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Wildfire and power grid nexus in a changing climate

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Abstract | Global wildfire events have caused escalating impacts all over the world in recent years, particularly in the western United States, due to extreme fire-weather, fuel accumulation, and numerous ignition sources. The 2018 Camp Fire in California, caused by powerline ignition, killed 84 people, and caused about $9.3 billion in housing damage, leading to the filing for bankruptcy by the responsible utility service holder - Pacific Gas & Electricity (PG&E). Wildfires caused by power lines tend to be larger and more devastating than other fires, as they are often ignited during high wind conditions, which makes it easy for fires to spread. Moreover, the spreading of wildfires and the corresponding ignition prevention actions would also cause power outages, resulting in tremendous economic impacts. This article reviews wildfire risks in a changing climate and its interdependency with power grid infrastructures, where the power grid resilience in the presence of wildfire is explored, including wildfire-induced grid risk analysis, prediction, and mitigation strategies. Some practical analysis and experiences in the US will be shared to provide valuable insights for researchers, policymakers, and industry practitioners.

Key points |

1. Analyzes global wildfire patterns and the role of advanced modeling techniques in predicting wildfire behavior, assessing risks, and informing mitigation strategies to better protect power systems infrastructure and human communities.
2. Explores the bidirectional interactions between wildfires and power systems, highlighting the risks of powerline-induced ignitions, infrastructure damage, and mitigation strategies to enhance resilience.
3. Comprehensive strategies for wildfire risk management, including proactive measures, real-time mitigation responses, and recovery plans to enhance resilience and reduce wildfire impacts on power systems and communities.
4. Proposes power system resilience roadmap against wildfire integrates wildfire models, proactive strategies, comprehensive planning, funding partnerships, and ongoing evaluation to ensure safety and sustainability amid escalating wildfire challenges.

1. Introduction

In recent years, extreme weather events such as earthquakes, floods, winter storms, hurricanes, and wildfires have caused significant power interruptions worldwide. Among these events, the increasing frequency and intensity of wildfires are profoundly affecting power system operations and planning globally. Regions such as the western United States, Canada, Australia, southern Europe, northern Eurasia, Chile, and Brazil have been notably impacted[1–4]. These wildfires have led to severe environmental, economic, and human damage. The Copernicus Atmosphere Monitoring Service (CAMS) reported that Canada recorded the highest wildfire carbon emissions since 2003[5]. Similarly, Greece experienced the largest wildfire in European Union history, and on August 8, 2023, Maui, Hawaii suffered its deadliest wildfire in over a century, marking a significant event in U.S. weather history[6]. In 2020, the U.S. faced over 58,000 wildfires, burning more than 10 million acres, as reported by NOAA[7,8]. In 2022, over 7.5 million acres were burned, with Texas having the most fires and Alaska having the most acres burned[5]. California remains a focal point, enduring the largest, most destructive, and deadliest wildfires, including the 2018 Camp Fire[9], which resulted in the highest insured loss[10]. In 2023, states with the most homes at risk for extreme wildfires included California, Colorado, and Texas. Texas recently experienced its largest wildfire, the "Smokehouse Creek Fire," which burned over 1 million acres[11], leaving at least 11,000 people without electricity.

Wildfires in the U.S. cause between $394 billion and $893 billion in damages annually, equivalent to 2-4% of U.S. GDP, as per a JEC report in 2023[12]. This is significantly higher than existing estimates in the literature[13]. Climate change is expected to exacerbate the cost of wildfires, making them burn longer and produce more smoke, thereby posing greater challenges to power delivery and generation infrastructure. Addressing the impacts of climate change has become a challenge for the electrical industry and humanity in general. This underscores the urgent need to modernize and fortify the electric grid to ensure continuous electricity access during wildfires and to mitigate the ignition risk posed by aging power transmission and distribution infrastructures. Consequently, discussions on the nexus between wildfires and the power grid in a changing climate have become increasingly prevalent[1,2] .

