Power System Wildfire Risks and Potential Solutions: A Literature Review & Proposed Metric

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National Renewable Energy Laboratory

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-80746
June 2023

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Suggested Citation

Panossian, Nadia, and Tarek Elgindy. 2023. *Power System Wildfire Risks and Potential Solutions: A Literature Review & Proposed Metric*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-80746. https://www.nrel.gov/docs/fy23osti/80746.pdf.

Contract No. DE-AC36-08GO28308

Technical Report
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June 2023

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Golden, CO 80401
303-275-3000 • www.nrel.gov

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List of Acronyms

AVHRR	Advanced Very High Resolution Radiometer
FIRMS	Fire Information for Resource Management System
FPI	Fire Potential Index
HIF	High Impedance Fault
MODIS	Moderate Resolution Imaging Spectrometer
NFDRS	National Fire Danger Rating System
NIFC	National Interagency Fire Center
NPS	National Park Service
NWCG	National Wildfire Coordinating Group
PSPS	Public Safety Power Shutoffs
PSS	Power Safety Shutoffs
TSO	Transmission System Operator
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VIIRS	Visible Infrared Imaging Radiometer Suite

Executive Summary

Several fire risk evaluation, fire tracking, and fire response resources are available. The risk metrics and fire response programs are sometimes modified to include a power system context. The risk metrics often evaluate the risk of fires causing power system faults or outages, especially on transmission systems. The response programs are modified to ensure the safety of power system equipment and first responders as well as to coordinate power system outages to both ensure safety during an active fire and prevent fire ignition during high-risk periods. Although some aspects of wildfire responses have been adapted to include power system concerns, adaptations to power system operations and maintenance to include wildfire risks and responses are still nascent. In particular, a risk metric that evaluates the potential for power system components to ignite wildfires could be a key help to guide power system upgrade efforts and power system fire safety measures.

This document serves as a brief literature review of wildfire risk metrics and response programs and how they relate to power systems. It also includes a proposed risk metric and structure for describing the risk of a power system component igniting a fire.

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1 Introduction

More than 10 million acres burned in 2020 from nearly 60,000 fires across the United States (NIFC 2021) the second highest burned acreage on record, with the top five years on record all occurring in the last 15 years (NICC 2022). There has been and will continue to be an increase in the instances and impacts of wildfires, as well as other extreme weather events, as a result of climate change (Dennison et al. 2014). These extreme weather events, including wildfires, often cause widespread power outages either directly when existing fires cause faults, indirectly when operators de-energize lines to assure safety of first responders near an existing fire, or indirectly when operators de-energize lines to prevent an ignition during a high fire risk period (Jazebi, De Leon, and Nelson 2020).

There are several methods of fire risk quantification, fire tracking, and fire risk management, with a few methods that put that risk in the context of power system interactions; however, a metric for the risk of power system components igniting a wildfire is missing from the literature. Transmission lines specifically are susceptible to faults from wildfires, but power systems can also cause wildfires by creating ignition points in susceptible areas.

This paper reviews current methods of quantifying and managing wildfire risks as well as forecasting, tracking, and suppressing wildfires as they affect and are affected by power systems.

1.1 Existing Wildfire Risk Metrics

General wildfire risk metrics, which are not specific to power systems, include many topological, climatological, and vegetation factors that contribute to fire ignition and spread. Some of the most prevalent factors are type of ground cover, precipitation, wind speed, ambient temperature, vegetation moisture, and terrain type and slope. Ground cover, which includes vegetation type (i.e. deciduous trees, shrubs, grasses), vegetation density, and surface characteristics (i.e. clay, rocks, or swampland), is a major determinant of wildfire intensity. For example, ground fires with sparse vegetation tend to burn slowly; a healthy forest typically burns with moderate intensity; whereas crown fires, where treetops burn in part due to excessive fuel accumulation, are the most intense wildfires with regard to temperature and speed of spread (U.S. National Park Service 2017). Colorado has seen an increase in crown fires in recent years ("Historical Wildfire Information | Fire Prevention and Control" 2022) in part because of the prevalence of dead trees from pine beetles, which are spreading to higher elevations given the effects from a warmer climate (Jolly 2011). Ground cover and vegetation moisture are tracked for potential fuel evaluation in the U.S. Department of Agriculture (USDA) ArcFuels plug-in available for ArcMaps (USFS 2021; Hicke n.d.). Precipitation and vegetation moisture are factors that help indicate the likelihood of an ignition point to start a fire (USGS 2021). In combination with wind speed and terrain, these factors can also help forecast the speed at which a fire would spread if one were to start (National Wildfire Coordinating Group (NWCG) 2021).

One risk metric, the Wildfire Risk to Communities, is published by the U.S. National Forest Service and is calculated by multiplying the fire hazard by the community vulnerability (Wildfire Risk to Communities 2021). Fire hazard is calculated from a combination of a simulated average likelihood of wildfire occurring in an area and the simulated intensity of a fire as given by flame length if a fire were to occur. Vulnerability is calculated from a combination of the exposure and susceptibility of fire for an area. Vulnerability as taken here does not include equity or socio-economic metrics such as the community's ability to recover from damage. This metric places California communities at the highest risk, with several other states, including Colorado, not far behind. The US Forest Services also publishes the Wildfire Hazard Potential (WHP) which gives a measure of risk of a wildfire which is difficult to contain occurring in an area and informs forest management practices ("Wildfire Hazard Potential | Missoula Fire Sciences Laboratory" 2015). Another risk metric is the Wildland Fire Potential Index (WFPI), an enhancement of the Fire Potential Index (FPI) ("Wildland Fire Potential Index (WFPI) | U.S. Geological Survey" 2021). On a scale from 0–150, the WFPI describes the relative flammability of an area given the vegetation and moisture (USGS 2020b). The WFPI can be based on one of two sets of satellite imagery data: the Advanced Very High Resolution Radiometer (AVHRR) or the Moderate Resolution Imaging Spectrometer (MODIS), with MODIS-based WFPI averaging just one point out of 150 higher than AVHRR WFPI (Nelson n.d.). The AVHRR-based WFPI is updated twice a day at 1km resolution ("Advanced Very High Resolution Radiometer (AVHRR) | EUMETSAT" 2020). The MODIS-based WFPI is updated every one to two days with sampling resolution down to 250m ("LP DAAC - MODIS Overview" n.d.). The National Fire Danger Rating System (NFDRS) is another system of metrics that predicts the chance of fire ignition and spread based on many metrics broken down into indices and components (NWCG 2021b). These include:

- Lightning activity level: lightning, thunderstorms, and rainfall combined into one metric
- Ignition component: the probability of a firebrand, an airborne ember, igniting a fire
- Spread component: the rate in feet per minute of a fire spreading
- Energy release component: the energy in British thermal units per square foot (BTU/ft^2) at the front of a fire
- Burning index: a combination of the spread component and energy release component to evaluate the difficulty in containing a fire
- Lightning occurrence index: a combination of the lightning activity level and the ignition component that shows the probability of 10 fires per million acres igniting
- Human-caused fire occurrence index: the number of human-caused fires expected each day
- Fire load index: "rating of the maximum effort required to contain all probable fires within a rating area during the rating period" (NWCG 2021b)
- Keetch-Byram drought index: metric for the effects of drought on fire potential based on soil saturation level.

The U.S. Geological Survey (USGS) also publishes the Expected Number of Large Fires per Predictive Service Area, which is a forecast of the probability of ignition and spread (USGS 2020a; 2021). Several of these predictive metrics are created at square kilometer resolution or as an aggregation of square kilometer resolution data (Nelson n.d.; NWCG 2021b; USGS 2021).

