bottom blue trace) the first current increase on the left side shows this initial fault followed by zero current once the protective device opens.

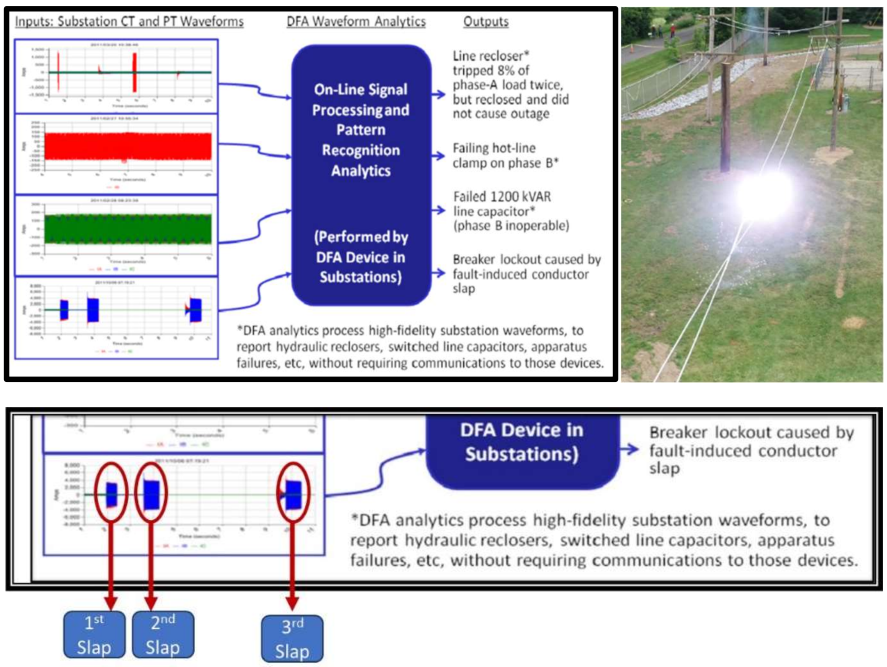

Figure 7.5
Waveforms and Trained Insight from the EPRI TA&M Developed Distribution Fault Anticipator

5. When the protective device re-closes back in (a few seconds or so later) the upstream conductors swing together and cause a new fault, this time with even higher currents than the previous event. This can be seen as the second current increase in the blue trace and again a protective device opens and the currents go to zero again
6. After the protection recloses, the conductors slap together for a third time. At this point the main breaker opens – locking out the circuit and the currents and voltage go to zero.

There are several different variations and combinations of fault – reclose – fault – reclose – lockout that can and do happen, but the key takeaway here is that this sequence of events, and the current magnitudes and the patterns are detectable, predictable and can be turned into recognition algorithms. In fact, not only can the power signatures for conductor slap be patterned, but the same patterning and algorithm development approach works for another dozen different kinds of fault incidents and fault causes. Further, taking the time synchronized voltage and current data from some of the other line sensors, either upstream or downstream of the fault location, make the algorithms even more accurate and insightful and even more useful for fault and ignition risk analytics.

Live Downed Conductors – This use case and its variations are described comprehensively in Section 7.2.1. Having a signature library with dozens of examples of each variation in downed conductors will help the industry identify new algorithms and enhance existing ones.

Hotline Clamp Arcing – Referring again to Figure 7.5.1 the red trace on the (middle left) is a classic example of the intermittent high frequency arcing pattern common with failing line clamps on distribution lines. These clamps can be proactively located and replaced before they become an ignition risk.

Capacitor Bank Contact Pre-failure – The capacitor bank switch failure is very easy to detect with power line monitoring and many examples exist where the associated switching transients may exceed three or four per unit of the line voltage amplitude – typically due to system resonances. Detecting these incidents and acting quickly can avoid failures of lightning arrestors and other power line assets before they become an ignition risk.

In short, if enough field samples for different fault incidents and for different fault types are curated in an industry fault signature repository, then researchers, vendors, and subject matter experts can all work on new algorithms and test them with a common fault signature library – hopefully to identify ignition incident causes and to understand how to avoid them.

7.5.3 What is needed to accelerate the industry toward the 2030 Vision?

A refresh of the fault signature repository with new fault entries and additional types of sensor data will assist considerably in helping researchers develop better algorithms with higher success rates. Another useful addition to the repository would be more comprehensive and detailed narratives like the conductor slap summary described here. Finally, it is important to keep in mind that several sensors can pick up the same fault event from a different location on the system and they see a different voltage or current profile depending on whether they are upstream or downstream of the fault location. The industry gap here is a lack of a single platform capable of ingesting all of the monitor/sensor data feeds in parallel and subsequently turning that data into either, immediately actionable recommendations, or into fault count statistics, or into a better-informed data repository with spatially labeled event data.

The following Table summarizes the follow-on recommendations.

Table 7.5
Fault Signature Repository Demonstration Projects Summary

Project Title	Development Required? Y/N	Lab or Field Demos Recommended? Y/N	Estimated Period of Performance
Develop Guidebook of Fault Types, their Characteristics and Data Criteria	Yes	Yes (Lab)	2 Years
Curate Statistically Valid Samples for Each Fault Type Identified	N/A	Yes - Derived from Funded Field Demos	2-4 Years
Develop Multi-Sensor Spatial Analysis Tools	Yes	Yes	3 Years

7.5.4 Which 2030 Future States are Impacted by this Work?

- *Full fault count/cause visibility and history for all power lines of interest*
- *A Unified fault and power quality (anomaly event) signature repository*
- *AI enabled monitors and sensors at protective and transition nodes*

7.6 Advanced and Intelligent Sensor Nodes and Awareness Platforms

7.6.1 Background and Objectives

Leveraging smart computing technology and combining it with artificial intelligence can convert virtually any data acquisition node from a passive monitoring and data transfer device - to an informed, adaptive, and intelligent decision tool for both ignition risk mitigation and for overall power system resilience.

A major benefit of (smart computing at the asset) is that in many cases, the collected data never has to move, and the computing device could be as simple and low cost as a smart phone running some AI enriched apps. Moreover, those apps could be modified as new learnings and improved algorithms are discovered.

A simplified example of smart computing enabled edge processing from Dryad Networks, was documented in the wildfire risk reduction technology catalog. The Dryad product detects smoke and it's AI chip (made by Bosch) claims to be the first gas sensor with artificial intelligence, and integrated pressure, humidity, and temperature sensors. The gas sensor is designed for low power consumption, mobile or connected applications, and it can detect seven unique gasses and compounds. More expensive and more computationally powerful examples include hardware such as the NVIDIA Jetson application.

Toward the wildfire objectives, use cases of interest for smart computing enabled applications include:

- Smoke Detecting Camera Nodes and Weather Stations – for Environmental Monitoring
- Adaptive Distribution Automation and Protection Hardware – For Ignition Risk Mitigation
- Smart and Risk Aware Power System Assets – For Weather Informed Optimization

Smoke Detecting Camera Nodes and Weather Stations for Environmental Monitoring – This particular use case has many stakeholders – most prominently, land managers. The key opportunity here is to use the cameras to conduct multi-purpose monitoring applications such as vegetation health and fire spread analytics. Another very compelling use case is areas with limited communications capacity. Typically smoke detecting cameras require a reasonably high bandwidth data stream but the edge computing use case could change the paradigm. This use case was a discussion point of emphasis and of repeat conversation with the Wildfire Advisory Group, where fire awareness data would be collected at a remote location, but the data is processed in-situ and doesn't need to move - unless requested. The tie-in is that in areas where communications are marginal and low bandwidth, the information gets processed into a low-resolution text which makes it easier to transmit to the response entity.

Adaptive Distribution Automation and Protection Hardware for Ignition Risk Mitigation – This use case describes the edge computing at a protective device, but the device could be any distribution asset that needs to respond, protect, or adjust its settings. Therefore, this discussion applies to many other risk aware power system assets. The most prominent example here is the DA device that has a role in isolating a portion of a circuit to perform a public safety power shutoff PSPS during extreme fire weather. By integrating a local micro-weather station and a smart power quality analyzer, the PSPS time could be reduced considerably and, in some cases, avoided altogether. In a different variation, the same intelligence could be used to determine when it was time to bypass the DA device in favor of a switch configurable fault current limiting fuse. These decisions and choices could be well informed and enhanced by integrating localized wind and weather data, vegetation condition data, and historical circuit fault data.

7.6.2 What is needed to accelerate the industry toward the 2030 Vision?

The 2030 consensus vision of the WAG projects a requirement for power system protective devices that are more intelligent, more adaptive to fire weather and more tightly coordinated and the WAG is interested in demonstration of technology that can begin to fulfill these requirements. The major research challenge that can be supported by both EPRI and National Lab research and development include faster protective device operation innovations and demonstrations with protective devices that have adaptive settings based on their understanding of the localized fire risks. Additionally helping the industry with ways to get actionable insights from areas with limited communications is an important goal for many high fire threat areas that are remote and difficult to access.

The following Table summarizes the follow-on recommendations.

Table 7.6
Intelligent Sensor Nodes Demonstration Projects Summary

Project Title	Development Required? Y/N	Field Demos Recommended? Y/N	Estimated Period of Performance
AI Enriched Camera Demo	Yes	Yes	3-4 Years
Intelligent Sensor Nodes Demo with DA Focus	Yes	Yes	3-4 Years
Test Coupons to Evaluate Heat Impacts on Assets	Yes	Yes	3-4 Years

7.6.3 Which 2030 Future States are Impacted by this Work?

- *AI or smart grid enabled monitoring and sensors at all relevant protective and transition nodes of interest without the need for data to be transferred.*
- *A comprehensive selection of fault energy limiting technologies*
- *Smart and risk aware interface and decision support for protective and sectionalizing devices such as smart computing - driven adaptive protection (i.e. one-shot reclose vs PSPS)*
- *Full understanding of vegetation ignition probability as fault energy is reduced*

7.7 Fire Friendly Asset Coatings and Coverings

7.7.1 Background and Objectives

Many utilities have experienced significant reduction in fault counts by hardening their overhead distribution lines. Such hardening can include stronger poles, covered conductors, covered connectors, and specialized coverings and tapes for all other exposed electrified hardware. While line coverings are a very mature area of research in the grid resilience space there are a number of challenges remaining with making coverings and insulators that have long field lifecycles, are animal, weather and moisture hardened and are flame and smoke friendly. The Wildfire Advisory Group considered the following ignition-mitigation and fire-hardening areas:

- Coverings that reduce ignition opportunities, such as asset covers, connectors, and the coverings used on the wires
- Flame-inhibiting applications, such as intumescent pole wraps, sprays, and applicants that reduce soot and particle deposition on electrified assets.

7.7.2 Coverings that Reduce Ignition Opportunities

When energized equipment fails, the failure mode may ignite portions of the equipment, such as synthetic components, insulating materials and animal guards, like those shown in **Figure 7-7**. While most equipment has protective fuses to quickly isolate the equipment, the fault energy may still be great enough to provide an ignition source to ground vegetation.

Figure 7.7
Testing at the EPRI Lab Reveals Many Coverings are not Flame Friendly

As a peripheral concern, EPRI testing on different brands of animal guards, insulating tape, conductor coverings, and other types of insulating materials reveal some insightful gaps that warrant new R&D:

- First, the materials that the guards, and other insulating electrical coverings are made from is not being consistently specified and designed to be either flame friendly, or moisture ingress proof.
- Secondly, the same insulative mixtures used for tapes, wraps, and other electric asset coverings have unique combustion concerns whereby the materials can either easily burn or can exacerbate the situation by dripping flaming liquid materials onto the vegetation beneath the coverings.

This issue is not chronic across every insulating material. However, testing needs to be done on each brand and type to understand how each mixture performs under a flame test.

7.7.3 Fire Protective Applications

One approach to reducing wildfire risk is to integrate fire-protective materials into overhead distribution infrastructure. Application of fire-protective materials would be expected to reduce wildfire risk by

- Mitigating ignition risk during exposure of overhead distribution components to ignition sources, such as an arc caused by vegetation or wildlife contact, and by
- Improving the fire resistance of overhead components exposed to a wildfire, thereby reducing the need for infrastructure replacement after wildfire exposure.

Fire-protective materials include a wide range of mixtures that inherently withstand high temperatures, react when exposed to high temperatures to create a protective barrier, react to locally inhibit the oxidation process by consuming energy, release moisture or an oxygen-depleting reactive compound, or a combination of any of these. Materials such as concrete and brick are inherently flame resistant. However, many commonly used materials in overhead distribution systems are not inherently flame resistant, such as wood poles, pole top insulators, wildlife guards, and others. Fire protection coatings and wraps have been developed to prevent wood pole combustion in the event of wildfire.

Despite the commercial availability of products that have demonstrated adequate wildfire protection, there are many questions left to be answered. Uncertainties remain regarding long-term performance, long-term resistance to weathering, environmental impacts, and end-of-life considerations, how application of protective materials interfere with inspection activities, how protective materials affect the degradation rate of the material to which it is applied (e.g., wood poles), and if repeat application or renewal is needed following exposure to a single wildfire event.