Resilience refers to the power grid's ability to withstand and recover from high-impact, low-probability events, and to prevent similar issues in the future[14]. Climate change and human-driven land use changes have not only extended the wildfire season but also intensified the severity and expanded the extent of the burned area[15]. As extreme weather events become more frequent, resilience now means safeguarding against and recovering from significant disruptions. Developing models that predict these events, assess their impact, and manage and mitigate their risk is crucial. However, recent wildfires in regions such as California and Australia have exposed the shortcomings of legacy power grids, leading to widespread blackouts and significant socio-economic impacts. The 2018 Camp Fire in Northern California, sparked by PG&E's electrical infrastructure, resulted in at least 85 deaths, the destruction of 18,800 homes and structures, and the burning of 153,336 acres[16], leading to a $13.5 billion lawsuit against PG&E[10]. Similarly, the Thomas Fire, sparked by two Southern California Edison (SCE) power lines in 2017, burned 280,000 acres, destroyed more than 1,000 structures, and incurred approximately $80 million in costs[17]. Other examples, such as the Witch Fire (2007), Black Saturday Bushfires (2009), Bastrop County Complex Fire (2011), and Attica Fires (2018), caused by power lines, have also resulted in significant damage and financial burdens[1]. Power lines can ignite wildfires, particularly in high wind or dense vegetation conditions.

Advanced methods to minimize ignition risks include utility companies de-energizing (i.e. shutting off) power lines during periods of high winds and fire danger. However, this preventive measure has many adverse effects and can disrupt essential infrastructure like hospitals or food supply. In 2019, PG&E planned power shutoffs left 2.7 million people without electricity in California[18], highlighting the need for improved resilience in 21st-century power grid infrastructure[19]. Wildfires can damage power lines and cause power outages that impact critical infrastructure and communities. For instance, a fire at an interconnector in the UK caused the power supply to cease for almost a week and was expected to operate at a reduced capacity for six months. According to the British Broadcasting Company[20], this caused a 19% increase in electricity prices the following day. Given the close relationship between human activity and wildland ecosystems and changes in the climate, power outages due to wildfires could become more frequent[1].

Wildfires present unprecedented vulnerabilities to both natural and built environments, including power grid infrastructure. Enhancing grid resilience against wildfires is essential for effective risk management. Implementing effective wildfire risk reduction strategies is necessary to minimize the impact of fires and power outages. It is crucial to analyze wildfire patterns and severity and understand the interaction between wildfires and power systems to develop these strategies. This article explores the relationship between wildfires and power systems, examining past blackouts, the impact of wildfires on power systems, and ignition sources. It also reviews several wildfire risk management frameworks for electric power systems and identifies research gaps to guide researchers, policymakers, and industry practitioners.

2. Global Wildfire Patterns and Wildfire Modeling

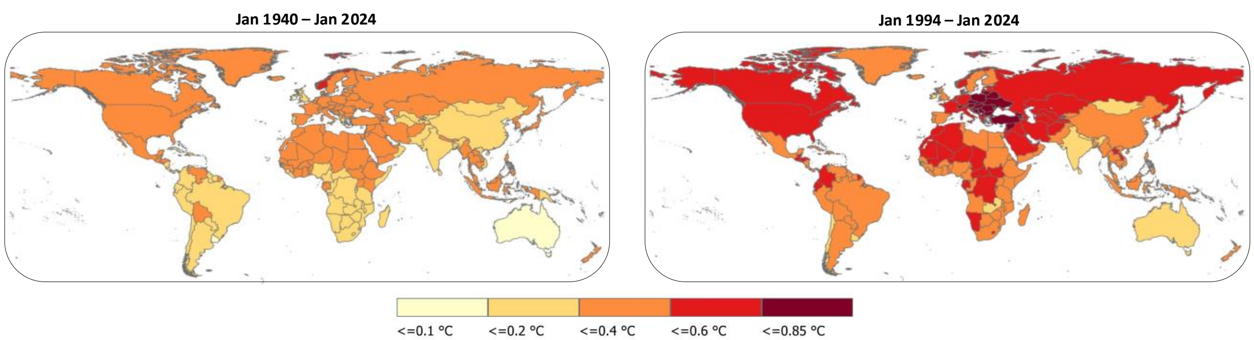

Fig. 1 (a) Trends in annual surface temperature (1994-2024, left) compared to the trend since 1940 to 2024 (right) show recent warming is much faster, especially in the Arctic where ice and snow loss accelerates warming (Data source: Copernicus Climate Change Service: https://ourworldindata.org/climate-change).

