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Three Lines of Defense for Wildfire Risk Management in Electric Power Grids: A Review

ALI ARAB[1], (Senior Member, IEEE), AMIN KHODAEI[1], (Senior Member, IEEE),
ROZHIN ESKANDARPOUR[1], (Senior Member, IEEE),
MATTHEW P. THOMPSON[2], AND YU WEI[3]
[1]Department of Electrical and Computer Engineering, University of Denver, Denver, CO 80210, USA
[2]Rocky Mountain Research Station, USDA Forest Service, Fort Collins, CO 80526, USA
[3]Department of Forest and Rangeland Stewardship, Colorado State University, Fort Collins, CO 80523, USA

Corresponding author: Ali Arab (ali.arab@du.edu)

ABSTRACT Wildfires pose a significant challenge to the natural and the built environments, as well as the safety and economic wellbeing of the communities residing in wildfire-prone areas. The electric power grid is specifically among the built environments most affected by, and contributing to, wildfires. In this paper, we propose a three lines of defense (3LD) framework for wildfire risk management in electric power infrastructure and review the literature from this lens. An overview of the physics and phenomenology of the wildfires as it relates to power grids is presented, and the logic for the proposed 3LD framework is discussed. The reviewed literature based on the 3LD theme includes the most relevant and emerging research work on wildfire prevention as the first line of defense, wildfire mitigation and proactive response as the second line of defense, and wildfire recovery preparedness as the third line of defense. This study reveals that while the state of the art, to a large extent, stands comprehensive in various aspects of power system resilience and wildfire risk management, there is a gap in the literature in addressing this emerging risk in a holistic, interdisciplinary approach.

INDEX TERMS Power systems, resilience, risk analysis, wildfire.

I. INTRODUCTION

The keystone of modern society is a resilient power grid that ensures an uninterrupted supply of electricity to citizens and interdependent lifeline infrastructure systems even during extreme external events such as wildfires. Legacy power grids, however, have faced challenges to support their customers in the wake of recent low-probability, high-impact disasters. Recent wildfires in California, Australia, and other parts of the world have shown this shortcoming and revealed the fact that these events not only can lead to catastrophic blackouts but also can result in the loss of lives and livelihoods. According to the U.S. Department of Energy, there have been more than 2.7 million customers without power along California's coast due to 2019 wildfires and subsequent grid blackouts, indicating the lack of adequate resilience for a 21st-century power grid infrastructure. Expansion of human development in fire-prone areas and corresponding potential for human ignitions lead to growing risk to communities and critical infrastructure [1], [2]. The 2018 Camp Fire alone in Northern California—which was sparked by PG&E's electrical infrastructure—took at least 85 lives and led to several firefighter injuries, burned a total of 153,336 acres, destroyed more than 18,800 homes and structures, and made PG&E face a multibillion-dollar lawsuit as a result [3], [4]. The Woolsey Fire, which is still under investigation for SoCal Edison's electrical infrastructure's role, took at least three lives, burned 96,000 acres, and obliterated more than 1,600 homes and businesses in Los Angeles and Ventura counties [4]. According to National Geographic, "*an explosion in the frequency and extent of wildfires worldwide is hindering recovery even in ecosystems that rely on natural blazes to survive* [6]."

There are several studies in the literature indicating that climate change has increased the frequency and intensity of wildfire disasters in recent years [7]–[10]. As the risk landscape for wildfires becomes more complex, it exposes the natural and built environments including power grid infrastructure to an unprecedented vulnerability. Major power grid components prone to damage include generation units, transmission lines, distribution lines, and substations. On the other

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hand, grid-induced wildfires and their subsequent first- and second-order effects on power system operations can lead to devastating environmental and socioeconomic impacts and irreparable damages to the reputation and financial stability of the utility companies. Each wildfire has its own idiosyncratic characteristics; however, the aftermath of most of these events is the damage to the grid and power outages. These outages can cascade into multiple service areas and critical infrastructure, including natural gas, telecommunications, water, transportation, and emergency services.

In this climate, the concept of grid preparedness and resilience against wildfires has become an important risk management measure, which focuses on identifying, developing, and implementing strategies for limiting the impact of wildfires and the subsequent wide-area, long-duration power outages. Managing wildfire risk involves analyzing both exposure and effects (i.e., likelihood and magnitude of potential consequences), and developing appropriate management responses to reduce exposure and/or mitigate adverse effects [11], [12]. In this study, we address this need by introducing a risk management framework based on both exposure and effects of wildfires to and from electric power grid infrastructure and use it as a lens to thematically review the literature surrounding the topic. Our goal is to provide an overview of the most relevant literature, identify the research gap in various aspects of wildfire risk management for electric power systems, and pave the way for the researchers new to this thrust to address the existing gap in the literature.

There is a wide range of review work in various aspects of wildfire management available in the literature, including [12]–[19], among others. However, there is a limited number of review papers on wildfire management in relation to power systems. The most relevant review work was presented in an informative two-part paper in [20], [21]. In [20], a review on different fields of science and industrial projects related to wildfire issues was presented. In [21], available technical solutions to minimize or prevent wildfires caused by power networks were reviewed. Our work is different from [21], [21] in three ways: a) we provide a thematic review from a risk and resilience perspective and propose a framework to find the gap in the literature of various research areas within the proposed theme; b) we provide a broader perspective by reviewing the relevant research work from power systems engineering, forest management, social sciences, and economics of disasters to facilitate an interdisciplinary dialogue among research communities; c) In addition to preventive measures before a wildfire, we also review research work related to managing the wildfire during and after a disaster runs its course.

The rest of this paper is organized as follows. Section II provides an overview of the basics of wildfire physics as it relates to electric power infrastructure, and outlines the three lines of defense (3LD) risk management framework. Section III reviews the literature on wildfire prevention as the first line of defense. Section IV provides a review on proactive wildfire response as the second line of defense. Section V reviews the most relevant research on recovery preparedness as the third line of defense. Concluding remarks and future work are presented in Section VI.

II. WILDFIRE RISK MODELING AND MANAGEMENT

Identifying, measuring, and managing the wildfire risk in electric power infrastructure requires an understanding of the physics and phenomenology of the wildfires. In the following subsections, an overview of the commonly used wildfire risk modeling methods is presented, followed by a discussion on the underlying logic for the 3LD framework for wildfire risk management in power infrastructure.

A. WILDFIRE PHYSICS AND RISK MODELING

There is a vast body of research on the physics of fires in the literature. However, wildfire risk modeling can be a challenging task due to the deep uncertainty involved. Wildfire risk modeling can include wildfire spread modeling, wildfire front properties (that involves geometric flame features), and wildfire impact modeling [22]. Reviewing the literature on the physics of wildfires is out of scope of this paper but can be found in [23]–[25]. However, an overview of the most important topics related to modeling the wildfire risk in power grids is presented in the following subsections.