7.7.4 What is needed to accelerate the industry toward the 2030 Vision?

In the coverings space, ideally it would be beneficial to work with the National Labs to develop a selection of insulating mixtures that are flame friendly, UV resistant, and weather impervious and provide the criteria to vendors for future products. EPRI could support with consistent and replicable test criteria to evaluate the performance of the prototype mixtures and any commercial products developed

In the fire protective applications space there is a need for a more versatile selection of sprays, coatings and sacrificial wraps for transmission and distribution assets and again, it would be beneficial to work with the National Labs to develop a selection of suitable products based on some WAG defined and SME defined specifications. The following Table summarizes the follow-on recommendations.

Table 7.7
Flame Friendly Assets and Coverings Projects Summary

Project Title	Development Required? Y/N	Field Demos Recommended? Y/N	Estimated Period of Performance
Coverings that Reduce Ignitions RD&D	Yes	Yes	3-4 Years
Fire Protective Applications RD&D	Yes	Yes	2-4 Years

7.7.5 Which 2030 Future States are Impacted by this Work?

- *Coatings for insulators and electrical hardware that do not retain contaminants*
- *Fire, and weather friendly, coverings for electrical assets*

7.8 Environmental Monitoring Action Plan

7.8.1 Background and Objectives

From an electric power system and wildfire interaction perspective, environmental monitoring has three key objectives. The first objective is to accomplish periodic physical inspections and observations of the power system right of way and its vegetation to better understand when remediation actions are needed to avoid faults, avoid tree fall-ins, or to avoid igniting ground fuels. The second objective is to have near real time visibility on the regional and local weather conditions to better prepare for storms and to respond to weather related outages. The third objective is having visual monitoring in place and to be able to detect smoke and fire starts and respond, before the incident becomes an uncontrolled wildfire

7.8.2 What is needed to accelerate the industry toward the 2030 Vision?

The consensus from the advisory group was that there are many important use cases for weather, vegetation health, and fire detection. While the periodic monitoring and inspection of vegetation in the right of way, is utility focused and is already allocated for with defined practices and budgets, the modeling and forecasting future states would be better served by conducting focused U.S. National Lab research instead of proposing electric utility demos.

The advisory team additionally emphasized the need for a more focused sub-advisory group that could help to define the resolution of the Fuelscape relevant parameters as there are different stakeholders that may have unique benefits from a certain resolution or with more frequent updates based on recent climate or weather conditions and so on. Specific considerations around frequency, resolution, and training needs are described more thoroughly in the Environmental Monitoring details section of this report.

The key takeaway was that focused National Lab research could equally benefit fire response organizations, foresters, communities, and other interested stakeholders beyond just the power industry. Because environmental monitoring and application in risk analysis is a key benefit to so many stakeholders, the wildfire advisory group has recommended pursuit of at a minimum, the projects identified in the following Table.

Table 7.8
Fuel Layers Development Projects Summary

Project Title	Development Required? Y/N	Field Demos Recommended? Y/N	Estimated Period of Performance
• *Unified regional and North American wide fuelscape layers that are (nearer to real time) accurate*	Yes	Yes	TBD
• *Replicable methodology to integrate wind,climate and weather data into fire risk and spread modeling tools*	Yes	Yes	TBD
• *A unified national fire weather forecasting service*	Yes	N/A	TBD
• *Training on publicly available modeling and simulation tools that support fire analytics metrics*	Yes	N/A	TBD

7.8.3 Which 2030 Future States are Impacted by this Work?

- Unified regional and North American wide fuelscape layers that are (nearer to real time) accurate.
- Replicable methodology to integrate wind, climate, and weather data into fire risk and spread modeling tools
- A unified national fire weather forecasting service

Appendix A

A.1 More Extensive Electrical Fault Detail and Background

This section is intended as a tutorial for those interested in learning more about electrical faults, arc energy and the work undertaken by the WAG to develop risk mitigation future states. The section is also supportive of the high-level summary materials in section 2

Background – Electrical faults occur when energized power (lines or conductors) contact other conducting surfaces. This can lead to a drastic increase in the current flow from one conductor to the other. Depending on how the fault occurs, there is a possibility of arcing. An arc is caused by the passage of current through air in the presence of the electric field on account of the two conducting surfaces being in-close proximity to one another. In a similar vein, when certain protection devices like expulsion fuses operate on the occurrence of a fault, they eject a small amount of heated material that drops to the ground from the fuse cartridge. Conductors could also drop to the ground and continue conducting current until the circuit is de-energized either by the protection system or manually by the operator once they become aware of the situation.

The amount of energy in the fault depends on both the magnitude of fault current and the amount of time that the fault remains energized. The greater either of these quantities, the higher the amount of energy injected into the vegetation. Referring to the fire triangle in **Figure A.1**, the energy from the fault provides the heat needed for an ignition, while the combustible vegetation in the surroundings serve as the fuel.

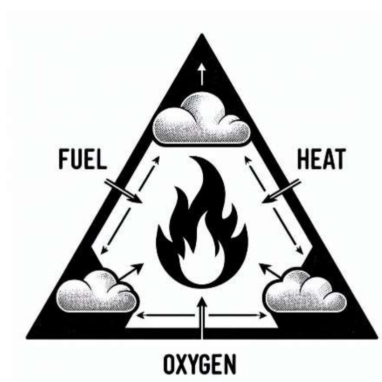

Figure A.1
Fire Triangle

When considering ways to reduce fault counts and to reduce the amount of fault energy that could ignite vegetation, electric service providers consider the following high-level mitigation options:

- **Fault Energy Reduction.** These include all options that either reduce the amount of current flowing into a fault or that speed up the opening of the circuit protective devices when a fault occurs.

- **Circuit Hardening.** These options reduce the total number of faults that occur on a given circuit by implementing technologies that reduce exposures and proximity to animals, trees, ground vegetation, extreme weather, mylar balloons, and other external fault hazards.
- **Circuit Reconfiguration.** These options reduce fault counts by modifying the existing circuit with strategic undergrounding, hybrid undergrounding, and more resilient poles and wires.

The following sections describe in more detail the current state of the art for these fault treatments.

A.2 Fault Energy Reduction Options

The idea behind fault energy reduction is to reduce the total amount of energy that is available to cause an ignition. This can be done either by reducing the amount of current that flows or by clearing faults as quickly as possible to minimize the fault duration.

A.2.1 Strategies for Reducing or Locating Ignition Sources

Fault energy can be reduced either by limiting fault currents or speeding up fault clearance, both of which reduce the amount of energy available to begin an ignition. If the location of a fault can be accurately determined, field crews or aerial fire response teams can be dispatched to said location to check for possible ignitions so that they may be extinguished before the fire has a chance to escalate into a wildfire. In addition to knowing the geographical location of the fault, knowing whether the faulted section is in the air or on the ground is also important as this impacts the probability of ground-level ignition.

A.2.2 Ignition Modes

Faults can ignite ground-level vegetation in several ways. Some ignition modes involve the arcs in faults, and some involve direct contact with vegetation.

A.2.1.1 Contact with vegetation

Contact by vegetation (phase to phase, phase to neutral, or just a phase contact) can ignite the vegetation. When vegetation first contacts energized conductors, the currents are small (often less than 1 Amp). As the current completes its loop through the vegetation, the current initiates burning of the vegetation, but the low currents are difficult to detect. The picture in **Figure A.2** illustrates vegetation between conductors during this low amperage phase of the fault.

Figure A.2
Tree limb burning together from each end (EPRI workshop, 2022)

The burning carbonizes the vegetation and creates hot gases. For vegetation bridging from one conductor to another, the normal progression is for the burning at the two contact points to extend inward until the gases created meet. It is the gases created from the burning that provide a high current path that can be detected. Detection of the high current then initiates the de-energization of the conductors, which stops the flow of current. But the burning that was already in progress may continue, and falling embers may ignite other fuel sources. The remnants of burning vegetation after voltage is removed necessitates that the fault locations are quickly and accurately identified so that personnel can be dispatched to the fault location to mitigate any secondary ignitions. Fortunately, the high conductivity of the gases created from vegetation burning means the fault impedance is low, and therefore traditional fault-location algorithms can be used to locate the fault with a reasonable degree of accuracy.

A.2.1.2 Arcs and conductors slapping together

Bare overhead conductors can at times come in contact with each other, as seen in **Figure A.3** either due to wind or because of some other external force causing the conductors to lose their spacing. When energized conductors make contact, there is a resulting spray of molten metal that may ignite secondary fuel. In addition to the molten metal droplets, the conductor may lose enough material strength that it breaks and falls to the ground. If the conductor is re-energized through the act of reclosing, the conductors on the ground may ignite vegetation and create a public safety hazard. Any fault with arcing can spray molten metal that may ignite vegetation. The amount of molten metal released depends on the fault type, the current magnitude, and the duration. Reducing fault durations is a prime candidate for energy reduction to reduce the possibility of ignition.

Figure A.3
Conductors slapping together after a downstream fault (EPRI workshop, 2022)

A.2.1.3 Expulsion fuses

Fuses are an inexpensive protective device that can be deployed en masse across the distribution system to isolate faults to small groups of customers. The way a standard expulsion fuse operates is to create an arc in a tube which builds up pressure and gases that expels the hot gases out of the fuse tube which extinguishes the arc. When the expulsion occurs, there is molten metal that is expelled with the gases. Although these metals must fall through the air many feet before reaching the ground, there have been reports of these metals igniting secondary fuel on the ground. **Figure A.4** shows an arc caused by a group of Mylar balloons bridging the air gap between energized conductors and a fuse in the background, ejecting molten materials and hot gases.

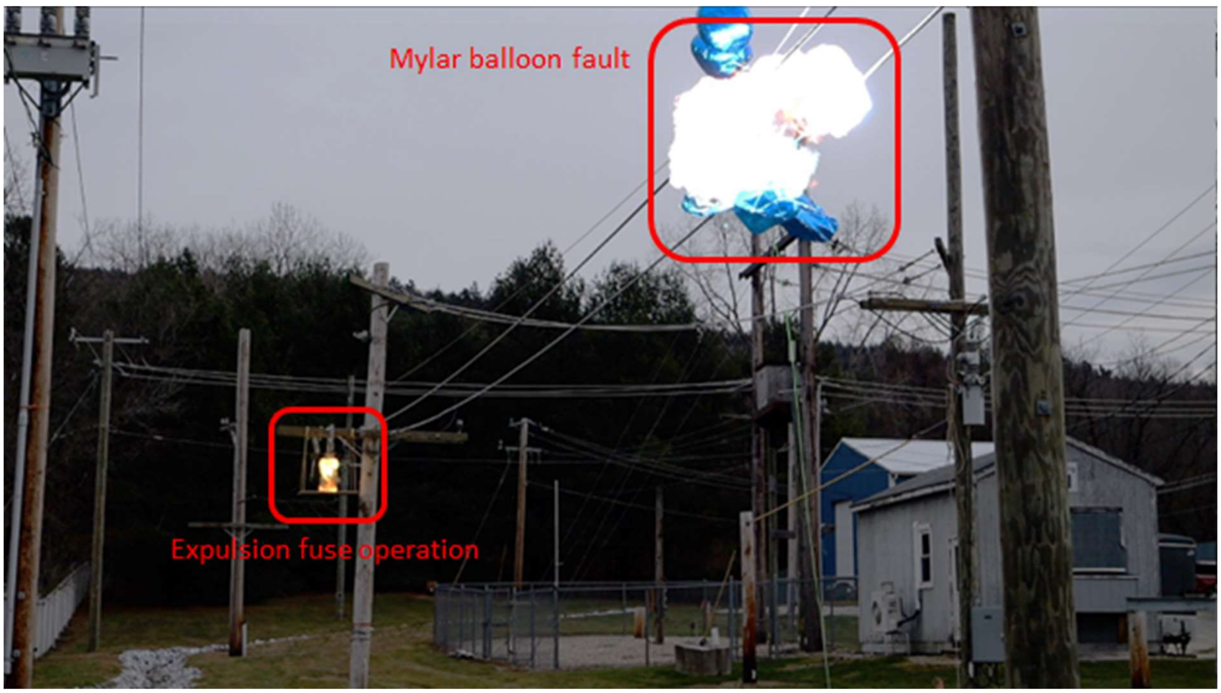

Figure A.4
Expulsion fuse operation following a Mylar balloon fault (EPRI WAG Workshop 2023)

A.2.1.4 Energized conductors on the ground

When energized conductors are on the ground, as seen in **Figure A.5**, the current from the conductor into the ground can cause electrical arcing, which may ignite any fuel in the area. There are several scenarios that may result in an energized conductor on the ground.

Figure A.5
Energized downed conductor [1]

In the first scenario, a conductor might be broken without a detectable fault. Conductors that break without a high-current fault occurring may fall to the ground while remaining energized. Without a high-current fault, normal protection cannot operate. One such example, which can be seen illustrated in **Figure A.6**, is the damage caused by vegetation lying across small wires. The small arc at the contact points may damage the conductor to the point of failure before enough gas and carbonization is created from the burning to produce a high current arc that is detected by protection devices. Because the high-current fault does not occur, the conductor falls to the ground without any detection by protective relays. Other examples include the mechanical failure of conductor splices, mechanical failure of clamps, and the mechanical failure of conductors damaged from previous high-current arcs, which lose their remaining strength due to vibrations and movement on the conductor strands that kept the conductor in the air when the high-current fault event occurred.