2.1. Global Pattern of wildfires

Wildfires arise from the intersection of dry weather, fuel, and ignition sources[21]. Weather significantly influences regional burned areas, with temperature, humidity, precipitation, and wind speed playing key roles in fire spread and intensity[21–24]. From 1979 to 2019, climate change and extreme weather conditions, such as heat and drought, have markedly increased the frequency and intensity of wildfires[25,26]. Models indicate that climate change has impacted fire weather across 22% of global burnable land[27]. NOAA[1] reports that Earth's surface temperature has increased by 0.14°F per decade since 1880, with this rate doubling since 1981[28]. This accelerated warming is likely intensifying the

[1] National Oceanic and Atmospheric Administration

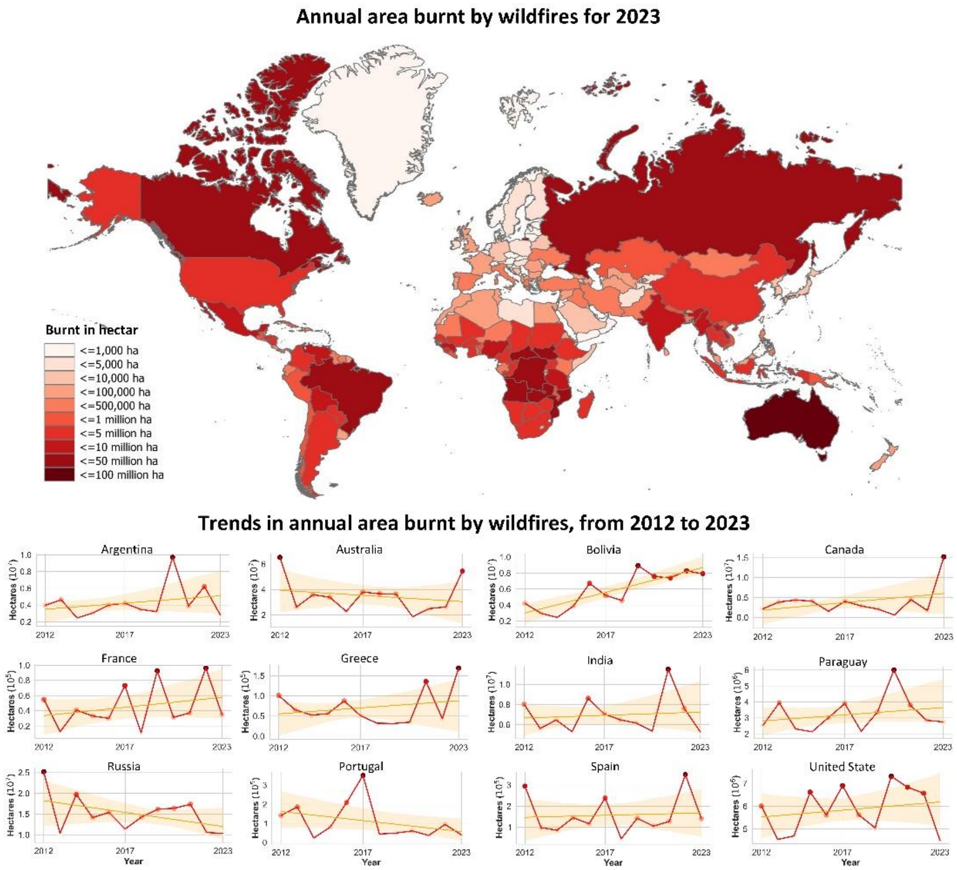

Fig. 1 (b) Annual area burnt by wildfires in hectares (data collected from Global Wildfire Information System: Data: https://ourworldindata.org/wildfires). The orange lines represent the overall trend in burnt area for each country during the specified period with the shaded areas depicting the confidence intervals for the regression trends.

global water cycle, leading to more intense rainfall[29], severe droughts, and changes in regional humidity (Fig. 1(a)). Recent hot extremes, unlikely without human influence, underscore the link between climate change and increased wildfire risk[30].

In April 2024, the Northern Hemisphere recorded its warmest month, at 1.75°C above average, surpassing the previous record set in 2016[31]. Human activities have likely escalated the frequency of extreme events, such as concurrent heatwaves and droughts[30]. The IPCC's "Climate Change 2021: The Physical Science Basis" reports that global surface temperatures have risen by approximately 1.09°C since the pre-industrial era, with projections ranging from 1.0°C to 5.7°C by 2100, depending on CO2 emissions. This warming trend is anticipated to heighten the likelihood and severity of wildfires globally[30]. Annual burned areas are estimated at 350 million hectares per year[32,33], with the burnable area affected by long fire weather seasons doubling in recent decades[33]. These trends illustrate the clear link between rising temperatures and increased wildfire frequency and severity. However, future wildfire activity will depend on complex interactions among climate conditions, fuel availability, and human activities.