California, Texas, and the Pacific Northwest also have their own fire risk metrics. The metrics that identify regions where a fire event would be severe and is likely to occur during a 30- to 50-year period are tracked for California and made publicly available in the annually updated California Fire Hazard Severity Zone Viewer (CalFire 2021). This risk metric considers fuel, terrain slope, and local climate. California fire risk could also be predicted from past events using the historical fire map provided by Cal Fire Perimeters that shows all burned areas in the state from 1878 through 2019 (Zentner and Hagan 2019). The Texas Fire Danger Forecast leverages several metrics from the NFDRS to create an overall scope of fire danger for regions across the state (Srinivasan 2021). The Northwest Interagency Coordination Center pulls together NFDRS metrics and weather data to forecast fire danger in the Pacific Northwest region of the United States for the coming week (NWCC 2021).

1.2 Wildfire Forecasting and Tracking

Once fire risks are known, they can be managed with programs that forecast fire ignition and spread, track fires, and contribute to fire suppression. Fire forecasting can be split into two categories: predicting where and when fires will start and predicting how fires will spread after they have started. Predictions of where and when fires will start are based on a combination of historical data as well as risk metrics, as discussed. Predictions of how fires will spread are primarily based on real-time weather forecasts, including wind speed, wind direction, temperature, and precipitation, as well as fuel availability. Fuel availability can change as firefighting teams clear brush and implement controlled burns. Fuel and wildfire tracking involves a combination of satellite imaging and ground confirmation. There are several wildfire tracking systems available. One is the Fire Information for Resource Management System (FIRMS), provided by the National Aeronautics and Space Administration (NASA 2021), which combines MODIS and Visible Infrared Imaging Radiometer Suite (VIIRS) data to create a global map of existing fires in the last 24 hours at a square kilometer resolution. Another mapping system is InciWeb, an incident mapping system that shows wildfires, prescribed fires, and burned area emergency response areas (NWCG 2021a). Satellite imaging provides a great summary indication of which areas have thermal hot spots, but often ground personnel are required to confirm fire areas given the large area covered by each pixel of the satellite image, the similarity between the thermal indicators of fires and areas that have already burned, and the time difference between when satellite imaging is captured and when fire maps are created and made available to on-site responders (Perez-Mato, Arana, and Cabrera-Almeida 2016). Fire departments can request more detailed information from the National Infrared Operations run by the USDA Forest Service (USFS 2021; Pruitt and Panossian 2021). Higher-fidelity fire tracking can also be done by using drone photography and monitoring (Tang and Shao 2015; Lin, Liu, and Wotton 2019). Rapid and real-time monitoring as well as response in Colorado is conducted via manned Multi-Mission Aircraft that can be on-site within an hour anywhere within the state (Pruitt and Panossian 2021; DFPC 2021). These tracking methods help firefighters prioritize resources and respond to critical areas. Fire suppression efforts go beyond clearing brush and burn backs (Fernandes and Botelho 2003) to include the use of water (Atroshenko et al. 2019) and sprayed fire suppressants applied via both ground and air equipment (M. P. Plucinski, Sullivan, and Hurley 2017; Matt P. Plucinski et al. 2013).

Fire risk metrics, forecasting, and suppression response methods often need to be altered when wildfires are near power lines. The following section discusses how risk metrics, forecasting, tracking, and suppression methods are altered near transmission lines. Section 3 addresses concerns of fires related to distribution systems.

2 Transmission System Interaction

Transmission systems have become a concern for fire response efforts. This concern stems from the increased prevalence and intensity of wildfires, which result in more frequent interactions between transmission components and wildfires (Dennison et al. 2014). Also, higher temperatures, heavily loaded lines, and aging infrastructure mean that fire ignitions from power systems are becoming more prevalent (Sathaye et al. 2011).

2.1 Power System Mechanisms for Wildfire Prevention and Forecasting

Operators can implement Public Safety Power Shutoffs (PSPS) to prevent fires during high fire risk periods by de-energizing nearby lines. PSPS reduce risks of ignition near transmission lines, but they are often costly for utilities to implement; costly for customers who lose power and must replenish resources or lose productivity time; and dangerous to populations that lose power during shutoffs when emergency services, safety devices, or healthcare devices lose power (Dian et al. 2019). Once fires already exist, Power Safety Shutoffs (PSS) can be implemented by de-energizing lines near fires to improve safe operation for first responders and avoid causing additional ignition points. The risks involved in safety shutoffs compound when they impact fire evacuation efforts including messaging services and emergency response coordination (Wong, Broader, and Shaheen 2020). Fire risk metrics, forecasting, tracking, and suppression efforts should consider transmission systems to ensure the safety of firefighters and local populations as well as to limit the instances and time required for PSPS and PSS.

Transmission systems can experience outages from wildfires, and, conversely, transmission system failures can cause wildfires. Transmission system outages from wildfires can be caused by faults (Bueno et al. 2019) and, in high-intensity fire cases, destruction of power system equipment (Beutel et al. 2013). The risk of a fault increases during a fire because of several factors. Line-to-ground impedance is reduced from increased air temperature (Shi et al. 2018). Line-to-ground impedance also decreases with the increase in the density of ash or smoke in the air (Pu et al. 2019). Line-to-ground distance also decreases as lines are heated and begin to sag (Shi et al. 2018; Wu et al. 2016). The effects of increased air temperature and smoke also reduce line-to-line impedance, which increases line-to-line fault risk (Wu et al. 2020). The risk of a line-to-line fault is also increased from line sag because this can cause lines to be closer together, especially when the wind blows and lines sway (Ratnam et al. 2020). In extreme cases, line slap might occur, creating a spark, which can be an additional ignition point (Jazebi, De Leon, and Nelson 2020). Most transmission lines are above ground and built of steel or aluminum towers, so the destruction of transmission poles is rare. Power equipment lifetimes are reduced when they are exposed to high heat levels, as during extreme loading or fire events (Zhang et al. 2016). In extreme cases, equipment might fail during an event, causing power outages, fire ignition points, or both. These failures are especially dangerous for transformers that have oil-based cooling systems (Mass and Ovens 2021). While ignition would still be supplied by a fault current, the transformer oil could add fuel and contribute to spread of a fire (Muller, Boiarciuc, and Perigaud 2009).

Several risk metrics quantify the risk of an outage caused by a fire near transmission lines. These metrics evaluate many of the same aspects as general fire risk metrics, such as ground cover, wind speed, and precipitation; however, they also incorporate aspects of the transmission system, including pole height, line-to-line distance, system maintenance, component age, and line-to-vegetation distance (Shi et al. 2018; Wu et al. 2016; Ratnam et al. 2020; Sangode and Metre 2020; Clarke et al. 2019).

These risk metrics are used to forecast power system outages caused by fires. Safety outages are often announced with very little notice, but improved forecasting can improve the notice time and allow affected populations more adequate time to prepare. Forecasting and historical tracking can also help guide the optimal placement and storage of fire suppression equipment, reducing the risk of fires spreading or causing trips (Lu et al. 2017). These outage forecasting systems are based on existing fire tracking, and they do not include longer-timescale predictions of seasonal averages for outage instances and durations (W. Zhou et al. 2020).

2.2 Power Systems Mechanisms for Wildfire Tracking and Response

Once fires are detected, they must be tracked, and transmission system operators (TSOs) need to communicate with fire response teams if fires get close to transmission lines (Z. Zhou and Chen 2018; Zhao, Gao, and Wen 2020). This communication and tracking are critical in determining when and for how long safety outages are needed (Wu et al. 2020; W. Zhou et al. 2020; Liu et al. 2020; 2019). Unfortunately, TSO-fire response communication is not standardized across the US and only occurs in some areas with varying levels of response from either side (Pruitt and Panossian 2021). High-impedance faults can be used to detect where a transmission line might have caused a fire through a downed line or an arc to ground (Bueno et al. 2019). There is a possibility of using impedance measurements to track fires before a fault occurs and after a fire has spread to an area near a line. Given the change in line impedance from a nearby fire, or change in impedance before an ignition fault, impedance tracking on transmission lines might be able to provide additional fire detection, tracking, or even prediction information to fire responders, but this capability has yet to be explored in depth.