1) INTENSITY AND RATE OF SPREAD

The main portion of the heat produced by the wildfire is through radiative and convective heat transfer rates. Fire front intensity and geometric flame characteristics are required to calculate these heat fluxes. The wildfire can be considered as a heat-generating body with a specific length, width, and tilt angle with respect to a given fuelbed that moves toward a direction with its specific rate of spread (ROS). The wildfire spread can vary from place to place. Fire-prone areas such as forested or grassland locations provide a better fuelbed for a progressing wildfire. This matter can be modeled in the wildfire rate of spread. The wildfire rate of spread can be obtained by Thomas formulae [26] as:

$$V_f = \frac{k(1+V_w)}{\rho_b}, \tag{1}$$

where V_f is the rate of spread, V_w is wind speed, ρ_b is fuel bulk density, and k is a constant that is assumed to be 0.07 $[kg/m^3]$ for wildfire or 0.05 $[kg/m^3]$ for the wood crib. The fire line intensity is obtained by Newman formula [27] as:

$$I_{FL} = 300L^2, \tag{2}$$

where L is the flame length. The radiative heat flux received by the target M can be calculated as:

$$\phi_r = \tau \varepsilon_{FZ} \sigma T_f^4 \left(\alpha_{vf}\left(r_{\text{inf}}, \beta_{\text{inf}}\right) + \alpha_{vf}\left(r_{\text{sup}}, \beta_{\text{sup}}\right)\right), \tag{3}$$

where ϕ_r is radiative heat flux, τ is atmospheric transmissivity, ε_{FZ} is flame zone emissivity, σ is Stefan-Boltzmann constant, T_f is flame zone temperature, α_{vf} is solar absorptivity, and

$$\beta_{\inf} = \tan^{-1}\left(\frac{h_M}{r_{\inf}}\right), \tag{4}$$

$$\beta_{\sup} = \tan^{-1}\left(\frac{L\cos(\gamma) - h_M}{r_{\sup} - (L\sin(\gamma))}\right), \tag{5}$$

where $r_{\inf} = r$ and $r_{\sup} = r + (h_M \tan\gamma)$ where h_M is the height of the target M above the ground, γ is tilt angle, and r is the distance from the fire front to the object of interest. Figure 1 illustrates the parameters in the fire geometry diagram used in fire intensity and rate of spread formulas [28]. Fire intensity and ROS both are key measures for fire fighter safety and fireline effectiveness. Faster approaching and higher intensity fires can make firelines ineffective, require more time to build lines, pose higher risk for firefighters, and cause more severe damage to the infrastructure [29], [30], including electric power systems.

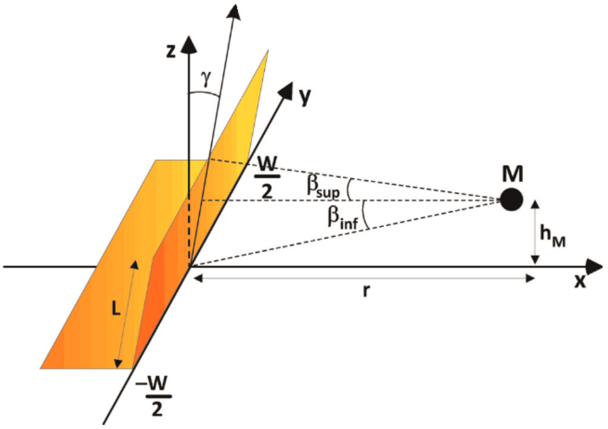

FIGURE 1. **Schematic diagram fire geometry extracted from [28].**

2) WIND SPEED

The wind speed has a major impact on the intensity and spread of wildfire. Extensive power outages may occur due to large-scale wildfires lasting from a few hours to several weeks. Wildfires have a rapid forward rate of spread (FROS) when fueled by dense uninterrupted vegetation. They can move as fast as 6.7 mph in forests and 14 mph in grasslands [31]. To fully study the effects of wind on the wildfire progression and its impact on the level of damage on the power system components, two points should be considered. First, high winds can cool down the power system components exposed to the wildfire. This matter can be formulated through the convective heat transfer terms considered in the wildfire spread model. Second, higher winds can also cause the fire front to get closer to the power system facilities or other infrastructures in the network. To model this behavior, both wind speed and wind direction should be incorporated in the risk modeling framework. Speed and direction of the wind are probabilistic in nature and both can significantly impact the wildfire spread model. This means that an appropriate probability density function (PDF) for these two parameters should be used in the wildfire spread model instead of their deterministic values. This, in turn, makes the problem solvable through probabilistic techniques such as Monte Carlo simulation. Various PDFs for wind speed and direction have been used in the literature, including Rayleigh distribution for wind speed and von Mises distribution for wind direction [32]. In practice, fire managers typically rely on gridded forecast weather using data from Remote Automated Weather Stations [33].

3) WILDFIRE REGIME AND ENVIRONMENTAL FACTORS

The frequency and severity of wildfires in an area or ecosystem is characterized as a wildfire regime, and nationally consistent data characterizing fire regimes and fuel conditions are frequently used to assess wildfire risk [34]. However, due to influences such as climate change, land use, fire suppression, and human-caused ignitions, fire regimes are changing, indicating a need for novel techniques to forecast future fire potential [35].

Rather than anchor into historical fire regimes, many operational models focus on existing conditions, recent fire history, and environmental factors to calibrate predictions [36]. Relevant environmental factors that can be considered in wildfire risk modeling can include the relative dryness of fuels—which varies throughout the season as well as from season to season [37]. In addition, as the ambient temperature varies by seasonal changes, the convective and radiative heat loss rates, which help to cool down the components, reduce significantly. As such, greater damages will be expected during seasons with higher temperatures. Other factors include but are not limited to Energy Release Component (ERC), Burning Index (BI), and Severe Fire Danger Index (SFDI), among others [38].

4) GRID RESILIENCE

The effects of a wildfire on each component of the power grid depend on various factors. For instance, the heat generated by the fire can increase the surface temperature of the overhead conductors in its vicinity. Beside the damages to the infrastructure such as poles and towers by the fire, or causing conductor sag, annealing, and loss of the tensile strength, this matter can decrease the ampacity of the power line due to the conductor's reduced thermal rating. This, in turn, can influence the optimal power flow of the network and therefore affect the operations of the entire power grid considerably [28], [32]. Moreover, the high temperature caused by the wildfire can have a significant effect on the lifetime of the transformers, battery units, and generation units nearby. Wildfires are characterized in terms of the cause of ignition, their physical properties such as the speed of propagation, the combustible material present, and the effect of weather on the fire. The health condition of each grid component, however, is a major factor to account for. The resilience of each grid component to wildfires can be quantified using a probabilistic modeling approach based on stochastic processes for the occurrence of wildfires during a given period, along with a wide range of fragility models.

Finally, the distance of each component of the power grid from the flaming front is considered as one of the most significant factors for wildfire impact modeling. Obviously, as the distance from the fire increases, the exposure and potential impact on grid components decreases. The distance of each component from the wildfire can be obtained by mapping the wildfire spread path onto the power grid layout. While this distance can be accurately determined, it is worth noting that the wildfire path is stochastic and is not known in advance, hence use of stochastic fire spread models is required to guide risk assessment.