Figure A-6
Tree limb burning across #4 copper wire due to localized heating prior to a high-current fault [2]

In the second scenario, a conductor is broken with a detectable fault. Many energized downed conductors occur due to the re-energization of conductors through the act of reclosing following a high-current fault condition. Reclosing is the practice of de-energizing a conductor for a detected fault, waiting some short period of time, then re-energizing the conductor to determine if the fault was temporary. Since some faults are temporary, reclosing clears the temporary faults without exposing electrical customers to an extended outage while the circuit is patrolled. There are a few common temporary faults: flashovers due to a lightning strike near the distribution line, an animal contact, Mylar ballon contact, and wind-induced conductor slap. Ideally, reclosing would only occur for a temporary fault and not occur either for a fault that has damaged the conductors to the point of them falling to the ground or for faults that are still present and will remain present until qualified personnel make repairs.

When a fault occurs that causes the conductors to fall to the ground, the act of reclosing will energize the conductors while they are on the ground. Example of faults that can bring conductors to the ground include trees falling across the lines, as seen in **Figure A.7**, vehicles hitting poles, and any fault with enough arcing to burn down wires, including wire slapping. The act of energizing conductors that are on the ground often results in the ignition of ground-level fuel.

Figure A.7
Wire Burndown – resulting in a live downed conductor [2]

A.3 Circuit Reconfiguration

Reconfiguring a line to avoid or minimize faults is a common resilience practice for electric service providers. The general idea is to look at areas where a reliability improvement can be accomplished with that reconfiguration and many times the result is a strategic (partial) or full undergrounding of the overhead system. The same ideation applies to faults that could cause an ignition incident, and getting the lines out of harm's way in terms of weather and trees is a significant risk minimization strategy.

A.3.1 Undergrounding and Wildfire Risk Reduction

Recent research by EPRI estimates that between 20% and 35% of the distribution system in the United States is currently installed underground. This percentage is considerably lower in areas with lower population density, such as agricultural land and corridors between residential centers and substations. However, in the context of wildfire resiliency, the distribution power lines represent critical pathways (termed here as "wildfire corridors") as they may (1) be impacted by wildfires, (2) contribute to the initiation of wildfires, and (3) enable wildfires to propagate. This is because they represent a long linear connection, where the loss of power significantly complicates the response to a fire.

A.3.2 Underground Options

When deciding whether to install underground distribution systems, a number of benefits and drawbacks—such as reliability, safety, environmental impact, and costs—need to be balanced. The primary pros and cons are detailed in **Table A.1**.

Table A.1

Benefits and Drawbacks of Distribution Undergrounding

Benefits	Drawbacks
• **Higher reliability**: Underground systems are less vulnerable to *severe weather events* such as storms, high winds, ice, and wind-blown debris. • **Improved safety**: The risk of accidental contact with live wires is almost eliminated with underground cables. • **Enhanced aesthetics**: The visual impact is significantly reduced when cables are placed underground. • **Reduced maintenance costs**: Underground cables have traditionally required *less maintenance* because they are less prone to weather-related wear. Moreover, the cost of vegetation management is increasing.	• **Higher installation costs**: Excavation of trenches or directional drilling together with the higher linear cost of cables results in a higher upfront investment. • **Larger environmental impact**: The initial excavation process disturbs the soil and ecosystems, often requiring special treatment and/or removal. • **Increased repair complexity**: When faults occur in underground cables, locating and repairing them can be challenging. Moreover, the cost of excavation also adds to the cost of repair. • **Constrained capacity**: Underground cables generate heat and cannot be cooled as effectively as overhead lines.

Overhead distribution lines are seen as the alternative to underground cables and are often referred to as "bare wires" where the air and insulators at the pole crossarms provide the insulation. If the bare wires "clash" in the wind, fall to the ground, or are bridged by trees, then the insulation is lost, and the resulting arcs may become sources of ignition. Over the past few decades self-supporting "covered conductors" have started to be used in critical areas to mitigate the concerns around bare wires. The drawback of the covered solution is that the multilayer extruded covering means that it has a heavier weight and a lower ampacity.

Traditional measures of reliability, such as SAIDI and SAIFI, have been used to quantify the efficacy of different distribution approaches. These indices, primarily SAIFI, show that from a "fire initiating event" (FIE) perspective, where it is presumed an electrical fault may cause ignition, underground systems have a lower SAIFI, thereby outperforming overhead systems. **Figure A.9** indicates that, for one utility, 9.8% (median) of the outages occur on underground components [3]. In this representation, fewer power interruptions are assumed to correlate with fewer incidents of power arcs and thus a lower probability of an FIE. Moreover, **Figure A.10** show that SAIFI reduces as the proportion of the distribution system is placed underground [4, 5, 6]. A complementary analysis shows that the SAIFI also correlates with the level of forestation: the denser the tree cover, the higher the frequency of outages. Consequently, there is good empirical evidence to show that faults, and the risks of wildfire initiation, are reduced by placing distribution lines underground. Thus far no analyses of reliability data have been conducted to show the efficacy of covered conductor solutions.

To date, the installation of underground cables, either as new build or an upgrade option, has been limited by the higher first costs when compared to overhead lines. If first costs only are considered, the median ratio of underground to overhead costs is approximately 2:1; however, this ratio reduces when the total life costs are considered [6]. If the location is heavily forested, then the vegetation management costs may be considerable, such that undergrounding has the lowest total (lifetime) cost (**Figure A.11**). The largest first-cost component is the excavation or drilling and other civil costs to install the cable as shown in **Figure A.12**. Civil costs may be increased by complicating or variable geology (**Figure A.13**) along the route.

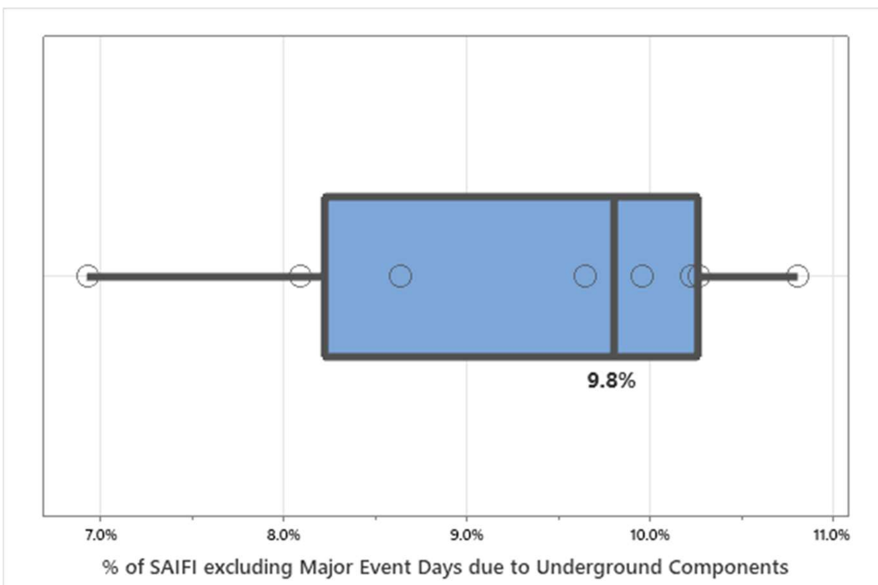

Figure A.9
Percentage of System Average Interruption Frequency Index (SAIFI), 2004 to 2011, attributed to underground components for a utility—box and whisker format [3]

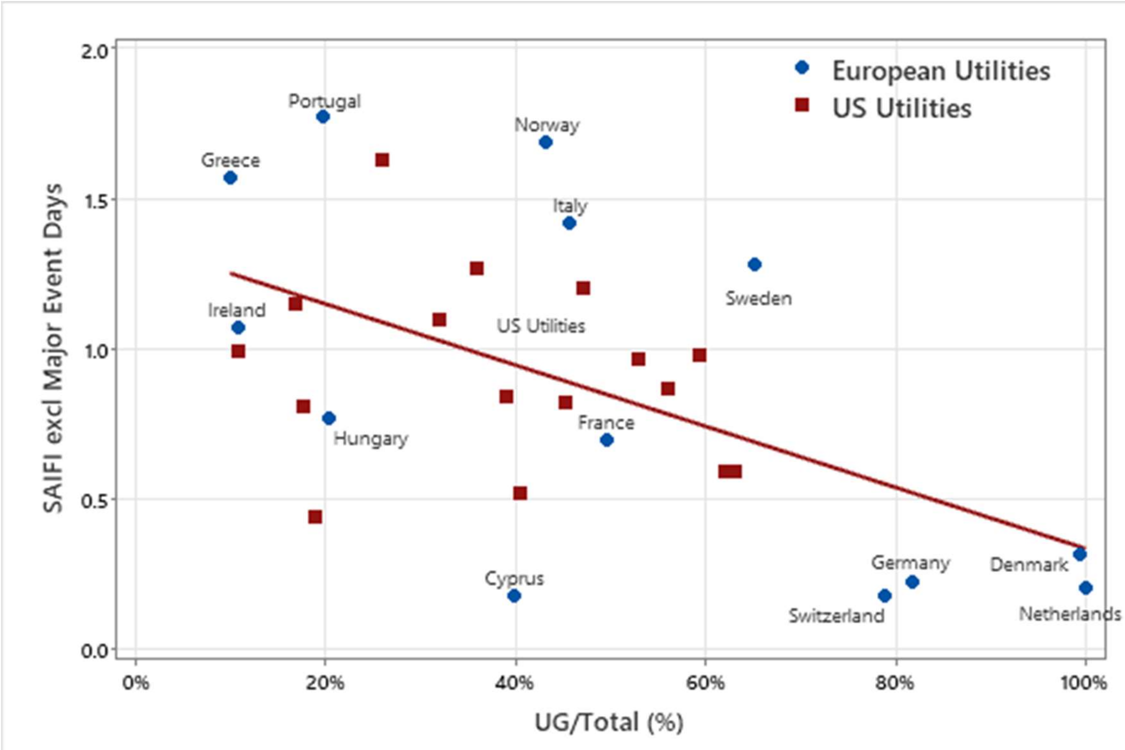

Figure A.10

Relationship between System Average Interruption Frequency Index (SAIFI) and the proportion of the distribution system placed underground [4, 5, 6]

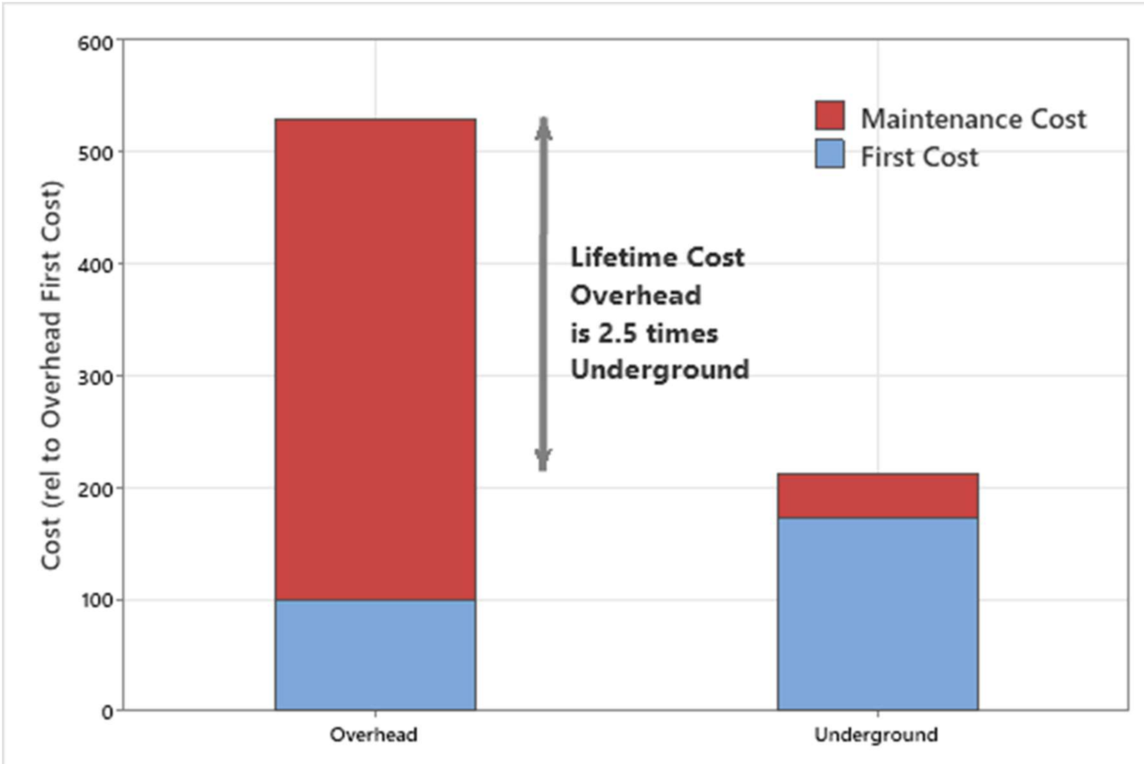

Figure A.11
Example of first and maintenance costs for a utility in an area with significant vegetation management

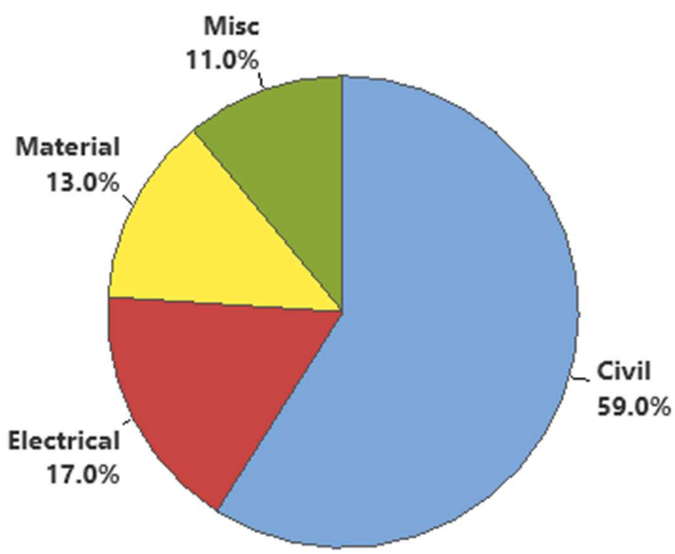

Figure A.12
Example breakdown of undergrounding costs from a utility

Figure A.13
Typical complicating geological factors for open trench installation

A.4 What Are the U.S. National Labs Doing in This Space?