Fire suppression methods also require special modification near transmission lines. First responders receive varying levels of training related to fire suppression near power lines and learn how to identify high voltage lines, but there is no standardized national protocol for this training (Pruitt and Panossian 2021). Traditional water sprayed from a hose can cause faults from lines to ladders, fire trucks, or even firefighters, creating the risk of a severe shock to responders and their equipment (Lu et al. 2018). This risk is also present when there are responders on the ground and water is released onto the area from an aircraft (Lu et al. 2018). Safety outages that de-energize lines can allow these methods to be used, but de-energizing can cause not only outages for downstream communities but also cascading outages when more loads are shifted to alternative lines (Jian et al. 2019). One method for avoiding faults from fire suppression is dropping water from an aircraft when there are no present ground personnel or ground fire response equipment. Because the aircraft is not grounded, there is no risk of a fault from the line-to-the aircraft (Carlini et al. 2019). Another method involves using a specialized nozzle that emits a water mist instead of a traditional fire hose nozzle (Wu et al. 2020; Lu et al. 2018). The dispersed mist is effective at fire suppression, but it does not lower the air impedance as much as spray from a standard nozzle, preventing a fault from occurring. Finally, fire suppression chemicals that are nonconducting can be used—especially with the two previously mentioned methods—to suppress fires without causing a fault and therefore a risk of shock (M. P. Plucinski, Sullivan, and Hurley 2017). These methods all require situational awareness, communication between transmission system operators and fire response teams, and the availability of specialized equipment.

3 Distribution System Interaction

Distribution systems and wildfires are likely to interact in urban or suburban edge locations where distribution lines to meet local loads are located near unmaintained or dense vegetation areas. These edge locations are often referred to as the wildland-urban interface in wildfire tracking ("Wildfire and the Wildland Urban Interface (WUI)" 2023). The Marshall Fire which started on December 30th 2021 in Colorado is an example of a wildland-urban interface fire and was able to quickly spread to destroy the most homes of any fire in Colorado history (Scott 2022). There are also risks for rural distribution lines, especially through dry areas, but given the sparse development in rural areas, they pose lower risk of destruction to property and life than wildland-urban interfaces. In response to larger fire incidents caused by power system equipment, Pacific Gas and Electric Company has started on a long-term plan to underground up to 10,000 miles of overhead primary distribution lines in wildfire risk areas with a focus on rural distribution lines (PG&E 2023).

Despite wildland-urban interface interactions and wildfire risks of rural distribution lines, distribution system wildfire analyses and wildfire resilience measures differ greatly from those of transmission systems. First, it is more likely for distribution system lines to be underground or insulated than transmission lines, thus avoiding risks of distribution line faults causing nearby fires. Second, wildfires are much less common in densely populated areas, reducing the interactions between distribution lines and fires, so the focus of prevention is near the system edges. Third, the lower voltages and lower loads served by distribution lines make a distribution line fault or outage less dangerous. The risks of fire associated with distribution lines also differ from the risks associated with transmission lines and fires. Aging distribution infrastructure is at risk of failure, especially during high-temperature weather conditions and under high-loading conditions (Sangode and Metre 2020). These overloads can cause transformer failures or line faults that could ignite fires when environmental conditions are amenable to an ignition. Aboveground distribution lines are often mounted on wooden poles, which can burn, causing outages during a fire (Beutel et al. 2013). Underground and aboveground insulated lines are less likely to cause a fault or a fire, but if a fire does occur, the burning shielding can create fumes that are unsafe to breathe (He et al. 2019). Although all these risks exist, much of the power system analysis of fire risk response is focused on transmission systems given the larger loads they serve, the higher risks associated with high voltage, and the difficulty in clearing faults and responding to fires given the vast remote expanses covered by transmission lines.

4 Utility Programs to Prevent Wildfires and Wildfire System Outages

Utility efforts to upgrade systems to reduce fire ignition and power outage risks have grown because of the increased prevalence of wildfires ignited by power system equipment and wildfires that cause power system outages.

Particularly in California, there have been several efforts focused on preventing safety outages given that 53% of acres burned in 2017 were caused by electrical equipment and lines (Porter and Crawfoot 2019). Six of the top twenty most destructive fires in California history were caused by powerlines including the Dixie fire which burned 963,309 acres in 2021 and the Camp Fire which was responsible for 85 deaths in 2018 (Cal Fire 2022). Undergrounding lines is an obvious way to prevent power system/wildfire interactions, but it is expensive, and it takes a very long time to complete (Haces-Fernandez 2020). The San Diego Gas & Electric Company *Fire Prevention Plan* lists several measures, including transformer upgrades, targeted line undergrounding, increased tree-trimming efforts, and resizing fuses (SDG&E 2018). Southern California Edison also has a fire management document describing additional risks and safety measures for first responders when dealing with fires near or on power system equipment (Brown and Whitman, n.d.). Pacific Gas and Electric Company has a PSPS program where weather forecasts—including forecasted fire spread—are used to predict where wildfire/transmission line interactions might become dangerous, and these predictions are used to plan and notify customers of transmission line outages (PG&E 2021). Los Angeles Department of Water and Power, the largest publicly owned utility in the country, has a Wildfire Mitigation Plan that includes increased vegetation management, replacing wood poles with metal, increasing line spacing, insulating lines, and more frequent component inspections (LADWP 2021). Xcel Energy, which spans areas in Colorado, Michigan, Minnesota, New Mexico, the Dakotas, Texas, and Wisconsin, has an ongoing Wildfire Mitigation Program focused on areas in the Rocky Mountains that includes increasing engagement with local communities and first responders, pole and line upgrades for higher wind speeds, added safety relays, increased component inspection frequency using drones and LiDAR, and expanded vegetation management (Xcel Energy 2020). These coordination efforts could be extended to include high-impedance fault detection, impedance monitoring for fire tracking, power system component risk assessment for prioritized upgrades, and downstream generation and storage installations to reduce risks during periods of high congestion.

5 Proposed Risk Metric

Many of these utility programs involve system upgrades and evaluating risk to concentrate upgrades on components which are most likely to cause wildfires. However, there is no risk metric available that combines environmental factors—as commonly seen in general wildfire risk assessment—and power system factors to determine which components are at the highest risk of igniting a fire. These factors are interrelated and so a cumulative sum of independent risk is not sufficient for power system evaluation. A risk metric that considers how the risk of ignition from a power system may increase based on environmental impacts on power system components and based on power system interactions with the environment would significantly improve the ability to effectively prioritize upgrades and evaluate the efficacy of wildfire prevention programs.

Such a metric is proposed here where such environmental risk factors have multiplicative effects on interrelated power system risk factors when present for the same component and location.

The environmental factors considered include ground vegetation, soil saturation, vegetation moisture, lightning incidence, wind speed, and ambient temperature. Some of these factors such as ground vegetation are long term characteristics while others, such as wind speed would require updating more frequently or evaluation during peak times or over a time horizon to determine if the environmental risk coincides with high electrical risks during the cycle of a day or a season.