B. RISK MANAGEMENT FRAMEWORK

The defense-in-depth (or deep defense) is a paradigm that has its origins in military strategy, which relies on multiple lines of defense rather than a single frontline. The strategy is focused on creating redundant barriers to impede the advancement of an attacker or a threat to lose momentum over time, so it will create an opportunity window to respond with back-up plans to contain the threat [39]. Outside of military science, this concept has gained significant traction in financial crisis management, enterprise risk management [40], cybersecurity [39], vaccine development [41], and nuclear power plant safety [42], among others. In the context of wildfires, a military tactic that consists of Primary Alternate, Contingency, and Emergency (PACE) plans has been adopted for large fire suppression in the Wildland Urban Interface (WUI). This approach includes building multiple layers of firelines between an active fire front and key communities or infrastructure to be protected during suppression operations, especially when weather condition is unfavorable [43].

With that background, we define a three lines of defense framework for managing the risk of wildfires in electric power infrastructure, as follows. The first line of defense focuses on strategies to prevent wildfires from occurring in the first place. Recognizing that the first line of defense may not always hold, the second line of defense is focused on mitigation strategies and proactive response to minimize hazardous impacts of wildfires on the power system and its surrounding natural and built environment, should a wildfire spark. Finally, if a wildfire sparks and spreads despite all the defensive measures in the first two lines, we need a third line of defense that is focused on resilience-building measures and recovery preparedness so the system can bounce back to its pre-wildfire condition as quickly as possible without suffering devastating losses. Each of these lines plays a distinct role within the utility's wildfire risk governance structure. Figure 2 illustrates the proposed framework and its three lines of defense. Table 1 shows the components of each of these three lines of defense and the articles which have been reviewed in each of these subject areas. As shown, the first line of defense includes prediction of the wildfires, timely detection of the fire-inducing faults in the grid, early detection of the wildfires, effective asset management of grid infrastructure, and effective vegetation management to prevent wildfires. The second line of defense includes the deployment of wildfire simulators to enable proactive responses, preemptive de-energization of the grid as a last resort option, effective wildfire suppression tactics, real-time wildfire monitoring and tracking capabilities, and effective emergency management of the grid operations during wildfires. Finally, the third line of defense includes efficient recovery logistics, energy contingency plans for the post-disaster supply of energy, comprehensive disaster risk financing mechanisms, and community engagement for obtaining buy-in from stakeholders and communities affected by the event. A total of 137 papers within this framework were reviewed, that includes, respectively 47,48,42 articles for the first, second, and third line of defense. The proposed framework is not meant to be comprehensive but is a lens that we use in the following sections to review the most relevant thematic research work and identify the gaps in the literature that can potentially affect the best risk management practices in the power and utilities industry. In addition, the proposed framework can be used as a roadmap for utilities to develop their wildfire risk management strategy.

FIGURE 2. Three lines of defense framework for wildfire risk management in electric power infrastructure.

TABLE 1. List of articles reviewed for three lines of defense subjects.

Line of Defense	Subject	Reviewed Articles
First	Wildfire Prediction	[44-48].
First	Detection of Fire-inducing Faults	[20], [21], [49-64]
First	Early Detection of Wildfires	[65-71]
First	Grid Asset Management	[72-82]
First	Vegetation Management	[13], [83-87]
Second	Wildfire Simulators	[14], [15], [88-97]
Second	Preemptive De-energization	[98-102]
Second	Suppression Tactics	[103-118]
Second	Wildfire Monitoring and Tracking	[119-123]
Second	Grid Operations Management	[28], [124-132]
Third	Recovery Logistics	[133-146]
Third	Energy Contingency Plans	[147-158]
Third	Disaster Risk Financing	[159-166]
Third	Community Engagement	[167-174]

III. FIRST LINE OF DEFENSE: WILDFIRE PREVENTION

An effective wildfire prevention strategy requires the elimination of root causes to the extent possible and prediction of the wildfire events, so appropriate preventive actions can be taken. In this section, we review the research work relevant to wildfire prediction, early detection, fire-causing faults recognition, asset management, and vegetation management.

A. WILDFIRE PREDICTION

Prediction of wildfire spreads regardless of their source is critical for firefighters and utilities to effectively mobilize their resources for emergency response. In this context, researchers in [44] developed a set of logistic regression models to predict the likelihood of ignition occurrence using a dataset consisting of 127,490 ignitions that occurred in a 5-year period. Population density, human accessibility, land cover, and elevation appeared to be significant explanatory variables for the spatial distribution of fire ignitions. Reference [45] proposed a predictive model to map the spatial distribution of the probability of fire occurrence in forest areas. They used a binary logistic regression model consisting of 10 continuous and categorical variables. Reference [46] proposed a neural network-based model for prediction of burned areas in forests. To improve the accuracy of their prediction, a new input structure was used, and Particle Swarm Optimization was adopted to determine the weights of the artificial neural network. Reference [47] developed a model to predict the extent of wildfires using soil moisture and temperature data obtained via remote sensing. Reference [48] presented the model implementation of a fire risk mapping system based on numerical weather prediction and space information on live fuel moisture content. The model incorporates land cover classification and automatic estimation of the live fuel moisture content based on moderate resolution imaging spectroradiometer (MODIS) vegetation indices.

While we found several research work on wildfire prediction, our systematic review of the literature shows that there is a gap in published research work on wildfire prediction when the root cause of the fire is linked to the power grid infrastructure—despite the fact that some of the most devastating wildfires were sparked by power grids.

B. TIMELY DETECTION OF FIRE-INDUCING FAULTS

Timely detection of faults capable of causing fires, voltage reduction, and limiting the fault current is ideally the best solution to prevent wildfires in the interaction of the power system with its surrounding environment. However, all these steps must be adequately fast to prevent wildfires from starting in the first place. It is known that low impedance faults with high amplitudes can initiate wildfires. However, they can be effectively detected by fuses and relays or be mitigated by fast circuit breakers and fault current limiters (FCLs). On the other hand, high-impedance faults due to their low current amplitude are extremely challenging to be detected with existing technologies, so they are a major driver of devastating large-scale wildfires caused by power grids [20], [21], [49].