The following programs are of interest in the quest to reduce electrical line faults.

A.4.1 Sandia National Laboratories

https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

A.4.1.1 Insulator Flashover from Wildfire Contaminants

Surface contamination on high-voltage insulators along with natural aging and carbon deposition (previous breakdowns) all may make insulator failure more likely. Sandia proposes to develop insulator failure thresholds by investigating the process of insulator aging and contamination using laboratory techniques. Thus, risk metrics that lead to increased risk of failure and failure thresholds may be developed, along with tracking criteria that may be used to predict grid health with respect to wildfires. This information may be used to develop tools for predicting high-voltage insulator contamination and aging. For parts of the grid impacted by wildfires, utilities may use these tools for planning mitigation efforts.

A.4.1.2 Instant Arc Detection to Reduce Wildfire Ignition with Fast Protective Relaying

Arc duration is proportional to fire-ignition potential, while current protection schemes may take between 0.1 to 1 second to execute. For distribution systems, a need exists for local, swift, data-driven, and bidirectional detection of faults and their locations such that current protection may operate in 0.004 seconds (4 milliseconds) or less. Sandia proposes using high-frequency, traveling-wave methods (1 MHz), along with machine learning to identify correlations that help in locating the fault to within 100 meters. Thus, instead of power shutoffs, protection schemes may open only those circuits necessary.

A prototype will be developed to sample, run algorithms developed, and make decisions regarding faults. This prototype will be tested in a microgrid. This effort will involve the Institute of Electrical and Electronics Engineers (IEEE) Power System Relaying and Control Committee Working Group D45, Reduction of Forest Fire Hazard; the DOE's Energy I-Corps program; and the Public Service Company of New Mexico (PNM).

A.4.2 Other Contributions

Additionally, the following U.S. government programs are involved in efforts to reduce electrical line faults:

Joint Fire Science Program (JFSP): https://www.firescience.gov/

A.5 References

1. *Modern Approaches to High-Impedance Fault Detection.* EPRI, Palo Alto, CA: 2018. 3002012882.
2. *Detection and Mitigation of Live, Downed Conductors: Industry Update.* EPRI, Palo Alto, CA: 2022. 3002024738.
3. *Distribution Grid Resiliency: Undergrounding.* EPRI, Palo Alto, CA: 2015. 3002006782.
4. *7th CEER-ECRB Benchmarking Report on the Quality of Electricity and Gas Supply.* 2022.
5. Annual Electric Power Industry Report, Form EIA-861 detailed data files
6. H. Orton and N. Hampton. *Long Life XLPE—Insulated Power Cables.* 2020.

Appendix B

B.1 Continuous Monitoring Expanded Detail

The sections that follow summarizes the advanced power system monitoring technologies that are in use by one or more utilities in high wildfire risk areas around the world today. In a similar structure to the previous Appendix A on faults, this Appendix B summarizes the present state of the art, the 2030 future state aspirations and discusses the research needed to fill the gaps necessary to achieve the vision.

Note that this section is not fully comprehensive with every technology available. Rather, it is representative of the key capabilities that are desirable for ignition risk monitoring. The fully comprehensive detail on technologies not included here can be found within the on-line fire risk mitigation technology catalog at this link.

B.1.1 Continuous and Full Waveform Monitoring

The preponderance of monitoring is focused on identifying and capturing and recording extreme or outlying events. The primary reasons are psychological and economical: psychological because our attention and priority is commonly drawn to measurement extremes, and economical because focusing on only the most extreme measurements reduces the data processing and investigative burden. Unfortunately, this focus on the extreme ignores the vast majority of data resources and lacks a nuanced understanding of what "normal operations" look like in data. Not knowing what normal looks like blinds us to more subtle excursions from normal that could be indicative of undesired changes in operations, conditions, or other patterns that, if noted and analyzed, might enable intervention and correction before issues become expensive, irreparable, or even hazardous.

There are a number of emerging techniques that EPRI is researching to improve the value derived from monitoring resources:

- **Continuous PQ Monitoring**. Using new and existing PQ monitoring resources on a continuous basis to monitor steady-state conditions can allow the creation of robust models of normal operation that can be used to detect even small variations. Coupling PQ monitoring data with other data sources, such as a geographic information system (GIS), can further enhance value and also speed identification of sources and locations of emerging issues.
- **Full Waveform PQ Monitoring**. Classical approaches to PQ monitoring generally ignore the waveshape of normal voltage and current sinusoids, focusing only on abnormal ones and only the most extreme elements even of those. This practice, while perhaps labor saving, leaves us blind to what normal waveforms look like, including waveshape, shifts in zero crossing, phase, and high-frequency content. EPRI has prioritized development of full waveform monitoring techniques, both for measurement and data processing. This can enable identification of subtle changes and can presage arcing and ignition events—or catch them earlier then heretofore possible.
- **Electromagnetic Compatibility (EMC) Monitoring.** Many electric grid conditions are accompanied by high-frequency radio-like emissions above 9 kHz. These emissions are not normally monitored and are therefore invisible. EPRI has developed an innovative and low-cost EMC monitoring platform called the Portable Radiated Emissions Measurement System (PREMS). Wide application of PREMS could allow detection of an entirely new range of signals that can be indicative of many of the phenomena important to wildfire detection, mitigation, and

prevention, including arcing, partial discharge, and internal malfunction of grid-connected equipment.

B.1.2 Distribution Fault Anticipator

If an incipient stage of a failing device or line fault can be detected and located, the final catastrophic failure may be avoided, and a fire will not be ignited. No existing protection device or power-line monitoring system commonly used today can detect the incipient stage of a clamp or switch failure. However, waveform analytics applied in real time to high fidelity captures of the electrical signatures of failing devices have been shown to identify certain failures at an early stage, long before catastrophic failure [1]. By using the results of these analytic algorithms, coupled with other utility tools such as advanced metering infrastructure (AMI), failures can often be found and fixed in a timely manner, thereby preventing a fire.

For more than a decade, researchers at Texas A&M University have conducted substantial research, funded primarily by EPRI and EPRI-member utilities to detect and anticipate incipient failures on distribution feeders using high-fidelity waveforms and sophisticated waveform analytics [2]. This work, which has become known as distribution fault anticipation (DFA) technology, has identified signatures produced by failing equipment; external intrusions into power lines; and improper or unexpected feeder events, including fault-induced conductor slaps. In many cases, utility companies have used this newfound “awareness” of feeder conditions and events to locate and correct incipient failures before they could escalate and produce catastrophic damage [3].

The DFA consists of substation-based monitoring hardware and software, connected to available potential transformers (PTs) and current transformers (CTs) used for relaying and metering. A representation of the DFA system is shown in Figure B.1 in the form of a data-processing hierarchy.

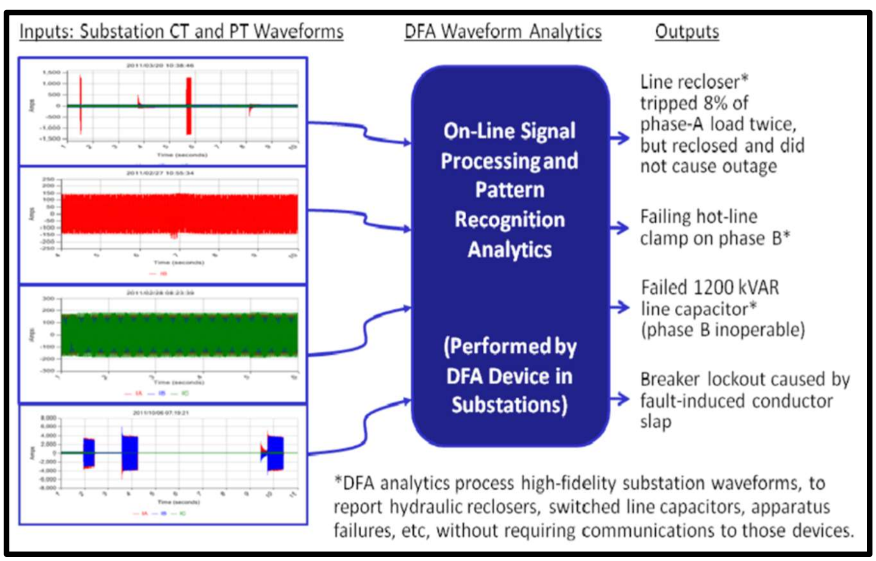

Figure B.1
Data-processing hierarchy employed by DFA field devices [4]

B.1.3 Distributed Radio Frequency Sensors

Overhead transmission and distribution lines connect urban environments and span continental grids, frequently traversing remote and difficult-to-access terrain. Stringent reliability, vegetation management, and fire protection standards create the need for utilities to navigate along power-line corridors and to conduct inspections from the ground, by helicopter, and by unmanned aerial vehicle. Periodic inspection is inefficient and incapable of detecting many failures, creating opportunity for innovation.

In an Incubate Energy Labs 2020 Pilot Project, the early fault detection (EFD) technology developed by IND Technology (IND.T), was tested [5, 6]. The EFD technology applies radio frequency (RF) sensors and advanced analytics for monitoring power-line conditions to detect and accurately locate failing network assets—those that are deteriorated, damaged, or compromised by external factors such as vegetation encroachment. In essence, EFD finds failure-causing faults before they happen.

EFD data collection units are installed about every 3 to 5 miles along power lines to supply RF signal data for algorithms running on a secure cloud server and trained for electrical circuit diagnostics. EFD systems could potentially revolutionize utilities' network operation, asset management, and work planning processes while cutting the number of transmission and distribution line faults causing customer supply outages and fires.

B.1.4 Overhead Line Sensing Technology

Energized, downed conductors are a significant ignition source. Arcing normally happens at multiple locations where a conductor contacts the earth. A conductor can remain energized on the ground because the current is often much lower than needed to operate a relay or a fuse. Fault currents range from 0 to 100 A [7, 8]. Ignition can happen quickly [9].

High-impedance faults can have unique characteristics. The currents from these are high in harmonics, and the current varies with time as the arcs flicker in and out. Energized, downed conductors often involve a broken conductor, and the broken conductor affects currents and downstream voltages.

Gridware is a tech startup out of California that has designed a unique, multi-detection monitoring tool for overhead lines that does not fit into any single functional category [10]. The Gridscope is designed for mechanical and electrical anomaly detection, fault detection, fault location, and automatic categorization of the condition. For example, it can distinguish between vegetation and animal contact, as well as line breaks, pole tilt, insulator failure, conductor clash, and a variety of other conditions. Because of its fault locating capability and deployment density, crews are directed to the precise location of the issue, without scouting the line, and can arrive with the equipment and materials needed to address the specific issue.

The hardware is typically installed on every other pole, each unit having multiple monitoring variables such as vibration, spatial orientation, and electric field sensing. It is a completely wireless sensing unit in that it has no externally connected probes or taps. Additionally, it is powered from solar energy and communicates wirelessly in a mesh configuration and outbound to the Internet using cellular communications.

EPRI conducted a series of blind tests involving several field applied scenarios: (1) a tree branch drop on a de-energized three-phase line, (2) an energized 13.2/23kV bare conductor break onto grass, (3) an energized 7.2/12.47kV covered conductor break onto grass, and (4) energized 13.2/23kV and

7.2/12.47kV bare conductor breaks onto asphalt. Images from all but the third test are shown in **Figures B.2 through B.4**. The Gridscope device and software were able to accurately determine the event type and time for each test, including whether the line was still energized on the ground. Several of the live tests did not draw enough fault current to trip the 40T fuse nor the hotline tag enabled U4 curve of the upstream recloser.