Environmental factors are collected and normalized from publicly available databases. Ground vegetation type is included because vegetation becomes the fuel to create a wildfire from an ignition point and certain vegetation burns more easily or at higher temperatures than others. Ground vegetation is evaluated based on the NACP Integrated Wildland and Cropland 30-m Fuel Characteristics (French et al. 2013) and scaled from 0 to 10 where 0 would have no fuel and 10 would be quick burning vegetation such as grassland. Soil saturation is considered because this indicates the likelihood of any debris catching fire given how wet the surrounding area is. Soil saturation is evaluated here based on the soil respiration as provided by Oak Ridge National Lab and scaled to fit 0 to 10 based on the maximum mean soil respiration across the continental US (Jian, J. et al. 2021). Vegetation moisture is included in the risk metric, because the flammability of surrounding vegetation is dictated by the moisture in the vegetation in addition to the vegetation type. Vegetation moisture can be estimated from the drought level on the US drought monitor which ranges from none, to D0 representing unusually dry, to D4 which is exceptional drought (National Drought Mitigation Center 2022). The drought level can be converted into a risk score where none is a score of 0 and D4 is a score of 10 with drought levels linearly scaling to risk scores between the two levels. Lightning strikes are included because they have the potential to both disrupt electrical network operations, and to ignite fires which could create risk for additional ignition points around power lines. Lightning risk is evaluated based on the number of strikes per ten square kilometers within the peak period of the year for long term evaluation and is taken from NASA's Very High Resolution Gridded Lightning Monthly Climatology (NASA n.d.) or can be evaluated over a horizon from weather tracking applications. Wind speed is included because high winds can increase ignition or spread risk when combined with some power system factors while decreasing risk when paired with others. High winds have the potential to spread fires quickly and increase ignition risks from line slap, line-to-vegetation contact, or downed wires, however, winds may cool lines and transformers in scenarios where the air temperature is below line temperature, reducing component overheating and related ignition risks. Wind speed and ambient temperature can be taken from various weather tools and are normalized to a zero to ten range where wind speed gusts are input in meters per second divided by 2 and temperature is input as degrees in Celsius divided by 4. With respect to wind and temperature, the risk factor may exceed 10 given the importance of capturing the impacts of extreme wind speeds and temperatures on wildfire risk.

Power system factors must be taken from utility or sampling data and include measurements which are continuous and can be normalized to a zero to ten scale such as line-to-vegetation distance, as well as inputs that are discrete such as whether lines are overhead as opposed to underground. Line-to-vegetation distance, line-to-line distance, and line-to-ground distance all influence the risk of a line arcing and creating an ignition point. These three metrics are inverted such that the value input is 5 meters divided by the measured distance. This inversion means that further distances approach zero risk while small distances generate higher risk values. Line and transformer age can indicate potential for defects causing ignitions and are normalized as the percentage of the expected component lifetime divided by ten. Line and transformer load versus rating are included because these capacity values indicate how close components are to thermal overloading, which could contribute to ignition. If long term evaluation is being conducted the line and transformer peak loads can be used for this factor, however, for horizon analysis, the full load profile should be used. Line and transformer load are also normalized based on the percentage rated and divided by ten. The oil type transformer, overhead, and uninsulated risk categories are discrete and should have values of 10 if the categorization is true. The transformer cooling style is represented in the oil type transformer risk entry, because oil cooled transformers can contribute to rapid fire spread if overheated as the oil provides additional fuel. Overhead lines pose a much greater risk of ignition than undergrounded lines, so if a component is overhead mounted its risk in that category is set to 10. Uninsulated lines also pose a much higher ignition risk so if a line is uninsulated the input risk for that category is set to 10.

In addition to these factors, the proposed metric also includes response measures as additional risk/mitigation factors to include available response measures to contain wildfires and prevent ignitions. The first mitigation factor is high impedance fault (HIF) detection which could allow system operators to quickly detect and possibly stop an ignition point, which is set to the average km of lines between HIF detection points, with a maximum of 10 if HIF is not implemented. The next mitigation strategy is the threshold of risk for a power safety shutoff with 10 corresponding to no power safety shutoff program implemented and 0 corresponding to shutoffs during any Red Flag weather warning. The provision of misting fire suppression equipment is a binary value with 10 indicating that no misting equipment is available and 0 indicating that all fire response teams have access to misting equipment to reduce arcing risk from active lines. The fire response team coordination metric is an indicator of how well the utility coordinates with the fire responders. The value for this metric is scaled linearly with the utility’s response time to any fire responder communication such that immediate response is a 0 and one hour or no communication has a rating of 10. The high fidelity tracking metric captures the resolution of tracking the fire location and is represented as the resolution in km multiplied by 5.

A key part of the proposed metric is to then capture the pair-wise interactions between environmental and power systems and response factors. For example, transformer age and ambient temperature are expected to compound risk as they could cause overheating and ignition, while line-to-line distance and lightning are less correlated. Table 1 captures an initial set of correlations with 100 indicating a correlation and 0 none. Additional research is required to better calibrate both these correlations and the scale factors used for the 0-10 ranges.

Once tabulated in a form similar to Table 1, an overall combined metric can be computed. First a user would fill in the green boxes with the rating on a scale of 0 to 10, with 10 representing the highest risk and 0 representing no risk, for the characteristic immediately above or to the left of the box. Then the co-risks (for example, high wind would make short line-to-line distances more dangerous, but overheating lines less dangerous) are accounted for in yellow boxes. Finally, a total risk factor is shown in the red box, which sums up the yellow boxes and normalizes to have a maximum score of 100 (accounting for non-correlated items).

Table 1: Risk Factor Interrelationship Chart: power system and environmental risk factors are multiplied when interrelated. Response measures reduce risk, so a score of 10 means that a response measure is not enacted. Users would input values for green slots and get resultant normalized risk as a final output out of 100.

	Environmental Factors	ground vegetation	soil saturation	veg moisture	lightning	wind speed	ambient temp
Power System Factors		10	10	10	10	10	10
line-to-veg distance	10	100	0	100	0	100	100
line-to-line distance	10	100	0	0	0	100	100
line-to-ground distance	10	100	100	0	0	100	100
line age	10	100	100	100	100	0	100
transformer age	10	100	100	100	100	0	100
oil type transformer	10	100	100	100	100	0	100
overhead	10	100	100	100	100	100	0
uninsulated	10	100	100	100	0	100	0
line peak load	10	100	100	100	0	100	100
transformer peak load	10	100	100	100	0	100	100
Response Measures							
HIF detection	10	100	100	100	100	100	100
power safety shutoff threshold	10	100	100	100	100	100	100
provision of misting fire suppression equipment	10	100	100	100	100	100	100

	Environmental Factors	ground vegetation	soil saturation	veg moisture	lightning	wind speed	ambient temp
fire response team coordination	10	100	100	100	100	100	100
high fidelity fire tracking	10	100	100	100	100	100	100

Total Normalized Fire Risk Score (out of 100) 100 Risk of power system equipment causing a fire

This metric would be applied to each line and component in a power system such that components with the highest risk factors would be upgraded first and risk reduction from upgrade efforts could be quantified. In Figure 1, power system risks metrics, not overall risk as taken from the interrelationship table, are applied to the region around Livermore, California with a synthetic realistic grid created through the SMART-DS project (Mateo et al. 2020). This location has been selected based on its range from moderate to very high fire risk according to environmental factors captured by the California Department of Forestry and Fire Protection's Fire and Resource Assessment Program (CalFire 2021), as well as its urban to wildland interfaces, and diversity of distribution systems from urban to rural feeders. Note that the grid-only risks are high for long rural feeders stretching south-east of Livermore during both midnight and mid-morning scenarios. This continued increased power system risk could require prioritized upgrades given the nearby wildlands and environmental risks of the area.