In this context, [50] assessed four relays for the detection of high-impedance faults in fallen distribution conductors using digital and analog techniques. One electromechanical relay was selected, and development and testing of its prototype for installation in six distribution feeders in the Pennsylvania Power and Light network were presented. Reference [51] proposed the design and development of a microcomputer-based high-impedance fault detection system by utilizing high-frequency changes in current. The same authors analyzed the characteristics of arc-generated burst noise signals at lower frequencies (below 60 Hz) to study their behavior during faulted and normal conditions in [52]. Their study revealed that by monitoring off-harmonic frequencies, more sensitive detection of high-impedance faults compared to conventional overcurrent protection could be realized. In [53], an arcing fault detection method using low-frequency current components was proposed. Two frequencies (i.e., 180 Hz and 210 Hz) were selected to investigate the magnitude variations associated with arcing faults at these frequencies. An adaptive, hierarchical algorithm for detection of high-impedance arcing faults on distribution feeders was introduced, and performance evaluation using recorded field data was presented. Reference [54] proposed a Kalman-filtering-based approach for analysis of signals generated by high-impedance faults. The proposed approach considers the time-varying nature of the fundamental and harmonic components. This study showed that the changes in low-order odd harmonics are valuable features to be used in the detection of high-impedance faults. Reference [55] proposed a neural network model for the detection of high-impedance faults in abnormal events on electric power distribution feeders. This study demonstrated the capability of neural networks to be applied for this class of problems. In [56], a relay for the detection of high-impedance faults in downed conductors was presented. This study showed the usefulness of third-harmonic current magnitude and the phase relation to the system voltage in high-impedance fault detection. Reference [57] proposed an adaptive method for detection of both low- and high- impedance faults using characteristics of the fault current in distribution feeders. In addition, the logic circuit required for implementing the proposed detection method was presented. Reference [58] devised a high-voltage laboratory setup as a source of fault current signal to investigate the high-impedance faults. In that study, an algorithm that compares the positive and negative current peaks in successive cycles measures the flicker in the current signal. It also compares the positive peak to the negative peak for each cycle to calculate the asymmetry of the current. The obtained fault current flicker and half-cycle asymmetry are used to detect the arcing in downed wires. Reference [59] proposed an approach for high-impedance fault detection on distribution feeders by balancing fault detection with fault discrimination to enable a more practical detection method for high-impedance faults in commercial systems. Multiple algorithms to detect different types of faults in conjunction with the use of an expert decision-maker were discussed in that paper. Reference [60] proposed a method to identify high-impedance faults on distribution feeders using wavelet analysis filter banks (WAFB). Electromagnetic Transients

Program (EMTP) was used for simulation of high-impedance faults and capacitor bank switching operations. The results indicate that WAFB can effectively discriminate current signals of high-impedance faults and capacitor bank switching operations. Reference [61] presented the performance evaluation results of high-impedance fault detection relays based on field experience. The relays were developed in Texas A&M University, commercialized by General Electric Company, and field-tested by Potomac Electric Power Company on 280 operating feeders for a period of two years. The results show that while 96 percent of the downed conductor incidents were detected, due to the relay's bias toward secure operation, only 58 percent of incidents were reported. Reference [62] incorporated a factor for environmental conditions to estimate the leakage current in the power distribution system under various weather conditions. A finite element modeling approach to calculate the power losses considering mechanical characteristics of tree tissues was presented and experimental analysis was performed to validate the results. In another study, [63] proposed a framework for monitoring tree-related high-impedance faults in medium-voltage networks. Regression analysis was performed to find the correlation between spectral indices and electrical conductivity of trees measured through experiment. The regression model in conjunction with finite element analysis on tree tissues was used to estimate tree-related high-impedance faults current in the network. Most recently, [64] presented an algorithm for detecting RMS current volatility in tree-related high-impedance faults. To identify the stage of ignition development, the physical ignition dynamics of a range of tree species under a phase-to-phase fault scenario was analyzed in that study.

We found that state of the art in the literature and the current best industry practice on fire-causing faults, particularly high-impedance faults that are responsible for major grid-induced wildfires, are focused on *detection* of these faults once they occur. However, there is a gap in research related to the *prediction* of these faults in the system to enable grid operators to act proactively and prevent them from occurring in the first place.

C. EARLY DETECTION OF WILDFIRES

Early detection of wildfires is of crucial importance in controlling the fire and minimizing the damage. In this context, [65] developed an algorithm that combines MODIS fire detections with lightning detections to identify lightning fires in the conterminous United States. Considering the spatiotemporal lag between the lightning strike and fire ignition, the proposed algorithm searches for spatiotemporal conjunctions of MODIS fire clusters and lightning strikes detected by the National Lightning Detection Network. The authors indicate that while this algorithm can be used for the detection of broad-scale spatial patterns of lightning fires, it has limitations in the detection of smaller fires.

Early detection of wildfires is also crucial in terms of providing a wider window of opportunity for an effective and timely response to wildfires. In this context, [66] presented an image processing model to identify wildfire smoke from heterogeneous sequences taken from long distance. Due to challenges with the collection of frame sequences, a virtual environment for the computation of synthetic wildfire smoke sequences was proposed in this study. An automatic-video-based approach for fire detection using spatiotemporal flame modeling and dynamic texture analysis was proposed in [67]. The goal was to develop a model for early-warning fire monitoring systems. Reference [68] proposed a framework for prototyping rapidly deployable mobile units for autonomous, real-time wildfire monitoring and georeferencing. Reference [69] described the development process of a thermal infrared camera with the uncooled microbolometer array for a 50-kg class satellite to be used for small wildfire detection. Reference [70] proposed a framework for wildfire detection using transfer learning on augmented datasets. An open-source dataset featuring images from over 35 wildfires was used, and the model was tested under a tenfold cross-validation procedure. Aerial patrol may also be used to improve the chance of detecting wildland fires at earlier stages. Reference [71] presented a three-step process to spatially quantify the risk of not patrolling a specified area for the detection of wildland fires in Canada. The proposed process produced a daily updated fine-scale risk index map that can be used to design optimal aerial patrol routes.

Our review of the early detection techniques shows that the existing literature is mainly focused on algorithmic and technological aspects of wildfire detection, yet there is a gap in using risk-based approaches that prioritize the exposure level and criticality of each wildfire-prone area to be incorporated in the detection learning algorithms.

D. GRID ASSET MANAGEMENT

Power grids can ignite wildfires and leave a devastating impact on communities, the environment, and the grid itself. There are various types of fire-causing failure modes and power system faults that can be prevented by an efficient asset management and preventive maintenance program. A comprehensive report by the Australian Powerline Bushfire Safety Taskforce revealed that since 1977, a disproportionate number of catastrophic wildfires, with major loss of life and property, have been caused by power grids [72]. The newest litigated example of such events includes the most devastating wildfire in California history, the Camp Fire in 2018 [4]. As investigated in [72], at least three types of faults in the power system have been responsible for major wildfires during the past decades, as follows: a) when a transmission line falls to the ground, an electric arc can ignite surrounding vegetation or other live fuels; b) when two energized transmission lines clash, the released molted metal particles that fall on the surrounding vegetations can cause an ignition; and c) an electric current that flows through vegetations, animals, or other live fuels can cause ignition, and thus start a major wildfire. Aside from faults that can occur during normal operations of the power networks, there have been cases of wildfires due to the explosion of transformers, the collapse of poles, fallen trees, and fallen conductors, which have been investigated in the literature.

Explosion of transformers is a well-known failure mode in electric power assets that, depending on their surrounding environment, can ignite a wildfire. In this context, [73] studied fire susceptibility and reliability of cast-coil transformers and found them to be more reliable compared to liquid-filled units. Reference [74] patented a method and device for the prevention of explosion and fire in electrical transformers. It requires modifications to the components of the transformers to protect both the transformer and the on-load tap changer from loss and to minimize the damage due to short-circuits. In another study [75], the flammability characteristics of liquid-filled and dry-type transformer technologies were compared and investigated. Reference [76] presented the results of two tests that were conducted in 2002 and 2004 under the worst-case conditions to study transformer explosion and fire prevention. Low impedance faults leading to electrical arcs in the transformer tank dielectric oil were created, and the correlation between arc energy and dynamic pressure was analyzed. Reference [77] developed numerical simulations on a 200 MVA transformer to study the preventive measures to protect oil-filled transformers against explosions.