Given this context, recent years have seen significant wildfire outbreaks in countries such as the United States, Canada, Australia[34], Southern Europe[35,36] (Spain, France, Portugal, Greece), as well as in South America (i.e. Bolivia, Argentina, and Paraguay), and India (Fig. 1(b)). From 2012 to 2023, trends in annual burned areas show increases in Argentina, Bolivia, Canada, France, Greece, India, Paraguay, Spain, and the United States, and decreases in Australia, Russia, and Portugal, despite ongoing significant wildfire events in these regions[37]. In 2023, major wildfires occurred in Australia, Bolivia, Canada, and Greece, highlighting the rising frequency and severity of wildfires due to climate change and other factors. However, observed trends in the global burned area have decreased despite increasing fire weather. As a result, climate projections alone cannot be used to understand future changes in wildfire activities[38]. Understanding the future dynamics of wildfire activities requires improved projections of climate-wildfire-vegetation feedback, potentially using dynamic global vegetation models (DGVMs) coupled with climate models to simulate future vegetation and fire scenarios. Future human activity, including changes in population, land settlement patterns, and fuel management, will play a crucial role in future wildfire risks.

Future changes in lightning frequency and distribution may influence wildfire risk but are highly uncertain, with some studies predicting increased lightning activity due to higher Convective Available Potential Energy (CAPE), while others suggest a decrease in lightning frequency[38]. There is likely to be regional variation in these changes, with stronger evidence of observed and projected increases in lightning frequency and ignition efficiency in North American boreal forests. This highlights the complexity and uncertainty associated with wildfires compared to many other climate hazards.

The contiguous United States has experienced an increase in the annual average temperature by 1.2°F over recent decades and by 1.8°F since the early 1900s[39,40]. Climate change has resulted in drier conditions, prolonged droughts, stressed forest vegetation, pest outbreaks, and increased surface fuel accumulation[41]. Consequently, fires in U.S. regions are now up to four times larger, three times more frequent, and more widespread in the 2000s compared to the previous two decades[42]. The National Interagency Fire Center reports that the 5-year average of annual wildfire suppression costs on U.S. federal lands is about $2.86 billion (2018-2022), 40% higher than the 2013-2017 average[43]. These trends are expected to persist until mid-century, potentially limiting fuel availability in some western forests[44].

California, particularly Los Angeles and San Diego Counties, has the highest probability of wildfire occurrence[45](Fig. 2 (a)). Other high-risk regions include the Northwest, Rocky Mountain (Colorado), Great Basin (Nevada and Utah)[46], Southwest and South (Arizona, New Mexico, and Texas), and states like Florida, Hawaii, and Alaska. The economic impacts of wildfires are significant, with the Wildfire Hazard Risk Index identifying Southern California, Southern Arizona, Northeast Nevada, Northern