The grid-only risks fluctuate mainly depending on system load with peak loads corresponding with the highest resultant power system wildfire risks. These higher loading times correspond with an increased chance of component overheating or line slap given lines sagging from increased temperatures from increased loads. However, the environmental risks vary seasonally and with weather patterns, so an interrelationship of both risks such as according to the metric demonstrated above is important to identify peak risk times and components. Some lines which show low grid-only risk even during peak load times (as shown by white lines in the bottom image of Figure 1) may have increased overall risk compared to risk shown due to increased environmental wildfire risk factors. Also, some high grid-only risk lines (shown in dark blue)

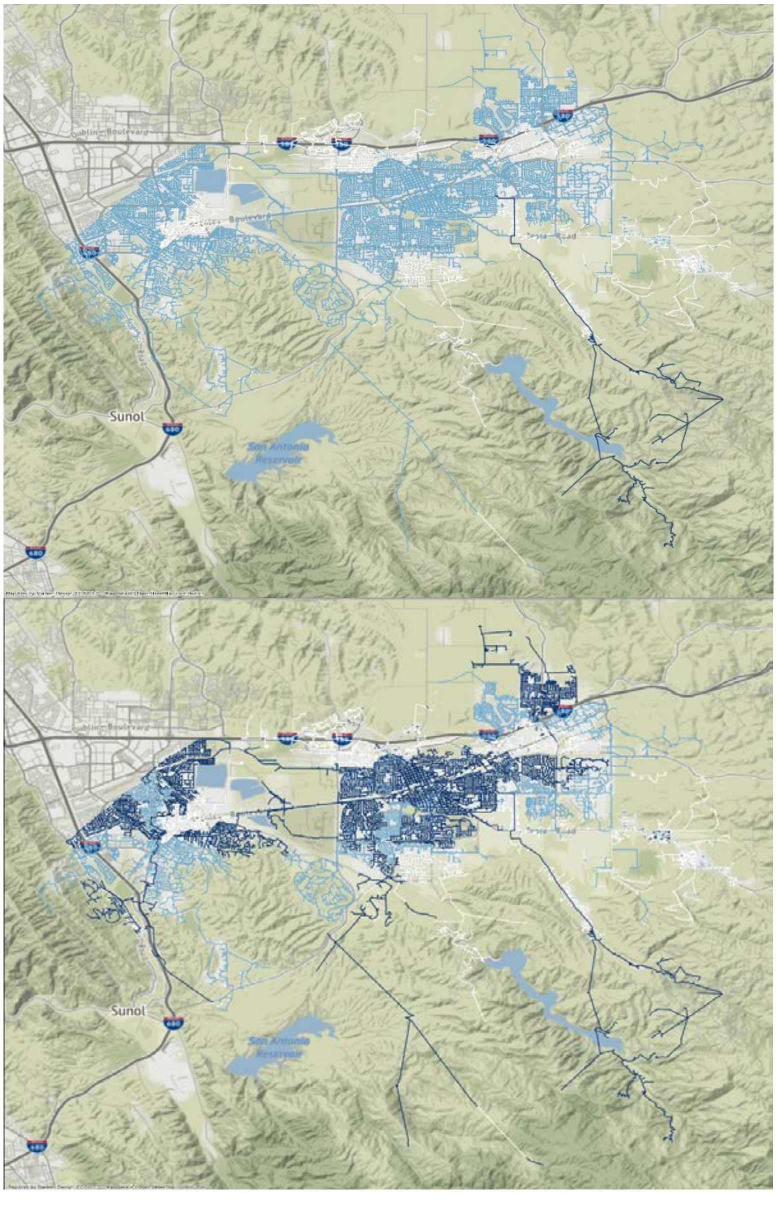

Figure 1: Midnight (top) and mid-morning (bottom) power system fire risk is shown for a realistic but not real distribution system in the Livermore, CA area. High risk is shown in dark blue and low risk in light blue. The risk corresponds mostly with component sizing relative to total load as a percent of rated load.

may have reduced overall risk given reduced environmental wildfire risk factors, such as being far from wildland fuels.

The distribution risks should be overlaid with environmental risk factors to determine overall risk. For example, the Fire Hazard Severity Zones for Alameda County are shown in Figure 3 below (Department of Forestry and Fire Protection 2022). Combining this type of map with the proposed metric could provide a more complete understanding of mitigation priorities. It is important to note that the Fire Hazard Severity Zones exclude areas maintained by local authorities. These other areas are often higher density populated areas which tend to have lower environmental wildfire risks.

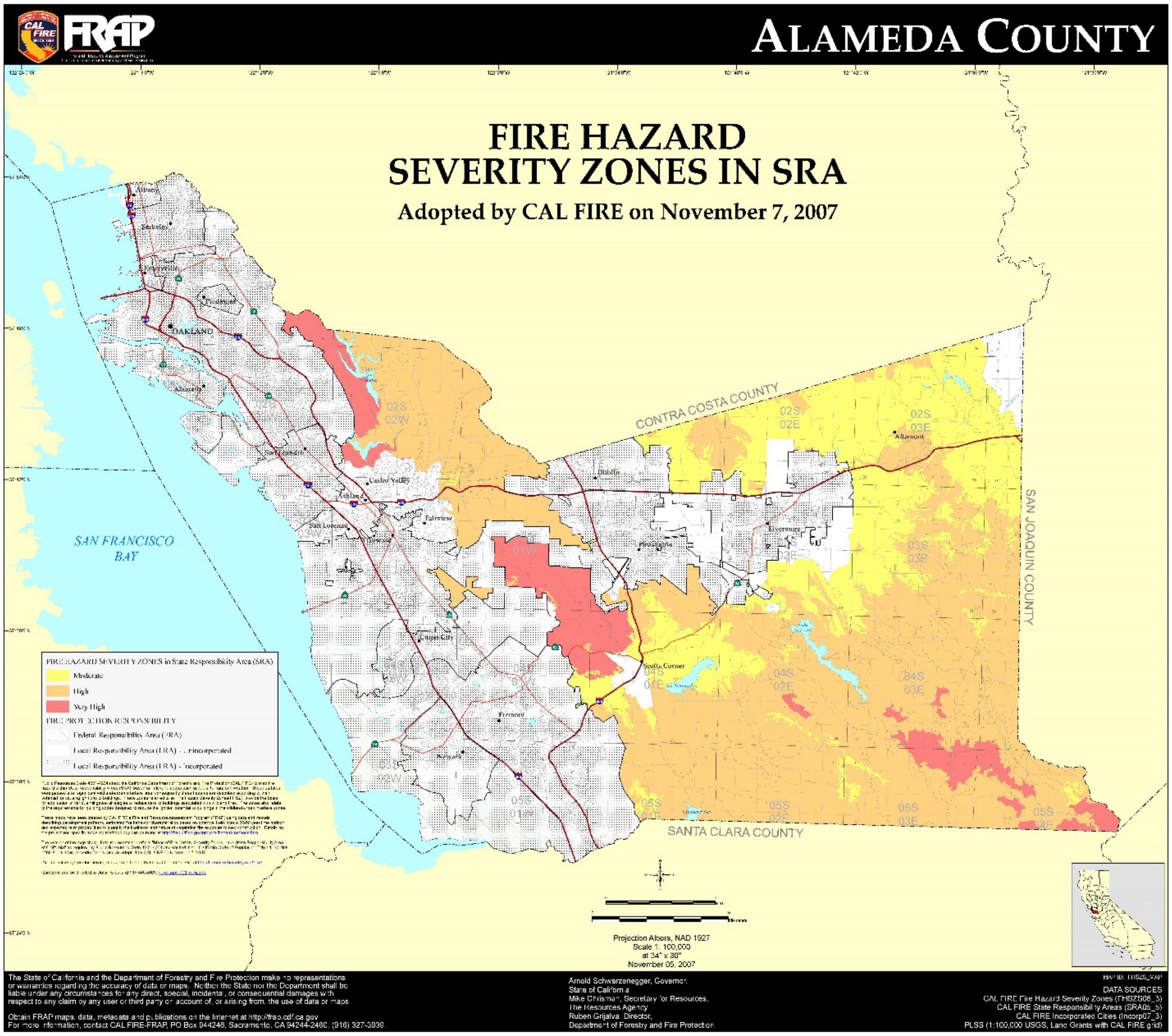

Figure 2: The Fire Hazard Severity Zones for Alameda County indicate highest wildfire risk south-west and far south-east of Livermore. This map was created by the Department of Forestry and Fire Protection and can be accessed via this link: https://osfm.fire.ca.gov/divisions/community-wildfire-preparedness-and-mitigation/wildland-hazards-building-codes/fire-hazard-severity-zones-maps/

The risk assessment tool presented here is still in the demonstration phase of development and requires validation and industry review. Additional considerations such as how to weight the interrelated factors are still being tuned. However, if applied to a wider area and refined with stakeholder feedback, this risk assessment tool could provide the missing piece in quantifying wildfire risk from power systems.