Figure B.2
Vegetation drop tests on de-energized three-phase line

Figure B.3
Energized 13.2/23kV bare conductor break onto grass

Figure B.4
Energized 13.2/23kV and 7.2/12.47kV bare conductor breaks onto asphalt

B.2 Environmental Monitoring

The goal of environmental monitoring is to provide more situational awareness, allowing utilities to act before issues occur and improve their response. Today, utilities do not know the exact environmental conditions surrounding their infrastructure. That is somewhat of an unfair statement because every utility monitors the conditions of their rights-of-way. For example, utilities leverage remote sensing to estimate vegetation risk; for example, some of the larger utilities are inspecting over 100,000 miles of overhead power lines annually. It may be that an annual cadence is optimal based on vegetation growth rates, weather conditions, and utility infrastructure. But it is just as likely that annual inspections are all that can be justified due to cost and resource requirements. By 2030, utilities need new tools, new methods, and a collaborative approach to improve both the number of circuit miles per year monitored and the number of issues corrected with greater situational awareness, utilities can understand the risks of their assets and respond accordingly.

B.2.1 Situational Awareness

If utilities have a near-real time, three-dimensional (3D) representation of their infrastructure and environment, how would they use it to reduce wildfire risk? Several wildfire mitigation plans identify light detection and ranging (LiDAR) inspections as an effective data source to model their infrastructure, map the environment, and detect spatial conflict. Complementing the LiDAR with imagery that captures the near-IR spectrum can identify tree stress indicated by deficient chlorophyll concentrations. These data are expensive and time consuming to collect at utility scale. By 2030, the industry needs to leverage hardware advances, robotic autonomy, and actionable intelligence through new artificial intelligence applications.

B.2.2 Data-Driven Decisions

High-frequency collection of remotely sensed data at scale is a major challenge. However, mining actionable information from those data is just as challenging. Today, many utilities rely on humans to interpret most of these data. Advancements in AI and computer vision promise a more efficient future; however, solely relying on computer systems may increase risk. Human experts are needed to validate, interpret, and build confidence in emerging data analysis techniques. Intelligent computing systems are needed to reduce the cost and complexity of analyzing utility data at scale. In 2030, EPRI expects humans and AI to complement one another when making data-driven decisions that influence utility action.

B.2.3 Collaboration and Transparency

Too often, data are not shared outside of a corporation. Data can contain sensitivities and other risks that can be used against an organization or its customers. This causes many organizations to work in silos and even duplicate efforts. In the rare scenarios in which data are shared, sometimes they are not used because of quality issues or other uncertainties in the data, which is unfortunate since remotely sensed data can support several use cases. In 2030, EPRI expects utilities to share, and use collected environmental data with outside organizations working in the same geographical areas. To support this, a research emphasis should be placed on (1) desensitizing remotely sensed data, (2) creating a central and shared repository for data access, and (3) creating the accompanying metadata related to how the data were collected and analyzed.

B.3 Continuous Monitoring Gap Analysis

Despite the promising potential of new monitoring technologies for wildfire mitigation, several gaps hinder their full utilization by utilities.

B.3.1 Data and Technology Gaps

Data availability and quality. Real-time, high-resolution data covering vast areas is often lacking, especially in remote locations. Existing data sources might be inconsistent or incompatible, making analysis and integration challenging. New data sources may include unknown errors leading to downstream quality issues.

Sensor and vehicle limitations. Sensors may have limitations related to resolution and accuracy. Data capture vehicles may be challenged due to regulations, perspective, and visibility, particularly in smoky or densely vegetated areas.

Data challenges. Real-time analysis of large datasets from multiple sources requires moving data out of the field, conflating with existing datasets, and analyzing using high-performance computing resources. All of this can be expensive and challenging to implement.

B.3.2 Cost and Implementation Challenges

Data capture challenges. Remotely sensed data has value to improve utility situational awareness, but it is challenging to deploy at utility scale. Fixed monitors require communications to transmit their data. Sensors currently require high bandwidth communication to stream more data than is necessary. Sensors need to communicate only the relevant insight rather than the raw data.

High up-front costs. Investing in fixed sensor technologies, more inspections, and the downstream data infrastructure can be financially prohibitive. Grid monitoring sensors are too expensive to be ubiquitous, but more sensors could be built directly into existing hardware designs.

Integration with existing systems. Integrating new technologies with existing data management and operational systems can be complex and time-consuming, requiring training and infrastructure upgrades.

B.3.3 Regulatory and Policy Hurdles

Data privacy concerns. Collecting and analyzing data over large areas raises concerns about privacy and data security. Clear regulations and policies are needed to ensure responsible data handling and utilization.

Drone regulations. Operating drones beyond line of sight, over people and homes, and in airspace requires navigating complex regulations. While special permits exist, coordination with other aircraft in the airspace can impede rapid deployment in critical situations.

Liability and insurance considerations. Potential liabilities arising from wildfires or accidents involving drones or Intelligent computing systems remain unclear, discouraging wider adoption due to insurance concerns.

B.3.4 Knowledge and Communication Gaps

Lack of awareness and confidence. Not all utilities fully recognize the potential benefits and limitations of these technologies for wildfire mitigation, leading to underinvestment and missed opportunities.

Limited collaboration and knowledge sharing. Collaboration between utilities, technology providers, research institutions, and fire agencies can be fragmented, hindering knowledge transfer and innovation. A national data repository (data and labels, from multiple utilities) of anomaly signatures should be set up to be used for research and development. Open-source data layers should be standardized so they can be ingested in any platform. For example, data from PQ monitors is one layer, and data from AMI is another layer, all ingested into the same platform and integrated into a visualization tool.

Ineffective communication of results. Effective communication of the capabilities and benefits of these technologies to stakeholders, including policymakers and the public, is crucial for wider adoption and support.

B.3.5 General Challenges for New Continuous Monitoring Deployments

Input from the advisory group provided the following list of general big data challenges that make continuous monitoring difficult to implement at scale. These challenges don't have specific projects to move the state-of-the-art, but they are discussed in the following paragraphs as documentation of the issues.

B.3.5.1 Situational Awareness with Fixed Monitors

Fixed sensors can monitor the state of electrical infrastructure to alarm on dynamic system changes. Full circuit coverage is optimal, but targeted installations in remote, inaccessible, or high wildfire risk areas are ideal locations to prioritize. These locations are typically the most expensive and difficult to inspect.

B.3.5.2 Situational Awareness with Remote Sensing

Traditional methods of performing inspections, taking measurements, and gathering data in the field are cumbersome. This is even more challenging when the area involves outdoor, high-voltage equipment that is high above the ground or inaccessible. Advances in remote sensing, mobile mapping, and computer vision could provide a more efficient method.

B.3.5.3 Data Fusion for Traditional Data Sources and Silos

The market is continuously producing new sensing technologies that utilities could evaluate, install, and deploy on their system. However, current options are often labor intensive to install, and generally not common enough across utilities to be included in standard maintenance and operational programs. Not only are there many potential sensing options to consider, but the industry does not currently have good understanding of which are truly needed. Utilities have a lot of data and there may be more extractable insights available through fusion of existing datasets. In 2030, utilities will look to fuse multiple data types together to explore new relationships and trends related to asset inspection.

B.3.5.4 Data-Driven Decisions

Collecting remotely sensed data at scale and installing fixed monitors for full circuit monitoring are major undertakings. Mining actionable information from those data is just as challenging. To analyze data today, many utilities rely on humans. Advances in artificial intelligence (AI), computer vision, and data fusion promise a more efficient future. However, solely relying on computer systems may expose risk. Human experts are needed to validate, interpret, and build confidence in emerging data analysis techniques. Intelligent computing systems are needed to reduce the cost and complexity of analyzing utility data at scale. In 2030, EPRI expects humans and AI to complement one another when making data-driven decisions that influence actions utilities take related to the health of their infrastructure.

B.4 What Is Needed to Move the Industry Toward the 2030 Vision

Addressing these gaps through research, collaboration, innovation, and policy development is essential to unlock the full potential. This will require a concerted effort from various stakeholders to make these technologies more accessible, reliable, and effective in protecting communities and infrastructure from wildfires. Two key challenges include; disparate data and smart computing at the node of interest.

B.4.1 Challenge #1: Disparate Datasets

Utilities have deployed large numbers of grid monitors, whether in the form of substation fault recorders, AMI, or other distributed intelligent devices such as reclosers. Each of these instruments produces data that may or may not be accessible by the utility. The future of grid awareness combines data from all of these sources and creates a geospatial dashboard for discerning where issues exist and where tolerances may be exceeded. A further objective is to make this data available to intelligent computing platforms for pattern detection and for predictions based on historical performance.

Next steps that are required in order to advance the usefulness of power quality data and achieve the visionary objectives of an (industry data sandbox) would include these broad tasks:

- Assembly and deployment of a large and comprehensive waveform and event signature library by incorporating large, existing resources available at EPRI (over 600,000 waveforms currently) and adding additional libraries from key stakeholders such as electric utilities, national labs, universities, and so on.
- Training of the waveform library using modern AI and machine learning techniques. Using neural networks with machine learning can aid in accurately classifying the recorded waveforms and help power system engineers diagnose and rectify the root causes of problems. However, many of the waveforms captured during a disturbance in the power system need to be labeled for supervised learning, leaving a large number of data recordings will either be processed manually by engineers or will go unseen. For example, faulted voltage and current waveforms can be

analyzed without human supervision to determine root causes. Common and unique signatures can be identified and used to classify a large dataset based on the nature and cause of the fault. These classes include cable faults (cable, joint or splice, and termination failures), animal and tree contact faults, lightning-induced faults, and faults cleared by current-limiting fuses [11].

B.4.2 Challenge #2: Smart Computing to Accelerate Detection of Faults

Technology is needed to accelerate the detection of faults on the grid via some combination of electromagnetic monitoring and other sensors, to locate those faults with precision, and to automatically open affected circuits to avoid ignition of fire.

B.5 What Are the U.S. National Labs Doing in This Space?

The following programs are of interest in the area of continuous monitoring.

B.5.1 Oak Ridge National Laboratory (ORNL)

B.5.1.1 GeoAI Group

https://www.ornl.gov/node/79427

B.5.1.2 Wildfire Sensor Fusion

https://www.ornl.gov/news/sensor-research-helps-fight-wildfires

B.5.1.3 Wildfire Research and Development Program

https://www.ornl.gov/news/scientists-dig-wildfire-predictions-long-term-impacts

B.5.1.4 Outdoor Test Bed for Power Line Sensors

Outdoor Test Bed Performance of a Power Line Sensor Using a Real-Time Event Simulator | ORNL

B.5.1.5 Distribution Arcing Fault Sensing

DOE OE Wildfire Webinar Series - Sensing & Detection | Fire Testing Capabilities - YouTube

Using high-fidelity optical sensing, ORNL is working to detect events, or details within events, that might otherwise be missed by traditional monitoring. They have developed what is called an optical sensor, combining measurements of AC voltage, current, acoustics, temperature, and vibration into event recordings. The novelty is the combination of sensors along with high sampling rate and high bit depth, surpassing traditional power monitors.

ORNL is working on a field trial with Lawrence Livermore National Laboratory (LLNL) and with PG&E to detect early indicators of arcing faults. ORNL is directly comparing their optical sensor to that of a micro phasor measurement unit (PMU) installed by LLNL on the same substation feeder in cooperation with PG&E. The R&D question is, "What features can these optical sensors detect in an arcing fault that others cannot?"

B.5.1.6 Distribution Waveform Signature Library

DOE OE Wildfire Webinar Series - Sensing & Detection | Fire Testing Capabilities - YouTube

ORNL is developing a waveform signature library consisting of a data management system, user interface, and intelligent event classification. The purpose is to advance machine learning and traditional analytics research to correlate these detectable events with root causes. The library takes in data from disparate sources such as COMTRADE, CSV, and plain text files. Data can be ingested from existing public repositories as well as sensors that ORNL is developing independently. A web application at the front end provides a user interface for uploads, downloads, and visualization. Users can upload labeled and unlabeled waveform signature data. ORNL is also working on a signature-matching tool to return top *N* matched signatures when a user uploads raw and unlabeled event data.

B.5.1.7 Line Splice Sensor

[Structural health monitoring of compression connectors for overhead transmission lines (spiedigitallibrary.org)]

ORNL has developed an innovative sensor system using "smart" patches affixed to the exterior of a compression connector. The motivation for this development is to provide information about the structural integrity of the connector, where current inspection methods only warn of electrical impedance that is out of specification. In the ORNL work, a piezoelectric ceramic material is integrated with the splice. This smart patch produces an electrical signal, that when processed, corresponds to a damage index. Laboratory tests included tensile strength and thermal cycling perturbations on the joint. The electrical signature is sensitive to variations in structural conditions so that utilities can correlate this analysis to the structural health of a connector, providing potential application in routine structural health monitoring. Associated patent: J.-A. Wang, F. Ren, "Systems, methods and patches for monitoring a structural health of a connector in overhead transmission lines," U.S. Patent, US 10,641,840 B2, May 5, 2020.