Various faults in transmission and distribution systems have been reported in the literature, technical reports, and litigation processes to be responsible for a significant number of wildfires. In [78], as a potential source of wildfires caused by the power system in high wind conditions, the flight paths of metal particles and embers produced by transmission lines were investigated. Reference [79] presented an investigation on conductor motion of overhead distribution system due to short-circuit forces. Reference [80] studied the 2007 wildfires driven by winds and attributed to power network in Southern California. The study indicated that the existing regulations on extreme wind events were not adequate to prevent reoccurrence or worsening of power line conflagration in the future. Reference [81] reviewed the failure mechanisms in distribution feeders that can lead to ignitions. Case studies of faults that can lead to wildfires along with prevention methods were discussed in that study as well. Reference [82] addressed the fire mechanism in wood poles of medium voltage distribution lines. The leakage current in wetted phase insulators that can flow through the wood poles was studied as a failure mechanism to ignite the fire under certain conditions. In addition, a risk assessment of different risk mitigation options was presented.

Our systematic review of the literature related to grid asset management reveals that despite extensive research work on this topic, particularly on transformers, there is a gap in research work when it relates to preventive maintenance and the role that it can play to prevent wildfires from taking place due to aging power infrastructure and lack of appropriate maintenance of the fire-causing components of the grid.

E. VEGETATION MANAGEMENT

The risk of igniting a wildfire by the power grid increases as the clear distance between conductors and trees decreases. Vegetation management is a critical component of rights-of-way (ROW) maintenance to prevent hazardous impacts of tree and vegetation contact with power lines and electric power infrastructure. ROW maintenance refers to the removal or trimming of trees and plants within an unsafe distance from power lines and utility equipment [83]. An efficient utility arboriculture and vegetation management plays a crucial role in reducing the risk of wildfires due to the interaction of power system infrastructure with their surrounding vegetation.

In this context, [84] introduced a mathematical optimization model for line strike risk rating considering tree height, tree density, line height, and clear width variables. The model shows that there is a point of diminishing return in the probability of line strike as clear width increases. In addition, it was shown that the main source of tree conflicts is from trees outside the maintained ROW. Reference [85] proposed a decision support tool for ROW maintenance to mitigate the risk of transmission line contact with fallen trees. This study indicates that the total height, height-to-diameter ratio, and live crown ratio of trees are the key features to trees with a high probability of tree fall. Reference [86] introduced a model based on a spatial fuzzy influence diagram for risk rating tree-related outages in the grid. The model incorporates topological relationship and the attribute dependency of the objects. The output from the model can create a vulnerability map of electrical networks to support vegetation management and maintenance planning. Reference [87] presented the results of a case study on wildfire risk reduction by automated monitoring of vegetation interference with power lines. An approach based on point cloud analysis in conjunction with cable mechanics was adopted to estimate the location of power lines in space and the vegetation in their vicinity. The proposed model automates the monitoring of vegetation growth and quantifies the volume of vegetation to be removed to reduce the risk of wildfires. Reference [13] provided a review of prescribed burning effectiveness for reduction of wildfire hazards. This study indicates that the best results of prescribed fire programs can be realized in heterogeneous landscapes and in geographical areas with a low likelihood of extreme weather conditions.

IV. SECOND LINE OF DEFENSE: WILDFIRE RISK MITIGATION AND PROACTIVE RESPONSE

Forward-looking, risk-informed wildfire mitigation and proactive response are of crucial importance to efficiently allocate the resources to control the extent of the damage. In this section, we review the research work on wildfire simulators, preemptive de-energization strategies, suppression tactics, wildfire monitoring systems, and emergency operations management in power grids during wildfire events.

A. WILDFIRE SIMULATORS

Wildfire simulation models can help to better understand the dynamics of wildfires and forecasting their propagation—which is extremely important in strategizing an effective disaster response. Some models are designed for or better suited to use in pre-fire assessment and planning [88] and others for real-time incident decision support [89]. In this context, [14] analyzed and compared the performance of 23 simulators applicable in forecasting wildfire propagations. In their analysis, FARSITE simulator developed by U.S. Forest Service [90] outperformed other simulation models. FARSITE is capable of computationally simulating wildfire propagation and analyzing its behavior for long periods under heterogeneous terrain, fuels, and weather conditions. According to Rocky Mountain Research Station's Fire, Fuel, and Smoke Science Program of the U.S. Forest Service, FARSITE has been merged into a more comprehensive wildfire analysis product called FlamMap [91]. FlamMap is capable of simulating potential fire behavior characteristics (such as spread rate, flame length, and fireline intensity), fire propagation, and conditional burn probabilities considering environmental conditions such as weather and fuel moisture [92]. FSPro is another fire simulator embedded within the Wildland Fire Decision Support System (WFDSS) [93] widely used for significant incidents in the USA. It generates fire spread probability maps by simulating fire spread from a known ignition location or fire perimeter under thousands of representative fire-weather scenarios based on historical weather station data. FSPro results are provided to fire managers through WFDSS to support real time fire suppression operations. There is numerous wildfire simulation modeling research work in the literature, addressing various aspects of this phenomenon. An example of more recent studies can be found in [15], [94]–[97].

B. PREEMPTIVE DE-ENERGIZATION

With the increasing threat of wildfires from power lines that may fail and cause wildfires, proactive shut-off of such lines has recently been used at the eleventh hour to reduce the risk of grid-induced wildfires. This practice is referred to as *preemptive de-energization*, also known as Public Safety Power Shutoff (PSPS). Despite the benefit of this practice in terms of minimizing the risk of grid-induced wildfires, it can pose its own risks and hardship, especially to vulnerable communities and individuals, essential facilities, and business continuity. Therefore, it only should be used as an option of last resort, considering its tradeoff and consequences. While there is no documented history of starting this practice by utilities, but during the 2007 wildfire season in California, SDG&E exercised this practice, and a year later requested the California Public Utilities Commission (CPUC) for authority to use PSPS as a preventive measure. That eventually led to California Public Utilities Code Sections 451 and 399.2(a) in 2012, which gave utilities preemptive de-energization authority to protect public safety [98]. Authors in [99] projected a significant increase in person-days of de-energization per year, based on recent historical climate data and publicly stated de-energization policies in California, particularly during the autumn season when vegetation is drier. Given the increasing exposure of the population to de-energization and its socioeconomic impacts, especially on vulnerable communities, more sophisticated de-energization strategies need to be developed. Among limited research work in this context, [100] developed a cost-effective solution to de-energize low-voltage overhead lines to clear high-impedance ground faults. The proposed solution is based on a metal hook under the conductors, connected to the poles and neutral wire. Reference [101] investigated the switching shift angle effect in the de-energization process in the final ferroresonance state. It was shown that incorporation of voltage shift angle could significantly increase the accuracy of parametric analysis of ferroresonance. Reference [102] proposed a power shut-off optimization model based on mixed-integer programming to support operational decision making of the grid in relation to wildfire risk. The proposed model finds an equilibrium between the maximum amount of power that can be delivered and the minimum risk of grid-induced wildfires ignitions by optimal de-energization of the grid.