6 Conclusion

Several existing fire risk assessment, suppression, tracking, and optimal response methods exist with varying considerations of transmission and distribution power systems. Many risk metrics consider only environmental factors, while many response methods consider only either transmission or distribution system impacts. A risk metric that considers both environmental and power system features is proposed here to allow prioritization of power system upgrades and fire response plans. One of the most important measures captured in the proposed metric is coordination between fire response teams and transmission system operators, which could be improved for many utilities and fire response teams. This coordination should include communications about power safety shutoffs, optimal storage placement and the allocation of fire suppression equipment, the use of misting nozzles when spraying water for fire suppression near transmission lines, and tracking high-impedance faults. Although past studies have demonstrated these approaches and shown improvement in fire suppression and decreases in fire-caused trips, additional risk metrics—including a metric describing the risk of power system components igniting fires and a metric describing the risk to power system components from nearby fires—could guide the use of funds for system upgrades, such as undergrounding lines and increasing pole height. Improvements in fire forecasting in conjunction with the application of high-fidelity tracking methods near power lines could also improve response and outage times. Finally, there are multiple areas to be explored further, including the use of power system impedance measurements for fire detection and tracking as well as the application of downstream generation and storage to reduce line ignition and outage risks.

Acknowledgements

The authors would like to thank the editing and contributions of Richard Bryce, Shibani Ghosh, and Bryan Palmintier at the National Renewable Energy Laboratory, as well as Line Roald and Sofia Taylor at University of Wisconsin, Madison.

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the National Renewable Energy Laboratory's Laboratory Directed Research and Development program. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

References

"Advanced Very High Resolution Radiometer (AVHRR) | EUMETSAT." 2020. May 5, 2020. https://www.eumetsat.int/avhrr.

Atroshenko, Yuliana K., Geniy V. Kuznetsov, Pavel A. Strizhak, and Roman S. Volkov. 2019. "Protective Lines for Suppressing the Combustion Front of Forest Fuels: Experimental Research." *Process Safety and Environmental Protection* 131 (November): 73–88. https://doi.org/10.1016/j.psep.2019.09.006.

Beutel, A., M. Ntshani, H. Geldenhuys, K. Thejane, B. Mclaren, and A. Khatri. 2013. "Pole-Top Fires Risk Assessment: A South African Perspective." In *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, 1–4. https://doi.org/10.1049/cp.2013.0627.

Brown, Scott, and Troy Whitman. n.d. "SCE Fire Managment." Southern California Edison. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3838361.pdf.

Bueno, D.M., E.M. Dos Santos, H. Stein, A.R. Fagundes, M.C. Franco, and A.H. Rodrigues. 2019. "High Impedance Fault Detection and Classification in Medium Voltage Distribution Networks." In *2019 IEEE PES Conference on Innovative Smart Grid Technologies, ISGT Latin America 2019*. https://doi.org/10.1109/ISGT-LA.2019.8895475.

Cal Fire. 2022. "Top 20 Most Destructive California Wildfires." Statistics | CAL FIRE. October 24, 2022. https://www.fire.ca.gov/our-impact/statistics.

CalFire. 2021. "California Fire Hazard Severity Zone Viewer." FHSZ Viewer. 2021. https://gis.data.ca.gov/datasets/789d5286736248f69c4515c04f58f414.

Carlini, E.M., L. Michi, L. Minto, F. Chiereghin, C. Genovese, R. Foppa, and A. Fedrizzi. 2019. "Forest Fire or Other Dangerous Situations: Safety Procedure for Overhead Lines." In *2019 AEIT International Annual Conference, AEIT 2019*. https://doi.org/10.23919/AEIT.2019.8893408.

Clarke, H., R. Gibson, B. Cirulis, R.A. Bradstock, and T.D. Penman. 2019. "Developing and Testing Models of the Drivers of Anthropogenic and Lightning-Caused Wildfire Ignitions in South-Eastern Australia." *Journal of Environmental Management* 235: 34–41. https://doi.org/10.1016/j.jenvman.2019.01.055.

Dennison, Philip E., Simon C. Brewer, James D. Arnold, and Max A. Moritz. 2014. "Large Wildfire Trends in the Western United States, 1984–2011." *Geophysical Research Letters* 41 (8): 2928–33. https://doi.org/10.1002/2014GL059576.

Department of Forestry and Fire Protection. 2022. "Fire Hazard Severity Zones Maps." CalFire. 2022. https://osfm.fire.ca.gov/divisions/community-wildfire-preparedness-and-mitigation/wildland-hazards-building-codes/fire-hazard-severity-zones-maps/.

DFPC. 2021. "Multi-Mission Aircraft (MMA) | Fire Prevention and Control." 2021. https://dfpc.colorado.gov/multi-mission-aircraft-mma.

Dian, S., P. Cheng, Q. Ye, J. Wu, R. Luo, C. Wang, D. Hui, et al. 2019. "Integrating Wildfires Propagation Prediction Into Early Warning of Electrical Transmission Line Outages." *IEEE Access* 7: 27586–603. https://doi.org/10.1109/ACCESS.2019.2894141.

Fernandes, Paulo M., and Hermínio S. Botelho. 2003. "A Review of Prescribed Burning Effectiveness in Fire Hazard Reduction." *International Journal of Wildland Fire* 12 (2): 117–28. https://doi.org/10.1071/wf02042.

French, N. H. F., D. Mckenzie, N. Hamermesh, and J. L. Mccarty. 2013. "NACP Integrated Wildland and Cropland 30-m Fuel Characteristics Map, U.S.A., 2010." *ORNL DAAC*, June. https://doi.org/10.3334/ORNLDAAC/1163.

Haces-Fernandez, F. 2020. "Wind Energy Implementation to Mitigate Wildfire Risk and Preemptive Blackouts." *Energies* 13 (10). https://doi.org/10.3390/en13102421.

He, L., G. Ma, Q. Hu, Q. Cai, Y. Bai, S. Tang, and J. Tan. 2019. "A Novel Method for Risk Assessment of Cable Fires in Utility Tunnel." *Mathematical Problems in Engineering* 2019. https://doi.org/10.1155/2019/2563012.

Hicke, Jeff. n.d. "Wildfire Risk and Fuels Management - USDA Forest Service." Accessed January 8, 2021. https://www.fs.fed.us/wwetac/highlights/wildfire-risk-and-fuels-management.php.

"Historical Wildfire Information | Fire Prevention and Control." 2022. Colorado Division of Fire Prevention and Control. 2022. https://dfpc.colorado.gov/wildfire-information-center/historical-wildfire-information.