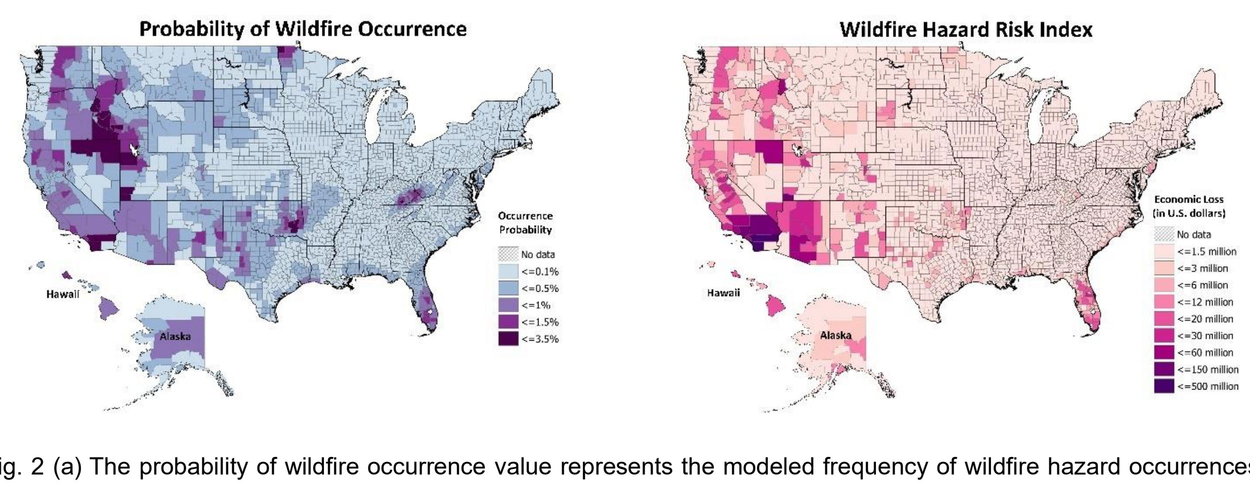

Fig. 2 (a) The probability of wildfire occurrence value represents the modeled frequency of wildfire hazard occurrences (events) per year at the county level (left). The Wildfire Hazard Risk Index presents the community's average economic loss from wildfire hazards each year (right)[44]. The figures are created based on the data that is sourced from Federal Emergency Management Agency 2023 (https://hazards.fema.gov/nri/data-resources). Department of Homeland Security (2023), and the U.S. Department of Agriculture's Forest Services' FSIM Burn Probability and Fire Intensity Level Data.

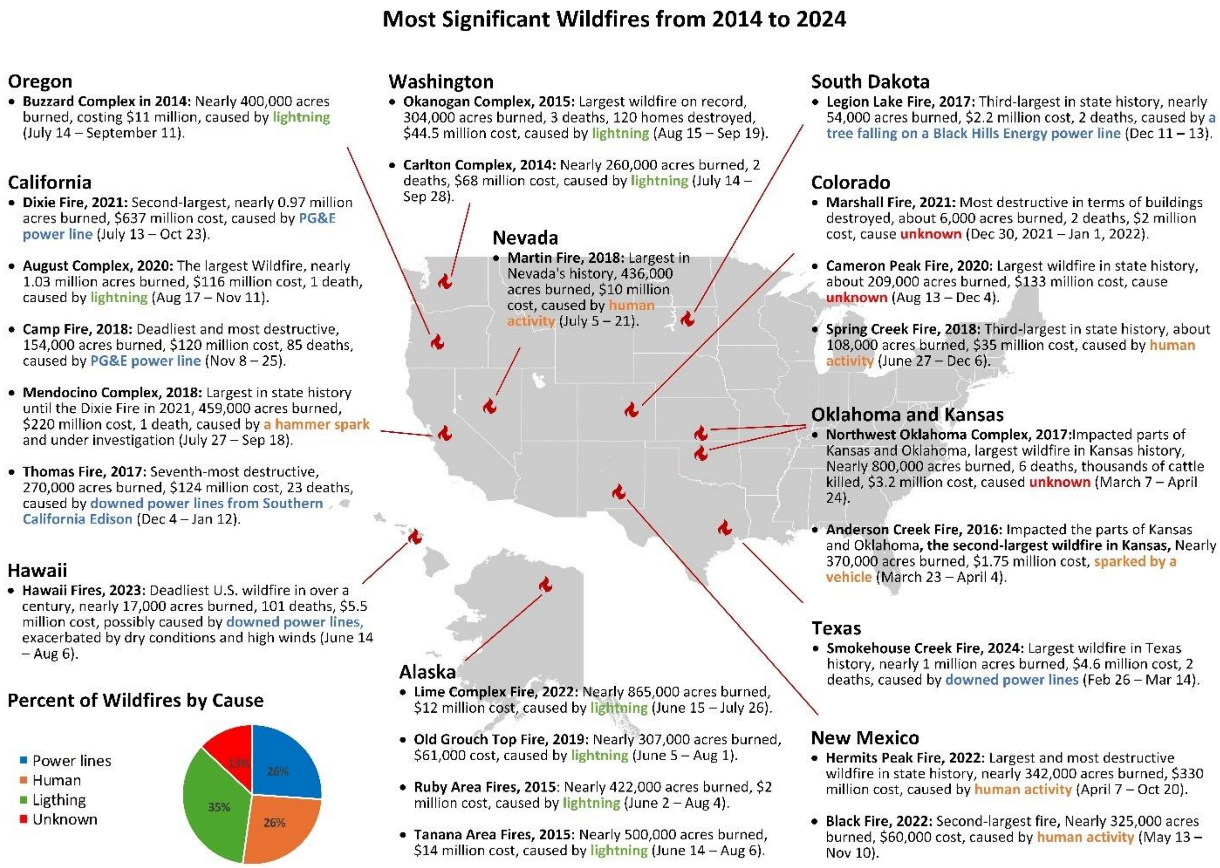

Fig. 2 (b) Key Wildfire Events in the U.S. (2014-2024). Data collected from the Annual National Climate Report (2014-2023) by the National Centers for Environmental Information and the Wildland Fire Summary and Statistics Annual Report (2014-2023) by the National Interagency Coordination Center.