B.5.1.8 Networked sUAS for Wildfire Mitigation

[DOE OE Wildfire Webinar Series - Sensing & Detection | Fire Testing Capabilities - YouTube]

ORNL is exploring use cases for small unmanned aerial systems (UAS), which are becoming more feasible for commercial use as electronic sensors and communication technology are becoming more miniaturized and lightweight. MAVnet is a multimodal autonomous network, commercially licensed in 2020, patent pending. It is a multinetwork command, control, and compute solution for small UAS. Remote flight allows a pilot to fly from anywhere, with no travel necessary. It combines three communication technologies, handing off automatically as needed: line-of-sight (as provided by the UAS manufacturer), cellular (which extends range), and SATCOM (which further extends range, allowing global operation and locations where no cellular signal exists). MAVnet retains the telemetry connection and seamlessly transfers among available networks. Consider, for example, an operator investigating a disaster site where the cellular network has been damaged and the pilot needs to extend beyond line of sight. The web-based ground control system provides weather monitoring, personnel tracking, and data processing along with an application programming interface for future development.

B.5.2 Sandia National Laboratories (SNL)

B.5.2.1 Instant Arc Detection to Reduce Wildfire Ignition with Fast Protective Relaying (dup. from Section 2)

https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

SNL is developing a technology to detect arcing faults and quickly de-energize the circuit to prevent fire ignition. Arc duration is proportional to fire-ignition potential, while current protection schemes may take between 0.1 to 1 second to execute. For distribution systems, a need exists for local, swift, data-driven, and bidirectional detection of faults and their locations such that current protection may operate in 0.004 seconds (4 milliseconds) or less. SNL proposes using high-frequency, traveling-wave methods (1 MHz) along with machine learning to identify correlations that help in locating the fault to within 100 meters. Thus, instead of power shutoffs, protection schemes may open only those circuits necessary. A prototype will be developed to sample, run algorithms developed, and make decisions regarding faults. This prototype will be tested in a microgrid. This effort will involve the Institute of Electrical and Electronics Engineers (IEEE) Power System Relaying and Control Committee Working Group D45, Reduction of Forest Fire Hazard; the DOE's Energy I-Corps program; and the Public Service Company of New Mexico (PNM).

B.5.2.2 Novel Lightning Monitoring of Critical Assets for Wildfire Risk Assessment

https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

Worldwide, lightning accounts for over 50% of all burned acreage. The current lack of lightning datasets with respect to lightning features key to fire ignition and grid or asset disruption preclude any response until the fire grows sufficiently large to be detected or causes asset disruption. SNL proposes to develop a well-instrumented monitoring system at an asset location to provide lightning current and energy data such that predictive early warning tools may be developed based on lightning's wildfire ignition characteristics. Algorithms combine optical space-based and radio-frequency ground-based data. SNL will understand the caveats and how well the algorithms work. The project's objective is to develop predictive early warning tools for ignition.

B.5.3 Lawrence Berkeley National Laboratory (LBNL)

Berkeley Lab Wildfire Research

https://wildfire.lbl.gov/

B.5.3.1 ELM-FATES Sensitivity to Forest Disturbances and Regrowth in the Central Amazon

Using remote-sensing data from the tropics, research led by the LBNL Earth and Environmental Sciences Area has found that of the three most-common tree disturbances in the Amazon—fires, clear-cuts, and wind throws—forest regrowth from fires takes the longest time [12], an important finding because the number of fires in the Brazilian Amazon has increased in recent years. An additional study by Negrón-Juárez et al. shows the potential of using Landsat imagery data for mapping forest regrowth from different types of disturbances, including clear-cutting and prescribed fire in forested areas.

B.5.4 Los Alamos National Laboratory (LANL)

B.5.4.1 Wildfire Modeling and Simulation

https://discover.lanl.gov/news/0506-holding-statement-cerro-pelado/

B.5.4.2 Wildfire Risk Analysis and Planning Tool

https://discover.lanl.gov/publications/1663/february-2022/getting-a-grip-on-wildfire/

B.5.5 National Renewable Energy Laboratory (NREL)

B.5.5.1 Wildfire Risk and Resilience Assessment Platform

https://www.nrel.gov/docs/fy22osti/83565.pdf

B.5.5.2 Wildfire Microgrid Resilience Initiative

https://www.nrel.gov/docs/fy22osti/83565.pdf

B.5.5 Pacific Northwest National Laboratory (PNNL)

B.5.5.6 Rapid Analytics for Disaster Response (RADR)

https://www.pnnl.gov/projects/rapid-analytics-disaster-response

RADR is an all-hazards detection system that combines multimodal imagery, AI, and scalable cloud computing with an infrastructure damage assessment tool to understand current impact and risk to infrastructure from wildfires, floods, hurricanes, earthquakes, and more. The system is built to deliver high-resolution, high-cadence, large-extent situational awareness for incident command and disaster management teams to understand hazard extent, communities affected, impacts to critical infrastructure, blocked transportation routes, structural damage, and safe locations to establish relief efforts.

B.5.7 Additional ORNL Publications

UAS Edge Computing of Energy Infrastructure Damage Assessment

https://www.ornl.gov/publication/uas-edge-computing-energy-infrastructure-damage-assessment

Energy infrastructure assessments are needed within 72 hours of natural disasters, and previous data collection methods have proven too slow. This is a scalable end-to-end solution using a prototype unmanned aerial system that performs on-the-edge detection, classification (i.e., damaged or undamaged), and geo-location of utility poles. The prototype is suitable for disaster response because it requires no local communication infrastructure and is capable of autonomous missions. Collections before, during, and after Hurricane Ida in 2021 were used to test the system. The system delivered an F1 score of 0.65 operating with a 2.7 seconds/frame processing speed with the YOLOv5 large model and an F1 score of 0.55 with a 0.48 seconds/frame with the YOLOv5 small model. Geo-location uncertainty in the bottom half of the frame was ~8 meters, mostly driven by error in camera pointing measurement. With additional training data to improve performance and detect additional types of features, a fleet of similar drones could autonomously collect actionable post disaster data.

Outdoor Test Bed Performance Using a Real-Time Event Simulator

https://www.ornl.gov/publication/outdoor-test-bed-performance-power-line-sensor-using-real-time-event-simulator

The simulator generated different power grid scenarios (electrical faults, capacitor bank operation, service restoration, etc.), and its analog-output signals were connected to the voltage/current amplifiers that feed the 20/34.5kV aerial cable loop through the potential transformer/current transformer (PT/CT) devices. Additional PT/CT devices were also wired with the medium-voltage aerial cable loop to measure the phase current/voltage signals and server as references.

Providing Geospatial Intelligence through a Scalable Imagery Pipeline

https://www.ornl.gov/publication/providing-geospatial-intelligence-through-scalable-imagery-pipeline

This is a look at ORNL's contributions to imagery preprocessing for geospatial intelligence research and development (R&D). First, the authors discuss the challenges involved in building an effective imagery preprocessing workflow and the world-class high-performance computing resources at ORNL available to process petabytes of imagery data. Second, they highlight how they developed imagery preprocessing tools over three decades while paving the way for current cutting-edge machine learning and computer vision algorithms that are impacting humanitarian and disaster response efforts. Third, they discuss how PIPE modules work together to turn raw images into analysis-ready datasets. Fourth, they look toward the future and discuss planned advancements to PIPE and computing trends that will affect geospatial intelligence R&D.

A Bayesian Model for Multivariate Discrete Data using Spatial and Expert Information with Application to Inferring Building Attributes

https://www.ornl.gov/publication/bayesian-model-multivariate-discrete-data-using-spatial-and-expert-information

When modeling sparsely observed multivariate data, strong prior information elicited from experts can be used to bolster predictive accuracy and counteract sampling bias. Similarly, modeling autocorrelation in space can help make use of co-occurrence patterns present in many types of spatial data. To make use of both expert prior information and spatial structure, the authors propose a novel graphical model for a spatial Bayesian network developed specifically to address challenges in inferring the attributes of buildings from geographically sparse observational data. This model is implemented as the sum of a spatial multivariate Gaussian random field and a tabular conditional probability function in real-valued space prior to projection onto the probability simplex. This modeling form is especially suitable for the usage of prior information in the form of sets of atomic rules obtained from experts. To perform inference with missing data, they implement a Markov chain Monte Carlo scheme composed of alternating steps of Gibbs sampling of missing entries and Hamiltonian Monte Carlo for model parameters. A case study in building attribution is presented to highlight the advantages and limitations of this approach.

Spatiotemporal Tracking of Wide Area Power Outage from Night-Time Light Imagery

https://www.ornl.gov/publication/spatiotemporal-tracking-wide-area-power-outage-night-time-light-imagery

Monitoring progress of power restoration following extreme events is essential for situational awareness about spatiotemporal distribution of populations without power and to help with response efforts. Because of the proprietary nature of restoration data, and the difficulty in obtaining power-outage data from utility companies in near real-time, this project used satellite-derived nighttime lights data from Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) to monitor wide area power outage and estimate impacted customers over time to assist with restoration. A discussion of the methodology and its implementation during hurricanes Maria (2017) and Eta (2020) is presented in this paper. Future work will focus on calibrating estimated customers based on light intensity and density distribution, and generation of restoration profiles for emergency response.

An Agenda for Multimodal Foundation Models for Earth Observation

https://www.ornl.gov/publication/agenda-multimodal-foundation-models-earth-observation

Archives of remote sensing (RS) data are increasing swiftly as new sensing modalities with enhanced spatiotemporal resolution become operational. While promising new breakthroughs, the sheer volume of RS archives stretches the limits of human analysts and existing AI tools, as most models are limited to single data modalities, task-specific, and heavily reliant on labeled data. The emerging foundation models (FMs) have the potential to address these limitations. Trained on vast unlabeled datasets through self-supervised learning, FMs enable generic feature extraction that facilitate specialization to a wide variety of downstream tasks. This paper describes a vision toward an FM for multimodal Earth observation data (FM4EO), discussing key building blocks and open challenges. We put particular emphasis on multimodal reasoning, a topic underexplored in EO. Our goal is a practical path toward FM4EO with capacity to unlock breakthroughs in few-shot learning scenarios, multimodal geographic knowledge integration, synthesis, and hypothesis generation.

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Appendix C

Modeling and Simulation Support Materials

C.1 What Are EPRI and the U.S. National Labs Doing in This Space?

C.1.1 Inventory and Assessment of Wildfire Hazard Data Products

As extreme weather events increase in frequency and society's dependence on electricity grows, EPRI launched Climate READi (REsilience and ADaptation Initiative) to deliver a comprehensive, consistent, and collaborative approach to mitigate physical climate risk, ensure resilient energy, and enable robust planning. This includes a look at wildfire's impact to the energy system and mitigation efforts.

EPRI's Ongoing Efforts: EPRI has completed an inventory and assessment of available wildfire hazard datasets, models, tools, and services as part of Climate READi. The goal of this work was to conduct an objective evaluation of existing wildfire risk assessment and wildfire smoke products based on a set of evaluation criteria to guide electric companies and other organizations towards the optimal products for specific applications. The wildfire risk and wildfire smoke data products vary widely in their purpose and functionality, complexity (including the types of data used), their definition of risk, spatial and temporal extent and resolution, and accessibility (e.g., methodological transparency, cost, ease of use). The outcomes provide stakeholders, including utilities, communities, and emergency response organizations, with options on how to ingest more actionable and up-to-date data layers into their risk analysis tools and information systems.

EPRI's Future Plans: As more and more utilities across the globe begin to leverage wildfire hazard assessment tools, EPRI intends to continue maintaining its catalog of available risk assessment and smoke data products. This work also helps to inform a climate data gap analysis being conducted in Climate READi that identifies critical climate data needs for physical risk assessments in the power sector. EPRI is also developing a subsequent RFP that will fund the development of climate data to fill these gaps.

C.1.2 Pacific Northwest National Laboratory (PNNL)

Rapid Analytics for Disaster Response (RADR)
https://www.pnnl.gov/projects/rapid-analytics-disaster-response
Rapid Analytics for Disaster Response (RADR) is an all-hazards detection system that combines multi-modal imagery, artificial intelligence (AI), and scalable cloud computing with an infrastructure damage assessment tool to understand current impact and risk to infrastructure from wildfires, floods, hurricanes, earthquakes, and more. The system is built to deliver high-resolution, high-cadence, large-extent situational awareness for incident command and disaster management teams to understand hazard extent, communities affected, impacts to critical infrastructure, blocked transportation routes, structural damage, and safe locations to establish relief efforts.

Fire Spread Modeling
https://www.pnnl.gov/news-media/taming-tomorrows-wildfires

A different approach to identifying the potential path of wildfires came from atmospheric scientists: two new models employ twenty-eight "wildfire predictors" to project current wildfire behavior. Used with climate change modelled estimates, these two models may project future wildfire behavior. Several variables such as atmospheric moisture levels, vegetation dryness, density of nearby population and others may better determine wildfire likelihood, the extent of the burn, and the amount of smoke sent into the atmosphere.