Jazebi, S., F. De Leon, and A. Nelson. 2020. "Review of Wildfire Management Techniques-Part I: Causes, Prevention, Detection, Suppression, and Data Analytics." *IEEE Transactions on Power Delivery* 35 (1): 430–39. https://doi.org/10.1109/TPWRD.2019.2930055.

Jian, J., Vargas, R., Anderson-Teixeira, K.J., Stell, E., Herrmann, V., Horn, M., Kholod, N., et al. 2021. "Soil Collection: A Global Database of Soil Respiration Data, Version 5.0," 0 MB. https://doi.org/10.3334/ORNLDAAC/1827.

Jian, Z., J. Guo, X. Xu, B. Wang, Y. Yi, and H. Ye. 2019. "Risk Analysis of Wild Fire on Electric Grid Transmission Lines Considering Cascading Failure." In *2019 3rd IEEE Conference on Energy Internet and Energy System Integration: Ubiquitous Energy Network Connecting Everything, EI2 2019*, 872–76. https://doi.org/10.1109/EI247390.2019.9061890.

Jolly, William M. 2011. "Mountain Pine Beetle Effects on Fire Behavior – Research Highlights - US Forest Service Research & Development." US Forest Service Research and Development Highlights. 2011. https://www.fs.fed.us/research/highlights/highlights_display.php?in_high_id=395.

LADWP. 2021. "Wildfire Mitigation Plan." https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-power/AboutUs-Power-Wildfire;jsessionid=grvrh5tcLqK9sgy4sQ1DnbkygHv3tyyJN7v90J4MR5L1vKjDn2G0!-1106340359?_adf.ctrl-state=xk3imtf9d_4&_afrLoop=663503797632770&_afrWindowMode=0&_afrWindowId=null#%40%3F_afrWindowId%3Dnull%26_afrLoop%3D663503797632770%26_afrWindowMode%3D0%26_adf.ctrl-state%3D19qnlzz8mc_4.

Lin, Z., H. H. T. Liu, and M. Wotton. 2019. "Kalman Filter-Based Large-Scale Wildfire Monitoring With a System of UAVs." *IEEE Transactions on Industrial Electronics* 66 (1): 606–15. https://doi.org/10.1109/TIE.2018.2823658.

Liu, Y., C. Wu, B. Chen, T. Zhou, J. Qin, and Y. Liu. 2019. "Study on Distribution Regularity of Overhead Transmission Line Nearby Wildfires." In *2019 3rd IEEE Conference on Energy Internet and Energy System Integration: Ubiquitous Energy Network Connecting Everything, EI2 2019*, 2456–59. https://doi.org/10.1109/EI247390.2019.9062009.

Liu, Y., D. Yang, J. Liu, N. Zhang, and L. Zhang. 2020. "Forest Fire Tripping Probability Prediction System Based on Partial Mutual Information Method." *Lecture Notes in Electrical Engineering* 584: 653–62. https://doi.org/10.1007/978-981-13-9779-0_53.

"LP DAAC - MODIS Overview." n.d. Accessed April 6, 2023. https://lpdaac.usgs.gov/data/get-started-data/collection-overview/missions/modis-overview/.

Lu, J., B.-H. Chen, Z. Fang, J. Hu, B. Wang, C. Wu, and S. Huang. 2018. "Electrical Safety of Suppressing Wildfires near High-Voltage Transmission Lines Using Water Mist." *Journal of Fire Sciences* 36 (4): 295–314. https://doi.org/10.1177/0734904118782668.

Lu, J., J. Guo, Z. Jian, and X. Xu. 2017. "Optimal Allocation of Fire Extinguishing Equipment for a Power Grid under Widespread Fire Disasters." *IEEE Access* 6: 6382–89. https://doi.org/10.1109/ACCESS.2017.2788893.

Mass, Clifford F., and David Ovens. 2021. "The Synoptic and Mesoscale Evolution Accompanying the 2018 Camp Fire of Northern California." *Bulletin of the American Meteorological Society* 102 (1): E168–92. https://doi.org/10.1175/BAMS-D-20-0124.1.

Mateo, Carlos, Fernando Postigo, Fernando de Cuadra, Tomas Gomez, Tarek Elgindy, Pablo Dueñas, Bryan Palmintier, Bri-Mathias Hodge, and Venkat Krishnan. 2020. "Building Large-Scale U.S. Synthetic Distribution Network Models." *IEEE Transactions on Smart Grid*. https://doi.org/10.1109/TSG.2020.3001495.

Muller, S., M. P. Boiarciuc, and G. Perigaud. 2009. "Protection of Oil-Filled Transformer against Explosion: Numerical Simulations on a 200 MVA Transformer." In *2009 IEEE Bucharest PowerTech*, 1–8. https://doi.org/10.1109/PTC.2009.5282154.

NASA. 2021. "Fire Information for Resource Management System (FIRMS) | Earthdata." EARTHDATA. 2021. https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms/.

———. n.d. "CMR Preview: LIS 0.1 DEGREE VERY HIGH RESOLUTION GRIDDED LIGHTNING MONTHLY CLIMATOLOGY (VHRMC) V1." EarthData. Accessed August 12, 2022. https://cmr.earthdata.nasa.gov/search/concepts/C1979883359-GHRC_DAAC.html.

National Drought Mitigation Center. 2022. "U.S. Drought Monitor." August 25, 2022. https://droughtmonitor.unl.edu/.

National Wildfire Coordinating Group (NWCG). 2021. "National Fire Situational Awareness." EGP Portal. 2021. https://egp.nwcg.gov/sa/.

Nelson, Kurtis. n.d. "A Comparison of Fire Potential Index Rasters Derived from AVHRR and MODIS Data." USGS Fire Danger Forecast. Accessed February 5, 2021. https://www.usgs.gov/ecosystems/lcsp/fire-danger-forecast/a-comparison-fire-potential-index-rasters-derived-avhrr-and.

NICC. 2022. "Wildland Fire Summary and Statistics Annual Report 2021." National Interagency Coordination Center. https://www.predictiveservices.nifc.gov/intelligence/2021_statssumm/intro_summary21.pdf.

NWCC. 2021. "Northwest Interagency Coordination Center." 2021. https://gacc.nifc.gov/nwcc/predict/outlook.aspx.

NWCG. 2021a. "InciWeb the Incident Information System." 2021. https://inciweb.nwcg.gov/.

———. 2021b. "NFDRS System Inputs and Outputs | NWCG." 2021. https://www.nwcg.gov/publications/pms437/fire-danger/nfdrs-system-inputs-outputs.

Perez-Mato, J., V. Arana, and F. Cabrera-Almeida. 2016. "Real-Time Autonomous Wildfire Monitoring and Georeferencing Using Rapidly Deployable Mobile Units." *IEEE Aerospace and Electronic Systems Magazine* 31 (2): 6–15. https://doi.org/10.1109/MAES.2016.150057.

PG&E. 2021. “Learn about Public Safety Power Shutoffs (PSPS).” 2021. https://www.pge.com/en_US/residential/outages/public-safety-power-shuttoff/learn-about-psps.page.

———. 2023. “Undergrounding: A Safer, Stronger and More Affordable Energy Future.” Conversion of PG&E Electric Overhead Power Lines to Underground. February 2023. https://www.pge.com/en_US/residential/customer-service/other-services/electric-undergrounding-program/electric-undergrounding-program.page.

Plucinski, M. P., A. L. Sullivan, and R. J. Hurley. 2017. “A Methodology for Comparing the Relative Effectiveness of Suppressant Enhancers Designed for the Direct Attack of Wildfires.” *Fire Safety Journal* 87 (January): 71–79. https://doi.org/10.1016/j.firesaf.2016.12.005.