C. SUPPRESSION TACTICS

Suppression of wildfires requires well-thought tactics and efficient operations management strategies. In 1996, the National Wildfire Coordinating Group published the Wildland Fire Suppression Tactics Reference Guide [103]. This publication provides tactical information on wildland fire fuels, fire behavior, and suppression by geographical areas of the United States. References [104] and [105] provided a review of wildfire suppression effectiveness at scales ranging from flames, firelines, whole incidents, and landscapes, identifying a range of knowledge gaps and data needs. Reference [106] proposed a preliminary domain theory for robot-assisted wildland firefighting. They assessed the effectiveness of Lockheed Martin's medium-sized ground vehicle, Squad Mission Support System (SMSS), considering six different functionalities of ground robots in wildland firefighting. Reference [107] developed a model predictive control (MPC) motion planning scheme for automated wildfire suppression. The proposed system is comprised of unmanned aerial and ground vehicles in a cooperative framework to suppress the wildfires in an optimal manner. Simulation and optimization models have also been developed in the past to distribute fireline construction and structure protection efforts to minimize fire size, or the expected property, infrastructure and natural resource damages (e.g., [108]–[111]).

A key bottleneck to operationalizing many of these proposed optimal control models is limited descriptive analytics of suppression operations and effectiveness [112], with corresponding limited success in defining performance measures of tactical efforts [113], [114]. Due in part to these deficiencies, some analysts have avoided prescriptive models and instead provided predictive analytics regarding control opportunities and firefighter safety to support strategic and tactical decision making [115]–[117]. In a more recent descriptive study, [118] proposed a temporal framework for large-scale wildfire suppression in practice. A qualitative descriptive analysis on suppression activities of 10 large wildfires in Victoria, Australia, was carried out, and the effectiveness of current suppression practices was assessed.

Our analysis of the literature shows that there is a limited body of research focused on efficient suppression tactics for wildfires, and even less work focused on wildfires that are caused by power grids.

D. WILDFIRE MONITORING AND TRACKING

Real-time monitoring and tracking of wildfire spread is an important tool for effective response and management of firefighting operations. In this context, [119] proposed a wireless sensor network deployed at ground level for remote sensing of local wildfire spreads. Using sensed wind speed information, the proposed system determines the spreading condition of the wildfire. In another study [120], a method to improve subpixel signal detection in airborne or orbital image sequences for wildfire tracking was proposed. This method estimates the motion between successive frames and monitors candidate detections over time. Reference [121] introduced a Kalman filter-based method for large-scale wildfire monitoring by a system of unmanned aerial vehicles that collects wildfire measurements online. A scalar field wildfire model was developed, and a Kalman filter was adopted to estimate the model parameters. Reference [122] proposed a distributed control framework for unmanned aerial vehicles used in wildfire monitoring. More recently, [123] presented a video-based smoke detection algorithm for wildfire monitoring cameras. The wildfire camera placement problem for minimizing the fire risk in an area was formulated as an integer program, and the model was validated through simulation of wildfire camera deployment in Southern California.

E. GRID OPERATIONS MANAGEMENT

Wildfires can pose a significant risk to power grid infrastructure and its operational capabilities. There is several research work in the literature investigating wildfire impacts on power systems over the past decade. Reference [124] studied the impacts of fire on the electric distribution network of a virtual city. Reference [125] proposed a model to estimate the temperature rise in the overhead line conductors during the wildfires. Reference [28] introduced a vulnerability assessment model for power systems during progressing wildfires. The model calculates the dynamic rating of the exposed lines considering the heat released by a progressing wildfire. Reference [126] presented a two-stage stochastic nonlinear optimization model for optimal operation of the power grid during wildfires. Reference [127] evaluated the flashover performance of insulators in high voltage transmission lines during the suppression of wildfires. Their study revealed that standard insulator dimensions used in EHV and UHV transmission lines might not be sufficient to meet the required performance in fire-prone areas. Reference [128] proposed a stochastic program to enhance the resilience of a power distribution system against wildfires. Dynamic overhead line rating, solar radiation, wind speed, wind direction, and generated power by distributed units were incorporated in modeling the impact of wildfires on conductor temperature and flowing current. Reference [129] studied the impacts of wildfires on reliability of transmission lines to be used as an input to maintenance program. Reference [130] designed an early warning system for power grids based on prediction of wildfire and transmission line outages. Reference [131] presented a risk assessment of transmission lines tripping fault induced by wildfires. More recently, [132] studied the impact of wildfires and beneficial electrification on electricity rates in California.

Our analysis of state of the art on grid operations management during wildfires shows that this area of research has received more attention by power systems engineering community compared to other areas in the literature.

V. THIRD LINE OF DEFENSE: RECOVERY PREPAREDNESS

No matter how efficient the first and second lines of defense are in managing the risk of wildfire occurrence and its subsequent impacts, a strong third line of defense is equally important to improve the resilience of the system and facilitate an efficient recovery process should an inevitable wildfire strike. In this section, we review the relevant research work on recovery logistics, energy contingency planning during disaster recovery, existing disaster risk financing mechanisms, and community engagement in the disaster recovery process.

A. RECOVERY LOGISTICS

Logistics preparedness is a key component of the disaster risk management process. The six elements of logistics, including personnel, equipment, transportation, inventory management, planning/policies/procedures, as well as information and communication technology [133], need to be addressed by utilities to streamline an efficient recovery of the system from wildfires. It requires a proactive assessment of wildfire impacts in various scenarios, proactive recovery planning for mobilization of resources to affected areas, and maintaining an adequate level of strategic stockpiles of critical equipment and grid components. In this context, [134] presented a wildfire occurrence risk assessment in high-voltage power line corridors using multi-source data and remote-sensing. Both natural and human causes were considered in the model, and a case study in the Hubei Province of China was presented. Reference [135] addressed the strategic planning problem of the Power System Stochastic Storage Problem (PSSSP) on optimal stockpiling of power system supplies for disaster recovery. The proposed model maximizes the amount of power served during the disaster recovery phase by optimal distribution of power system repair components in the affected areas. A mixed-integer programming and a general column-generation approach were presented, and their computational performance were compared. Reference [136] provided a literature survey on applications of operations research in disaster operations management and emergency logistics that can also be applied to wildfire recovery in power grids. References [137]–[143] proposed a series of models for recovery logistics of power grids during hurricanes that can be applied to other extreme events such as wildfires. Reference [144] proposed a co-optimization model for optimal dispatching of repair crew and mobile power sources to enhance the resilience of post-disaster recovery logistics of distribution networks. The model was formulated as a nonconvex mixed-integer nonlinear program and then transformed into a mixed-integer linear program to improve its computational efficiency. Reference [145] presented a framework to support post-disaster communications by integrating microgrids and cellular networks. In the proposed model, microgrids power the critical infrastructure and cellular network base stations in select disaster areas to facilitate wireless mesh networks and local edge computing for post-disaster emergency communications. Reference [146] proposed a pre-disaster preparation plan for a multi-commodity logistics of distribution networks. A two-stage stochastic program with recourse was adopted to determine the optimal number and location of depots, repair crews, and equipment, considering the uncertainty associated with the extent of damage in the distribution network.