C.1.3 Sandia National Laboratories (SNL)

Data-Driven Wildfire Analytics
https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

Sandia is modeling wildfires using accurate and current characterization of vegetation fuel along with existing work from the Resilient Energy Systems-funded Lab Directed Research and Development (LDRD). They are using weather station data and satellite imagery to generate machine learning (ML)-derived characterization of vegetation. Thus, utilities may better assess, plan, and adapt to wildfires. Outputs from the model include burn probability, energy release component, and wildfire behavior. Sandia proposes to run simulations with active fire perimeters as inputs.

Optimized Vegetation and Resiliency Treatments to Reduce Wildfire Threat
https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

Sandia proposes an optimization tool for prioritizing wildfire threat mitigation efforts. Due to the expense of wildfire threat mitigation, utilities should have a data-driven approach that may be used to compare investments. The mitigation type may be modelled and simulated to determine how well each performs regarding these objectives: vegetation mitigation, fuel reduction (with nearby landowners), and grid hardening. Thus, a data-driven decision tool may assess benefits and costs of mitigation relative to the aforementioned objectives. Inputs that feed into the wildfire risk calculation include characteristics of fuels based on satellite imagery and canopy metrics provided by LiDAR. Sandia will partner with two utilities, Public Service Company of New Mexico and Western Area Power Administration consecutively over a two-year period.

Visualizing Uncertainty: Design Choices Impact Decision Making
https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

Various representations of uncertainty may result in differing decision patterns—regarding when or if homes should be evacuated, for instance, or when a PSPS may be necessary. Sandia hopes to support optimal decision making regarding grid operations through better understanding of how those decisions may be affected by visualization.

First Principles Investigation of Wildfire Ignition by Lightning
https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

This effort by Sandia National Labs aims to develop an experimentally-driven computational model to understand the predictability of lightning-ignited fire from first principles. According to a publication by Moris et al from 2020, “there are no datasets that unambiguously relate igniting lightning to the corresponding wildfires” due to the time lag between the ignition and detection of the lightning-induced wildfire. Thus, no data is available to inform near-real-time prediction models that might signal a preemptive response to those potential locations of the wildfire.

Using its on-going code development—EMPIRE (plasma discharge physics and chemistry) and SIERRA (fire reaction dynamics)—Sandia proposes to develop a computational model concerning the predictability of lightning-ignited combustion. Thus, the lead time for early or preemptive suppression may be shortened. Guidance for requirements regarding lightning monitoring and wildfire prediction tools may also be provided.

SMOKEWISE: Smoke and Wildfire Impacts on Solar Energy Resilience
https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

Because modeling wildfire smoke is complex, Sandia proposes developing a landscape, climate, wildfire-smoke-modeling platform with at-scale effectiveness enabled by machine learning and neural-network-surrogate models to make annual predictions of solar energy reduction due to aerosol loading from smoke. This will allow managers and decision makers of targeted forest management plans to have explainable model output. SMOKEWISE is a wildfire smoke surrogate model using physics-based fire and smoke modeling paired with vegetation growth and succession model (LANDIS-II). It is designed to inform power and infrastructure resilience planning by modeling the near and long term impacts that wildfire smoke has on PV generation.

Accelerated Electrical Grid Recovery Post Wildfire
https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

In partnership with electric grid utilities, Sandia proposes to develop and demonstrate a methodology for post-wildfire electric grid infrastructure recovery and contingency analysis for fires in the vicinity of critical electrical infrastructure. These efforts will speed recovery and reduce electrical interruption time by accelerating the identification of highest priority mitigation efforts. Inputs to the algorithm include health, age, and design of critical components along with wildfire information such as temperature, contamination, and weather conditions.

Dynamic Monitoring for Grid Vulnerability to Fire
https://energy.sandia.gov/programs/electric-grid/wildfire-electric-grid-resilience/

The goal is for near-real-time determination of wildfire risk with respect to critical infrastructure, including wildfire impacts leading to cascading failure. Determine near-real-time fuel moisture by applying machine learning to weather station data. Identify component damage by using wildfire-spread software and Sandia grid modeling and interactive map.

C.1.4 Other Contributions

Burned Area Modeling
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020EF001910?af=R

In this study, a machine-learning model was built to predict burned areas monthly by incorporating land surface characteristics, predictors of local meteorology, and socioeconomic variables. The burned areas so indicated were laid out upon the contiguous United states as grid cells (0.25° x 0.25°). In addition, large-scale air circulation patterns were included as predictors—improving temporal correlations from 14% to 44% in several regions. Other important contributors to the burning of large areas in southeastern and western US are dry winters and fuel dryness in the fire season.

The machine learning model effectively predicted areas in the United States burned by wildfire while the interpretation of contributing factors was improved using the Shapley additive explanation (SHAP).

Appendix D Utility Telecommunications and Wildfire Risk Reduction

D.1 Overview

This appendix provides a compilation of wildfire mitigation techniques identified in other sections of this report that require telecom, an overview of the current state of utility telecom, a projection of the likely state of utility telecom in 2030, a high-level gap analysis of the differences, and some items that would help bridge the gaps.

Electric utilities use a variety of telecommunications technologies to support their business and system operations. In general, these telecom capabilities consist of two types; services obtained from commercial communications service providers (CSPs), and private networks that are often constructed, owned, and operated by the utilities themselves.

The CSP services are predominantly used to support the business operations of a utility, while the use of private networks is more prevalent in support of electric grid operations. In either case, electric utility investments in telecommunications are significant and vital in enabling electric utilities to perform all manner of routine and emergency functions.

D.2 Wildfire Mitigation Techniques That Require Telecom

Many of the wildfire mitigation techniques described in other sections of this report require a telecommunications capability. The following is a list of risk-reduction topic areas where this is the case:

- Monitoring (environmental and grid)
- Fault energy limiting
- Total fault count reduction
- Inspection tools
- Weather forecasting
- Vegetation management
- Event response

D.2.1 Telecom Use Case Requirements

Each telecom use case has an associated set of performance requirements, with the main elements being the minimum data rate (also known as throughput or bandwidth), and latency (which is the delay or time between the transmission of the message by the sender, and its receipt at the distant terminal).

Beyond these two primary technical performance items, there are additional physical attributes and business considerations that must be identified and evaluated when selecting a telecom system. These include items such as the following:

- Coverage area (wireless systems) and network reach (wired systems)
- Economics (both capital and operational expenses relative to benefits)
- Power supply (what voltage and current, and if a need for primary and backup sources)
- Size and weight of the terminals (limits where the equipment may be housed or mounted)
- Environmental constraints (determining if ventilated or heated/cooled enclosures are required)
- Cybersecurity (mitigation of any inherent vulnerabilities)

D.2.2 Compilation of Wildfire Mitigation Telecom Use Cases and Requirements

Other sections of this report identify a variety of wildfire mitigation techniques, some of which require telecommunications. Those have been collected into **Table D.1** with a brief description of the telecom use cases and notes about either the communications requirement or challenge.

Table D.1

Report Main Sections—Telecom Use Cases and Requirements

Report Section	Technology or Use Case	Approach	Communications Requirement/Challenge
Fault Energy Reduction	Fast detection and de-energization for broken conductors	De-energize before conductors hit the ground. Power-line carrier communications may provide advantages.	Many sensing locations High data rate Low-latency
	Advanced distribution automation	Coordinate fast-tripping devices.	Low-latency
	Switchable inline current-limiting fuses	Install current-limiting fuses in series with other protection devices only when reclosing is disabled.	Typical SCADA communications protocol and performance
	Enhanced performance of high-speed protection modes	Include coordinate reclosers with fuses and to coordinate between reclosers.	Low-latency
	Detection of conductor slap and galloping	Have widespread deployment of sensors.	Many sensing locations Low-latency
Monitoring for Situational Awareness	Overhead line sensing technology	Use Gridware Gridscope multidetector monitoring tool.	High density (typically installed on every other pole)
	Identification of downed conductors and their location	Employ LiDAR, imagery, and remotely sensed data.	Many sensing locations

Section 6 of this report contains a summary from the catalog of technologies applicable to wildfire mitigation. Telecommunications use cases in Section 7 are concisely presented in **Table D.2**.

Table D.2
Database of Technologies Section Telecom Use Cases and Requirements

Category	Technology	Technology Description	Communications Requirement/Challenge
Grid Monitoring	Substation synchrophasors	Employs distribution phasor measurement units, standard protection equipment, and high-speed communication to detect the break from circuit voltage signatures and issue trip commands so that the affected section is de-energized 200 to 500 ms after the break.	Private LTE cellular network
	Smart meters (AMI)	Provides increased system awareness.	Short range of mesh technology and low-power unlicensed radios Backhaul needed at takeout points
	Faulted circuit indicators (FCI)	Uses intelligent fault sensors that communicate status back to the distribution operation center.	Satellite network required where 2G/3G coverage is limited or unreliable
Fault Energy Limiting	Reclose blocking—automated	Quickly disables reclosing and sectionalize areas of high fire risk based on changing conditions. Uses real-time fire risk models.	Typical SCADA communications protocol and performance
	Protective device communication	Just as high-speed tripping is important to the stable and secure operation of the bulk transmission system, it is important to the distribution system, although for different reasons. This is critical also to the amount of energy that is supplied to a fault, which potentially is an ignition source. Shortening the fault clearing times on distribution then is	Same communications options used in the bulk electric system are valid choices (e.g., fiber, leased circuit, wireless). Communications should be monitored during normal and trip conditions and alarmed for prolonged failures. Speed and quality issues

		important for wildfire mitigation.	
	Power-line carrier signaling	Uses 4kV to 34kV distribution system protective relaying.	TWACS® is one example of a proprietary two-way communication protocol.
Environmental Monitoring	Smoke detection cameras	Network of long-range, geo-located cameras are mounted to existing or dedicated structures and are coupled with image processing and AI to alert on early detection of smoke.	Remote locations where power supply and communications may be scarce
	Gas-sensing remote smoke detectors	Remote smoke sensors are based on proven technology similar to smoke detectors for the home but are specifically suited for forest application. Early wildfire warning is one potential application for these sensors, where the sensor output is monitored and interpreted by supporting electronics that will then send a positive detection message if the sensor output meets any of the defined profiles of smoke.	Lack of availability of a power source Lack of an existing communications network
	Micro weather stations	Wind direction, speed, temperature, and humidity can provide clues about the conditions leading to development of the wildfire.	Remote locations where power supply and communications may be scarce
Asset Condition Monitoring	Line sensing technology	Gridware Gridscope multidetector monitoring tool	High density (typically installed on every other pole)

And finally, examination of the report section on shovel-ready demos yields a shorter Table D.3, but also includes some telecom requirements and challenges.

Table D.3
Shovel-Ready Demos Section Telecom Requirements

Demo Title	Background and Objective	Communications Requirement/Challenge
Drone Docks for Rapid Situational Awareness	Network of drone docks that can inspect electric utility rights-of-way routinely or on-demand	Wireless connectivity, and remote or automated command and control of the aircraft
Rapid Airborne Data: Collection, Processing, and Intelligence	Rapid damage assessment that leverages airborne remote sensing	Satellite communications proposed

While there are some important differences in the communications requirements of the various use cases across the three tables, conclusions can be made about a common telecom solution that would simultaneously satisfy all of them. Such a communications solution would need to have these attributes:

- Ubiquitous reach or coverage
- Rapid deployment
- Low cost
- Small terminals with low power consumption
- High data rate
- Low latency
- Highly scalable (100s to 1000s of endpoints per square mile)
- Resilient (independent from commercial networks)

D.3 Current State of Utility Telecom Systems

There are several types of telecom systems widely in use by electric utilities. Following is a brief description of several with a focus on fundamental characteristics that are most relevant to the communications requirements and challenges for wildfire risk mitigation.

D.3.1 Advanced Metering Infrastructure

Advanced metering systems are widely deployed in the United States by electric utilities for the purpose of remote and automated reading of residential and commercial meters. Most of these systems use unlicensed RF spectrum in the 900 MHz band. The use of unlicensed spectrum comes with significant limitations on transmitted power from the Federal Communications Commission (FCC), the effect being very short range (100s of meters) between nodes using this wireless technology.

Therefore, AMI systems use a mesh topology, meaning that groups of meters form clusters and the communications traffic that is sent in packets are passed along, from node to node, until reaching a “take-out point” where the traffic is sent across a backhaul link to a meter data management system (MDMS) at the “headend” location. The end result being that AMI systems exhibit high latency (several seconds) relative to other commonly used wireless technologies such as cellular.

Use of AMI platforms to connect devices other than meters, such as sensors and other distribution automation components, is a developing trend.

D.3.2 Utility Fiber-Optic Infrastructure

Utilities that construct private networks frequently use fiber-optic infrastructure. There are several reasons for this. First is that this technology is capable of extremely high data rates, with terabits per second achievable on a single fiber. Also, economics are favorable in terms of the small size and weight of fiber relative to legacy copper cables. Finally, fiber-optic cables are available with non-dielectric designs and therefore have certain safety and electromagnetic compatibility advantages when installed on overhead electric transmission and distribution structures.