Plucinski, Matt P., Elsa Pastor, Matt P. Plucinski, and Elsa Pastor. 2013. “Criteria and Methodology for Evaluating Aerial Wildfire Suppression.” *International Journal of Wildland Fire* 22 (8): 1144–54. https://doi.org/10.1071/WF13040.

Porter, Thomas, and Wade Crawfoot. 2019. “2017 Wildfire Activity Statistics.” Sacramento, CA: California Department of Forestry and Fire Protection. https://www.fire.ca.gov/media/10059/2017_redbook_final.pdf.

Pruitt, Caley, and Nadia Panossian. 2021. “Request for Input on Electrical Power System Risk to Wildfire Ignition and Personnel,” July 19, 2021.

Pu, Z., Y. Xiong, T. Wu, Z. Lu, and C. Fang. 2019. “Simulation Analysis on Influence of Combustion Particles on the Gap Electric Field under DC Voltage.” In *ICHVE 2018 - 2018 IEEE International Conference on High Voltage Engineering and Application*. https://doi.org/10.1109/ICHVE.2018.8641966.

Ratnam, E.L., K.G.H. Baldwin, P. Mancarella, M. Howden, and L. Seebeck. 2020. “Electricity System Resilience in a World of Increased Climate Change and Cybersecurity Risk.” *Electricity Journal* 33 (9). https://doi.org/10.1016/j.tej.2020.106833.

Sangode, P.B., and S.G. Metre. 2020. “Power Distribution Operational Risk Model Driven by FMEA and ISM Approach.” *International Journal of Quality and Reliability Management*. https://doi.org/10.1108/IJQRM-06-2019-0206.

Sathaye, Jayant, Larry Dale, Peter Larsen, Gary Fitts, Kevin Koy, Sarah Lewis, and Andre Lucena. 2011. “ESTIMATING RISK TO CALIFORNIA ENERGY INFRASTRUCTURE FROM PROJECTED CLIMATE CHANGE.” LBNL-4967E. Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States). https://doi.org/10.2172/1026811.

Scott, Michon. 2022. “Wet, then dry extremes contributed to devastating Marshall Fire in Colorado | NOAA Climate.gov.” January 7, 2022. http://www.climate.gov/news-features/event-tracker/wet-then-dry-extremes-contributed-devastating-marshall-fire-colorado.

SDG&E. 2018. “San Diego Gas & Electric Company Fire Prevention Plan.” https://www.sdge.com/sites/default/files/documents/SDGE_Fire_Prevention_Plan_2018.pdf.

Shi, S., C. Yao, S. Wang, and W. Han. 2018. “A Model Design for Risk Assessment of Line Tripping Caused by Wildfires.” *Sensors (Switzerland)* 18 (6). https://doi.org/10.3390/s18061941.

Srinivasan. 2021. “TWC | Texas Fire Danger (TFD).” March 2, 2021. https://twc.tamu.edu/tfd.

Tang, Lina, and Guofan Shao. 2015. “Drone Remote Sensing for Forestry Research and Practices.” *Journal of Forestry Research* 26 (4): 791–97. https://doi.org/10.1007/s11676-015-0088-y.

USFS. 2021. “National Infrared Operations = USDA Forest Service.” 2021. https://fsapps.nwcg.gov/nirops/.

USGS. 2020a. “Fire Danger Forecast.” 2020. https://www.usgs.gov/ecosystems/lcsp/fire-danger-forecast.

———. 2020b. “Fire Potential Index Map.” 2020. https://www.usgs.gov/ecosystems/lcsp/fire-danger-forecast/fire-potential-index-map.

———. 2021. “Map of Expected Number of Large Fires per PSA.” 2021. https://www.usgs.gov/ecosystems/lcsp/fire-danger-forecast/map-expected-number-large-fires-psa.

“Wildfire and the Wildland Urban Interface (WUI).” 2023. U.S. Fire Administration. March 29, 2023. https://www.usfa.fema.gov/wui/index.html.

“Wildfire Hazard Potential | Missoula Fire Sciences Laboratory.” 2015. USDA Forest Service. 2015. https://www.firelab.org/project/wildfire-hazard-potential.

Wildfire Risk to Communities. 2021. “Wildfire Risk to Communities.” 2021. https://wildfirerisk.org/explore/0/08/.

“Wildfires and Acres: Total Wildland Fires and Acres (1983-2020).” 2021. National Interagency Fire Center. 2021. https://www.nifc.gov/fire-information/statistics/wildfires.

“Wildland Fire Potential Index (WFPI) | U.S. Geological Survey.” 2021. 2021. https://www.usgs.gov/fire-danger-forecast/wildland-fire-potential-index-wfpi#:~:text=WFPI%20(Figure%201)%20is%20developed,and%20relates%20to%20vegetation%20flammability.

“Wildland Fire Spread and Suppression (U.S. National Park Service).” 2017. February 13, 2017. https://www.nps.gov/articles/wildland-fire-spread-and-suppression.htm.

Wong, Stephen D., Jacquelyn C. Broader, and Susan A. Shaheen. 2020. “Review of California Wildfire Evacuations from 2017 to 2019.” *UC Office of the President: University of California Institute of Transportation Studies*, March. https://doi.org/10.7922/G29G5K2R.

Wu, C., J. Lu, B. Chen, Y. Liu, T. Zhou, and T. Zhou. 2020. “Control Strategy for Large-scale Fires near Power Transmission Lines and Its Application.” *IET Generation, Transmission & Distribution*. https://doi.org/10.1049/gtd2.12053.

Wu, C., Y. Zhong, H. Liu, Y. Wang, D. Niu, and F. Gao. 2016. “A Novel Application of BP Neural Networks to Evaluate the Safety of Power Grid in Wildfire Disasters.” *International Journal of Simulation: Systems, Science and Technology* 17 (27): 32.1-32.5. https://doi.org/10.5013/IJSSST.a.17.27.32.

“WWETAC - ArcFuels.” n.d. Accessed January 8, 2021. https://www.fs.fed.us/wwetac/tools/arcfuels/.

Xcel Energy. 2020. “Xcel Energy: 2020 Wildfire Mitigation Plan.” Hearing Exhibit 102, Attachment SLJ-1 Proceeding No. 20A-XXXXE. https://www.xcelenergy.com/staticfiles/xe-responsive/Company/Rates%20&%20Regulations/Regulatory%20Filings/Wildfire%20Protection/Hearing_Exhibit_102-Attachment%20SLJ-1.pdf.

Zentner, Emily, and Chris Hagan. 2019. “A History Of California Wildfires.” CalFire. Capradio.Org. 2019. http://projects.capradio.org/california-fire-history.

Zhang, J.Q., M.H. Fan, W. Li, H. Xie, H.C. Wu, and S.P. Wang. 2016. "Fire Safety of Cables in Power Grid: Tracking Combustion Test Standards of Cables and New Insights on Test Framework." In *CIGRE Session 46*. Vol. 2016-August. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85045268874&partnerID=40&md5=f4a1322fbe7a8cbc3441e0b34ccdd685.

Zhao, X., Z. Gao, and G. Wen. 2020. "Remote Sensing Image-Based Wildfire Recognition Using Capsnet for Transmission Lines." In *IOP Conference Series: Earth and Environmental Science*. Vol. 513. https://doi.org/10.1088/1755-1315/513/1/012072.

Zhou, W., W. Chen, E. Zhou, Y. Huang, R. Wei, and Y. Zhou. 2020. "Prediction of Wildfire-Induced Trips of Overhead Transmission Line Based on Data Mining." *2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, 1–4.

Zhou, Z., and G. Chen. 2018. "Research on Logic Optimization and Reliable Calculation Model of Satellite Based Wildfire Monitoring for Power Transmission Line." In *IOP Conference Series: Earth and Environmental Science*. Vol. 192. https://doi.org/10.1088/1755-1315/192/1/012019.