Our review shows that while there is a wide range of research work on recovery logistics of power grids in disasters, there is very limited research work dedicated to recovery logistics of the power grid in the face of wildfires.

B. ENERGY CONTINGENCY PLANS

Recovering from wildfires can take from a few days to several months, depending on the extent of damage to the infrastructure. A proper wildfire risk management by electric utilities requires a contingency plan to ensure the supply of electricity to critical facilities and vulnerable communities after the disaster. A long-term solution involves the deployment of microgrids to improve the resilience of the system to disasters [147]. An emergency response can include the deployment of mobile emergency generators [148] and power storage units [149] in disaster areas, among others.

In this context, [150] investigated the problem of integrating distributed generators (DGs) and proposed a vulnerability index based on loss of load to measure the adverse consequences of disaster-induced outages on microgrid security. Reference [151] proposed a multi-objective optimization model to evaluate the resilience of a power network and its coupled microgrids. A resilience index was adopted to incorporate the capacity of the power system to self-recover from an unanticipated catastrophic event. Reference [149] developed a simulation and modeling tool to demonstrate the use of flywheel energy storage (FES) units in securing critical loads during a network outage in a facility microgrid. Reference [148] introduced a model for pre-positioning and real-time allocation of mobile emergency generators (MEGs) as distributed generators to restore critical loads by microgrid formation to facilitate a resilient response to natural disasters. The proposed model minimizes the expected duration of outages by taking into accounts the load size and priority. The problem was formulated as a scenario-based two-stage stochastic program that incorporates scenarios on damages to the distribution system and the damage and congestion in the road network. Reference [152] presented an approach to assess the availability of microgrids during and in the aftermath of natural disasters. Distributed generators and local energy storage as two critical groups of components of power supply in microgrids were considered. Markov state-space model was adopted to perform microgrid availability assessment. The availability results were calculated using minimal cut set approximations and validated with Monte Carlo simulations. Reference [153] introduced a new class of microgrids, called provisional microgrids, which share similar characteristics as conventional microgrids, but rely on one or more connected microgrids for islanding purposes. This class of microgrids enables rapid deployment of renewable generation units in the network and prevents underutilization of distributed energy resources in the system. In another study, [154] proposed a resiliency-oriented microgrid optimal scheduling model, aiming to minimize the load curtailment by efficient scheduling of available resources when power supply from the main grid is interrupted for a prolonged period. The unit commitment solution, energy storage schedule, and adjustable load schedules were used to assess microgrid capability in supplying local loads during grid interruption. The results demonstrate that the proposed model guarantees operational robustness in the face of grid uncertainty, is economically viable and facilitates a quick islanding capability with minimum load curtailment and consumer inconvenience. Reference [155] proposed an operational mechanism for restoration of critical loads from power outages due to faults caused by natural disasters. The mechanism is based on the formation of multiple microgrids energized by distributed generators and by utilizing automatic remotely controlled switches in the system. A distributed multiagent coordination model was introduced to facilitate the post-disaster autonomous communication requirements. The smaller microgrids can be connected to form larger microgrids during the restoration of the main grid. Reference [156] developed a two-stage stochastic program for optimal microgrid operations considering the impacts of natural disasters and by incorporating the uncertainties associated with electric vehicles, wind energy, and market prices. For higher accuracy, the AC network constraints were formulated in the model, and it was linearized to improve its computational efficiency. The effectiveness of the proposed model was demonstrated using a large-scale microgrid testbed. Reference [157] adopted Monte Carlo simulation modeling to assess the impacts of microgrids on the resilience of power systems to extreme events. A comprehensive review of strategies to use microgrids for resilience enhancement of power systems can be found in [158].

Similar to the previous subsection, our review of the literature reveals that while there is an extended body of research on energy contingency planning in the face of disasters in general, there is a wide gap in the existing research work to investigate this issue, specifically from wildfire lens, given its idiosyncratic characteristics.

C. DISASTER RISK FINANCING

The economic and financial losses caused by wildfires can reach into several billion dollars, threatening financial health and solvency of the utilities. In addition, they can significantly hinder the ability of utilities to recover, which can lead to dire consequences for shareholders, ratepayers, and policymakers [159]. Developing and implementing a tailored disaster risk financing strategy will increase the ability of impacted parties to respond more quickly and resiliently to disasters [160]. There is a wide spectrum of disaster risk financing mechanisms that can facilitate a utility's ability to access capital to cover the risk of wildfires. These mechanisms are not necessarily mutually exclusive and should be bundled together to ensure required coverage for various wildfire scenarios, as will be described in the following subsections [159]. It is worth noting that our analysis shows a wide gap in the literature to provide innovative actuarial analysis and investigating the effectiveness of various disaster risk financing mechanisms in power grid infrastructure in the face of wildfires.

1) FUNDED SELF-INSURANCE

In this approach, a utility retains all or a fraction of the risk by setting aside adequately funded reserves to cover unexpected losses and restoration costs. For instance, a utility can create a wildfire reserve account that collects funding over time until it reaches a pre-determined account balance. This account should be designed to return to ratepayers the collected amount that exceeds the required wildfire reserve level. While this mechanism can reduce the post-disaster financial burden to utilities and ratepayers, it will take time to build such reserve, and it may face regulatory challenges in some jurisdictions [159]. More details on economic theory and optimal level of self-insurance against natural disasters can be found in [161].

2) COMMERCIAL INSURANCE

Commercial insurance has been traditionally used by utilities to cover the wildfire risk. Depending on the jurisdiction, the cost of insurance coverage is distributed to the ratepayers' bill as wildfire premiums. However, recent increasing wildfire events have made this mechanism significantly more expensive for some utilities because of their increased risk exposure due to climate change [159].

3) CATASTROPHE BONDS

Catastrophe bonds (also known as CAT bonds) are a class of disaster risk financing mechanisms that can be used for transferring the disaster (wildfire) risk from sponsors (utilities) to investors. The sponsors can form a Special Purpose Vehicle (SPV) financial entity to collect principal from investors and make premium payments in return. The premium spread depends on the expected loss for investors. If a *triggering event* (wildfire in this case) with previously defined specifications in a defined timeframe occurs, the principal is given to the sponsor (utility in this case), so they can cover their loss; otherwise, the principal along with return on investment is returned to the investors [159]. More details on CAT bonds can be found in [162].

4) CAPTIVES

As an alternative insurance mechanism, captives are a class of insurance firms that is established by one or a group of companies to insure the owners (the parent companies). One or a group of utilities can form a captive insurance entity that collects insurance premiums, issues wildfire policies, and pay out claims—like a traditional insurance company, but only to its utility parent companies. This mechanism is especially useful to cover uninsurable or difficult-to-insure risks due to increased exposure, such as post-2017 and 2018 wildfires in California. In addition, it can be beneficial to utilities in hard insurance markets to reduce the risk transfer costs [159]. More details on optimal risk financing through captives can be found in [163].