Idaho, and Hawaii as the most affected[47]. From 2014 to 2024, key wildfire events in the U.S. revealed that 35% were caused by lightning, while 26% were attributed either to power lines or human activities (Fig. 2(b)). In California, 60% of notable wildfires[48], as well as all wildfires in Hawaii, Texas, and South Dakota, were caused by power lines, resulting in significant damage and fatalities. The 2023 Hawaii Fires[6] were the deadliest in over a century, while the 2024 Smokehouse Creek Fire[11] was the largest wildfire in Texas history. Wildfires in the Northwest (Washington and Oregon) and Alaska were primarily caused by lightning, while those in the Great Basin, Rocky Mountains, and Southern areas were mainly due to human activities. This trend underscores the urgent need for improved wildfire management and mitigation strategies.

2.2. Wildfire Modeling

As wildfires become more frequent and severe, the demand for advanced wildfire risk assessment products has significantly increased. Effective risk assessment relies on accurate wildfire modeling, which is complex due to the various interacting factors that influence fire intensity, spread, and impacts on human life and infrastructure[49]. Models typically address wildfire spread, wildfire front properties, and wildfire impact. Wildfire spread models predict fire perimeter advance, rate of spread, fire line intensity, and fuel consumption. Wildfire front properties models describe the geometric features of flames, such as height, length, depth, and angle of inclination. Wildfire impact models analyze the effects of wildfires, including heat and emissions, on human well-being and infrastructure.

Wildfire simulation models are vital for understanding fire dynamics and improving fire propagation forecasting, crucial for effective disaster response[19]. Table 1 lists the most renowned and practical wildfire models, detailing their primary applications, key features, benefits, and drawbacks, and explores their use in Power System Resiliency Assessment (PSRA).

Over the last decade, numerous wildfire simulation models have been developed worldwide, crucial for predicting wildfire behavior and assisting in effective fire management. FireSim, developed by Technosylva, is widely used for real-time fire behavior prediction and risk assessment by major utility companies like PG&E and SCE[50–55]. The Interagency Fuel Treatment Decision Support System (IFTDSS), a user-friendly tool developed by the US Forest Service, integrates multiple models to support wildfire risk assessment and fuel treatment planning. Researchers have used IFTDSS for spatiotemporal wildfire analyses to determine Minimum Travel Time Fire Spread (MTT), fire intensity, Fireline major path, and fire spread rate as inputs for the Solid Fire Model to assess power system vulnerability to wildfires[56].

The Solid Fire Model, a physics-based approach for fire behavior simulation and computing radiative heat flux transfer emitted uniformly from a visible flame, was employed to quantify the Dynamic Line Rating (DLR) of conductors impacted by a wildfire[49]. This approach has been further developed to assess the operation of a resilient distribution system towards wildfire[57]. MTT predicts fire perimeter expansion by calculating minimum travel time across a 2D landscape network[59], enabling complex wildfire simulations like FARSITE and FlamMap, which simulate thousands of fires and generate burn probability and intensity maps over large areas[58].

Burn-P3 is an NRCan-developed, landscape-scale physics-based wildfire simulation model that uses the Prometheus[59] model to evaluate fire characteristics and produce burn probability maps[38]. ELMFIRE is an open-source physics-based wildfire spread modeling used for real-time forecasting and risk assessment, with detailed inputs and complex data requirements[38]. US Forest Service developed several wildfire simulations, such as FlamMap, FARSITE, FSPro, FSim, and BehavePlus, each designed for specific applications like fire behavior prediction, risk analysis, and fire management, enhancing wildfire response and planning. Notably, some of these models have been successfully integrated into PSRA.

A recent study utilized FlamMap[60] to evaluate burn probability and the Solid Fire Model to estimate heat flux, assessing wildfire risk and mitigation for an electrical substation. Another recent study presents a data-driven framework integrating Farsite and power flow analysis to determine the risk and vulnerability of transmission network components against grid-ignited wildfire[61]. While FlamMap and FARSITE have benefits, they also come with drawbacks, including high computational costs and the requirement for detailed input data.