The current state of utility fiber-optic networks is that, in general, the bulk electric system (BES) has been built out with a significant percentage of transmission routes carrying fiber. These cables are mainly used by utilities for protection and control (PAC) applications; also in many cases, excess fibers are leased to third parties for nonutility communications. The use of fiber by utilities on their distribution networks is less prevalent than on transmission lines. An exception to this trend exists for a few municipal and/or co-operative utilities where a decision was made to enter the cable television (CATV) and internet service provider (ISP) businesses. This improves the economics because the single infrastructure investment provides benefits to electric service operations as well as the CATV/ISP business. Chattanooga EPB is one notable example of this approach [1].

D.3.3 Private Fixed Wireless Systems

There are two basic types of fixed wireless systems in widespread use by electric utilities. First are broadband, digital point-to-point (PTP) microwave radio systems. These provide high-speed data transport between fixed locations such as substations. They generally use parabolic dish antennas and either licensed or unlicensed RF spectrum.

The second type of fixed wireless widely used by electric utilities are point-to-multipoint (PTMP) systems. These are lower capacity systems than PTP microwave and typically operate at a lower frequency band such as 900 MHz. Again, they may be on either licensed or unlicensed RF spectrum. The antennas are smaller than PTP microwave, with vertical omnidirectional types often used at base stations and directional Yagi antennas normally used at remote sites. The network topology of PTMP systems are typically a star, with dozens of remote sites connecting to a single base station. From the base station some form of backhaul communications is used to bring the traffic to the utility data center or energy control center.

D.3.4 Land Mobile Radio Systems

Land mobile radio (LMR) systems primarily are used to provide voice communications for the mobile workforce. While these systems may in some manner be considered legacy, as they predate the commercial cellular industry, they do provide a measure of resiliency by being able to operate standalone and independent of commercial networks, which is highly valuable during storm damage recovery.

Low-speed data capabilities are also a feature of many utility LMR systems and may be used for a variety of use cases. Primarily these LMR data use cases are for the mobile workforce, such as transmitting trouble tickets, work orders, and automatic vehicle location. They can also include limited support of sensors and other remote devices used on the distribution system.

D.3.5 Wireless Cellular Service

Commercial cellular service provided by mobile network operators (MNOs) is also widely used by electric utilities for both business and operational communications use cases. These systems are based on harmonized, global standards from the 3rd Generation Partnership Project (3GPP) and have a market penetration of five billion subscribers representing 55% of the global population [2]. The resulting economies of scale make the wireless cellular solution a compelling low-cost choice wherever it can meet the technical requirements.

The current generation of wireless cellular technology (4G LTE) provides high data rates (multi-megabits per second) and low latency (milliseconds). Next generation 5G networks being deployed now, and proposed 6G currently in development, improve performance in speed, latency, and other attributes. Utilities should be made aware of recent EPRI research that highlights several techniques that can be used with existing 4G LTE networks to achieve the low latency requirements of many PAC use cases [3].

The main drawback of the MNO solution for many of the wildfire mitigation use cases is that there is limited coverage in many backcountry locations. This is a result of MNOs needing to optimize their investments in network buildouts and therefore limiting deployment of infrastructure where there is insufficient demand for service.

D.3.6 Wire-Line Commercial Service Providers

Wire-line CSPs can generally be divided into two types of companies: first being public switched telephone network (PSTN) operators, and the second being CATV operators, also known as multisystem operators. Historically, the two provided different types of services, but now both are primarily focused on internet access for residential and business customers, but also a variety of network services for enterprise customers.

Wire-line networks have transitioned from legacy copper media (twisted pair for PSTN and coaxial cable for CATV) to exclusively using fiber-optic cable in their outside plant buildouts. Like wireless cellular, wire-line networks are generally not built out in areas where there are not homes and businesses.

D.3.7 Satellite Services

A communications technology that theoretically has 100% outdoor coverage is satellite service. Two main types that are in widely deployed geostationary orbit (GEO) and low-Earth orbit (LEO).

D.3.7.1 VSAT satellite service

Very small aperture satellite (VSAT) terminals are ground stations used to connect with GEO satellite service providers. VSAT is one of several types of fixed satellite services (FSS). VSAT FSS providers offer internet access as well as private network services to enterprise customers. Data rates in the megabit per second range are available; however, latency is high relative to terrestrial networks due to the distance to the satellite and a multi-hop network topology. Electric utilities and other critical infrastructure operators are users of VSAT services, but often in limited instances where other options do not exist and are too expensive to buildout. One important planning consideration, especially in northern latitudes, is the need for unobstructed line of sight from the Earth station location to the south, as the geostationary satellites are over the equator.

D.3.7.2 LEO satellite service

Low Earth orbit satellite networks are built using a constellation of large numbers of satellites in orbits that are much lower than geosynchronous satellites. This difference enables the use of much smaller ground terminals, including handheld units. Additional, and of greater significance for many use cases, are latencies in the 10s of milliseconds with LEO instead of 100s of milliseconds from FSS GEO systems. Since LEO satellites are not stationary over the equator, unobstructed view to the south is not required. On the other hand, in locations where there are obstructions to the horizon, such as dense forest or mountains, performance is decreased since fewer satellites are in view at any point in time.

D.3.8 Power-Line Carrier Communications

Power line carrier (PLC) communications is a method of using the electric system power conductors to carry an RF signal. A legacy technology dating to the beginning of the utility industry, it is still widely used in electric utility networks for its original use case—transmission-line protective relay communication. The other widespread use of PLC technology by electric utilities is for automated meter reading (AMR), primarily in rural or remote areas.

Probably the most successful AMR PLC technology is TWACS from Aclara (a Hubbell company). TWACS is an acronym for Two-Way Automated Communications System, and it is a "proprietary solution that uses a unique pattern of current pulses" to communicate between field devices and a headend device at the substation [4].

A more recent development with PLC technology is a standardization effort called the PRIME Alliance (with PRIME being an acronym for PoweRline Intelligent Metering Evolution [5]). The alliance has created open standards and protocols for narrowband PLC communications for interoperability in metering and smart-grid applications. In addition, the group has extended its work and developed a hybrid solution that integrates PLC with RF wireless. Hybrid chipsets that combine PRIME PLC with wireless are available from semiconductor vendors, and products such as meters, data concentrators, and gateways that use these chipsets are available from multiple original equipment manufacturer (OEM) vendors.

D.4 Summary of Current State of Utility Telecom

There are a variety of telecom technologies widely used by utilities in support of operational communications from remote devices on their transmission and distribution networks. These solutions are implemented with either private utility networks or services from CSPs. The tables of wildfire mitigation techniques identified in other sections of this report do not present any technical performance challenges that cannot be met with today's technologies. The challenges are rather in the area of economics as a result of many of the wildfire mitigation solutions requiring communications in backcountry areas where there is presently a lack of reach or coverage from existing telecom solutions.

D.5 2030 Future State of Utility Telecom

Utilities in 2030 should have telecommunications capabilities that can economically meet any of the combination of performance, capacity, and latency required for any of the wildfire risk mitigation techniques that are chosen for implementation. These telecom capabilities should also be easily scalable and available for rapid deployment.

Additionally, utilities have a preference that the future state minimize reliance on CSPs. There is a twofold motivation behind this goal, with the first being resiliency. With telecommunications and utility sectors both being critical infrastructure, reducing or eliminating interdependencies results in improvements to resiliency for both [6]. The second reason derives from the regulatory environment that incentivizes capital expenditures (CAPEX) and penalizes operational expenditures (OPEX).

A clear trend is in place that makes it likely that the 2030 vision will be realized. This trend is that an increasing number of electric utilities have begun programs to implement private LTE/5G cellular networks.

D.5.1 Private LTE/5G

There are multiple reasons utilities are embarking on private LTE/5G implementations. First is that the technology is a good fit for utility operational communications requirements.

> *In many respects, LTE is ideally suited to the requirements of data communications that support the modernized grid. Most critically, as a cellular system, it is a true FAN [field area network], providing geographically ubiquitous wireless service over a broad area, which greatly reduces the cost and logistics associated with provisioning new communications capabilities in the grid. Its control functionality is specifically designed to handle "bursty" transmissions of small to moderate amounts of data, to or from a virtually unlimited number of different user devices, with a minimum of control overhead and with low latency. The air interface incorporates multiple levels of error detection and correction for highly robust connectivity. The radio channel automatically adjusts modulation and coding schemes to efficiently accommodate a wide range of signal-to-noise ratios (SNRs). Because it is specifically intended for IP connectivity at both the user device and connection to external networks, LTE will efficiently support migration of grid communications from various serial data schemes to packet data format* [7].

Second is the enormous economies of scale that result from the worldwide commercial success of 3GPP standards. This has led to vendors leveraging their experience and product portfolios and extending this to the enterprises and industrial networking markets. Private LTE/5G networks are being built on corporate campuses, factories, and other large facilities to better meet their needs than traditional solutions such as Wi-Fi.

Finally, and most important for utilities, is the issue of RF spectrum. Utility implementations differ from typical enterprise needs in that the geographic scale is much larger, with network coverage needing to match the utility's entire service territory. To meet these coverage requirements economically, suitable RF spectrum is needed, and until recently the only way to obtain this was to compete with MNOs in FCC spectrum auctions. This situation has changed with the recent availability of two 3GPP standardized spectrum blocks—Band 8 (900 MHz) and Band 48 (3500 to 3700 MHz).

In summary, private LTE/5G is a "utility grade" future state solution that enables a network convergence that replaces dozens of independent solutions that exist in the current state.

D.5.2 Cellular Nonterrestrial Networks

Included in 3GPP 5G/6G standards are the capability of mobile handsets to directly connect with satellites, which are labeled in the standards as nonterrestrial networks (NTNs). There are issues to resolve with the potential for interference when the same RF spectrum is used for both terrestrial and NTN. In any case, NTN implementations are just now coming to market, beginning with text and emergency messaging solutions. But a roadmap exists, and full voice and data NTN capabilities will likely be available in the 2030 future state.

D.5.3 Hybrid Power-Line Carrier and Wireless

The application of PLC technology to many of the wildfire mitigation communications use cases appears to be a good fit. The PRIME Alliance hybrid solution would enable not only an ability to reach devices attached to the power line, such as grid monitoring sensors and reclosers, but the wireless component could reach environmental sensor solutions such as smoke-detecting cameras, gas-sensing detectors, and micro weather stations.

A 2030 vision for PLC is leveraging the decades of experience of PLC protective relaying in the bulk electric system, and applying this to high-speed protection of distribution lines in high-risk wildfire areas. Also, PLC could be used to perform widespread change settings on remote protective devices that presently require a field visit. Finally, because PLC rides on the power conductors, it has an inherent ability to detect broken or downed conductors. This can be combined with protective devices for rapid response to interrupt the fault current.

D.6 Utility Telecom Gap Analysis

Today there are long lead times to deploy a utility private network communications solution to a distribution asset. Therefore, the often-used fallback approach is to procure cellular modems on a commercial MNO. This is particularly true for pilot implementations of distribution modernization projects that require telecommunications. However, when the use case is scaled up the OPEX increases and the use of MNO solutions can become unsustainable. In any event, MNO coverage challenges exist in many backcountry areas where wildfire mitigation solutions need to be deployed.

The list of 2030 future state capabilities would bridge the gap that currently exists; these are private LTE/5G, cellular NTN, and hybrid PLC/wireless. The first and last require utility CAPEX and therefore must pass the hurdles of have a positive cost benefit analysis and solid business case justifications. Successfully completing this can be a challenging endeavor for utility planners.

D.7 What Is Needed to Realize the 2030 Vision

Realization of the cellular NTN item in the 2030 vision is outside the control of the utility industry. The only action that can and should be done is to monitor the progress of NTN deployments and evaluate its effectiveness in satisfying the use cases as it becomes available. Both lab and field pilot projects are appropriate before committing to large scale roll-outs of this solution.

The recommendation for hybrid PLC/wireless is different in that utilities can certainly take a more active role. Since there is availability of standards-based interoperable equipment from OEM vendors, lab and field pilot projects can be defined and started now. This will take cooperation between utility PAC and telecommunications teams.

Finally, to make progress in realizing the last technology in the 2030 vision, private LTE/5G, a more forceful and multipronged approach may be needed. Utilities have been struggling in obtaining regulatory approval for PLTE programs. Utility collaboration can be helpful in sharing lessons learned and success stories to ease the path for those that decide to head in the direction of PLTE.

One final note of interest (peripherally related to the telecoms topic) would be the future state:

- Intelligent monitoring and sensors at all relevant protective and transition nodes of interest without the need for data to be transferred.

This use case was a discussion point of emphasis and of repeat conversation with the Wildfire Advisory Group, where fire awareness data would be collected at a remote location, but the data is processed in-situ and doesn't need to move unless requested. The tie-in is that in areas where communications are marginal and low bandwidth, the information gets processed into a low-resolution text which makes it easier to transmit to the response agent. A good example considering remote camera video is described in the shovel ready demos section

D.8 References

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EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA

800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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