5) RISK POOL

Risk pooling is a disaster risk financing mechanism for sharing risk among a group of participants. The participants combine their financial resources to cover losses whenever a pool participant experiences a loss that is covered in the pool. This mechanism is particularly useful when commercial insurance is impossible, difficult, or expensive to obtain, and there is an adequate number of participants that can form a stable risk-sharing pool [159]. In the case of wildfires, particularly in wildfire-prone areas with increased exposure, such as California, where there are several utilities servicing the area, risk pooling can play a crucial role in managing the financial risk of wildfires. More details on disaster risk financing through risk pooling can be found in [164].

6) RECOVERY BONDS

Recovery bonds are a class of post-disaster risk financing mechanisms (as opposed to pre-disaster financing mechanisms described earlier) that can be used for acquiring capital to pay for unexpected damages from disasters. Depending on their jurisdiction, utilities can issue recovery bonds through various mechanisms, so they can access a larger amount of capital to pay for reconstruction expenses and other liabilities. In return, the investors will receive a return on their investment based on coupon rates on the bonds. This mechanism has been used by utilities for financing hurricane damages [165] and has recently been legislated for covering the utilities' liabilities due to wildfire events in California [166].

D. COMMUNITY ENGAGEMENT

The resilience of impacted communities and their engagement in the recovery process is a vital resource to increase wildfire disaster readiness and successful recovery. Reference [167] describes five steps as part of an adaptive capacity roadmap to enhance the community resilience to disasters, as follows: a) communities must reduce risk, develop equitable economic resources, and pay attention to their vulnerability; b) local communities must be engaged in every step of the mitigation process; c) established organizational networks and relationships with communities are crucial to the rapid mobilization of resources to people affected by the disaster; d) interventions are necessary to boost and protect social supports in the aftermath of a disaster; and e) communities must practice flexibility and build effective and trusted information and communication resources in the face of disasters. Therefore, utilities and local governments should facilitate community engagement on an ongoing basis to obtain their buy-ins and ensure a smooth recovery process from potential wildfires in the future. In this context, various studies on the importance of social capital and community engagement in the recovery process for floods [168], earthquakes [169], hurricanes [170], and wildfires [171]–[173] are presented in the literature. A systematic literature review on community engagement for disaster preparedness can be found in [174].

VI. CONCLUSION AND FUTURE WORK

We introduced a 3LD framework for wildfire risk management in power grids and used it as a lens to provide a thematic review of the literature on this topic. The 3LD framework as a theme provides an overarching perspective on advancements and gaps in the literature on a wide range of solutions that are needed to manage the risk and resilience of power systems before, during, and after a wildfire strike. We reviewed the state of the art on research work related to wildfire prediction, detection of fire-causing faults in the grid, early detection of wildfires, grid asset management, vegetation management, wildfire simulators, preemptive de-energization, suppression tactics, wildfire monitoring, grid operations management during wildfires, recovery logistics, energy contingency planning, disaster risk financing, and community engagement in the recovery process. Our analysis revealed that while the literature, to a large extent, stands comprehensive when it comes to disaster risk management in electric power grids, there is a wide gap in the literature to investigate the issue from a wildfire perspective. On the other hand, while there is a relatively comprehensive body of research on various aspects of wildfire risk management in general, there is a gap in the literature to address the issue from a power grid perspective. Given the emerging wildfire risk landscape—due to climate change—and the increasing complexity of power systems—due to demand, supply uncertainties—this subject deserves a collaborative, comprehensive and multidisciplinary approach by the research community to address this challenge. We also found that existing research work is primarily focused on reactive approaches after the event runs its course; however, to a large extent, it falls short of providing proactive solutions to reduce the risk and prevent the wildfires in the first place, particularly its ignition by power infrastructure, when there is a restrain on existing resources and on conditions of the aging infrastructure assets.

Wildfire risk is an old problem with a new level of intensity and consequences to the human life, nature, and the built environment. It requires to revisit old solutions in order to develop new approaches to minimize its impacts especially when it relates to the resilience, safety, and security of the power system infrastructure. Considering the devastating impacts of recent wildfires on the society, the environment, and the economy, as well as existing gaps in the literature and industry practices, a new level of investments by government and industry is highly needed to fuel the research and development in various aspects of this research thrust.

In our future work, we intend to investigate the operational risk that is defined as “the risk of direct and indirect loss resulting from inadequate or failed internal processes, people and systems or from external events” in the electric power infrastructure in the face of wildfires. We aim to develop a proof-of-concept for a disaster operating system (Disaster OS), to integrate various aspects of analytical requirements for wildfire risk management to be used for real-time management of the grid before, during, and in the aftermath of the wildfires.

DISCLAIMER

The findings and conclusions in this paper are those of the author(s) and should not be construed to represent any official USDA or U.S. Government determination or policy.

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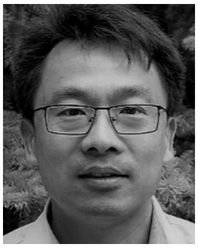
ALI ARAB (Senior Member, IEEE) received the Ph.D. degree in industrial engineering from the University of Houston, Houston, TX, USA, in 2015. He was the Data and Analytics Manager of Protiviti, New York, NY, USA. He is currently an Assistant Research Professor of electrical and computer engineering with the University of Denver, Denver, CO, USA, and a Financial Sector Consultant with the World Bank, Washington, DC, USA. His research interests include smart grid resilience, artificial intelligence, decarbonization, and climate finance.

AMIN KHODAEI (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the Illinois Institute of Technology. He is currently a Professor of electrical and computer engineering with the University of Denver. He has authored/coauthored more than 180 peer-reviewed technical articles on various topics in power systems operation, planning, and economics. His particular expertise is on the design of the grid of the future in the era of distributed resources by investigating the role of microgrids, DERs, EVs, and other emerging technologies.

ROZHIN ESKANDARPOUR (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the University of Denver. She is currently a Senior Research Associate with the Electrical and Computer Engineering Department, University of Denver. Her expertise spans the areas of quantum computing applications in smart grids and improving power system resilience using artificial intelligence.

MATTHEW P. THOMPSON received the B.S. degree in systems engineering from the University of Virginia, Charlottesville, in 2001, the M.S. degree in industrial engineering and operations research from the University of California at Berkeley, Berkeley, in 2002, and the M.S. degree in forest management and the Ph.D. degree in forest engineering from Oregon State University, Corvallis, in 2008 and 2009, respectively. Since 2009, he has been a Research Forester in the Human Dimensions Program of the Rocky Mountain Research Station, USDA Forest Service, Fort Collins, CO. He co-leads the Wildfire Risk Management Science Team and has published more than 75 articles. His research interests include risk and decision analysis, analytics, operations research, and wildfire management. In 2016, he received the Presidential Early Career Award for Scientists and Engineers.



YU WEI received the B.A. degree in forest economics and management from Hebei Agriculture University, China, in 1994, the M.A. degree in forest economics and management from Beijing Forest University, China, in 1997, and the M.S. degree in computer and information science and the Ph.D. degree in natural resource management from the University of Minnesota, in 2003 and 2004, respectively. He is currently a Professor with Colorado State University, Fort Collins, CO, USA. His research interests include forest systems analysis, wildland fire decision support, operations research, GIS, and machine learning.

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