Additionally, SiroFire presents deterministic fire spread prediction with a graphical interface, requiring advanced GIS[62]. WRF-Fire incorporates weather data with fire modeling but at a high computational cost[63]. FIRETEC offers 3D fire behavior simulation with coupled fire-atmosphere interactions, demanding detailed input data[64]. WFDS is to simulate smoke and heat transport but is still in the early validation stages[65]. FIRESTAR simulates large-scale wildfires, requiring detailed input data and may be complex[65].

Wildfire simulation models are vital for understanding and managing wildfires. Some, like FireSim and IFTDSS, are integrated into PSRA, while others are valuable for fire behavior prediction and risk assessment, highlighting the importance of ongoing model development to improve wildfire management strategies amid growing threats from climate change and other factors. Future developments may involve integrating stochastic elements, leveraging machine learning algorithms for improved forecasting, and employing early technologies to enhance wildfire propagation models.

Table 1: Wildfire Model Comparison

Wildfire Model	Developer	Primary Application	Key Features	Benefits	Drawbacks	Used in PSRA	Ref
FireSim	Technosylva[2]	Deterministic and probabilistic modeling, real-time fire behavior prediction.	Physics-based wildfire models, initial attack assessment, impact analysis, urban encroachment algorithms, real-time data calibration.	Quickly determine fire path and impacts, all-in-one platform: wildfire risk forecasting, spread predictions, risk mitigation, and fire behavior analysis.	May not capture all complexities of fire behavior, not free for use	Used by PG&D, SCE, San Diego Gas & Electric, Xcel Energy, Bear Valley Electric Service, liberty for Wildfire Mitigation Plan	50–55
IFTDSS	US Forest Service	Fuel treatment planning and wildfire risk assessment	Web-based application, integrates multiple models (FlamMap, FARSITE, BehavePlus)	User-friendly interface, comprehensive US data, step-by-step fuels treatment testing, supports decision making, free access, generates maps, graphs, and tables.	Requires detailed input data, may be complex to use	Using IFTDSS, they provided a wildfire characterization package enabling proactive decision-making for the Wildfire Mitigation Plan.	56
Solid Fire Model	-	1D/2D Flame model for deterministic/probabilistic wildfire risk modeling, fire management, firefighting.	Physics-based approach, detailed fire behavior simulation, computes radiative heat flux transfer	An easy-to-use tool for evaluating wildfire risk, aiding fire management decisions, and integrating into power system risk assessments.	Does not account for crown fires and spotting, represents the flame only as a radiant surface (solid-flame assumption), and may lack accuracy.	The developed resilience assessment quantifies how wildfire characteristics like ignition probability, intensity, spread rate, temperature, and severity affect the failure likelihood of power system components.	49,57, 66–72
MTT (Minimum Travel Time)	US Forest Service	Underlying model for FlamMap and FSim	Physics-based prediction for fire perimeter expansion, calculates minimum travel time across a 2D network of landscape nodes.	Approximates complex fire behavior models at low computational cost (makes it well-suited for running many wildfire simulations), predicts fire behavior and perimeter expansion effectively.	Not designed to predict final fire extent—final perimeters depend on simulation duration, requires detailed input data.	A study evaluated wildfire risk mitigation measures by PG&D, using MTT for detailed ignition risk predictions based on data from over 25,000 miles of high-risk lines[58].	58,73
Burn-P3	Natural Resources Canada (NRCan)[3]	Landscape-scale wildfire simulation	Physics-based model that uses Prometheus model, evaluates fire characteristics, produces burn probability maps.	Detailed predictions, supports planning, open source	Extensive input data, computationally intensive.	No	38,59
ELMFIRE[4]	Chris Lautenberger	Real-time and historical fire spread forecasting	Physics-based model that considers fuel, topography, weather, and fire suppression; Monte Carlo analysis	Real-time forecasting, quantifies fire risk and exposure.	Complex inputs, requires detailed data	No	38
FlamMap[5]	US Forest Service	Deterministic fire behavior prediction and landscape analysis under constant conditions.	Physics-based model, produces raster maps, integrates multiple fire models, provides environmental condition data	Detailed fire behavior maps, comprehensive analysis	Not simulate spatial and temporal variations in fire behavior due to constant environmental conditions	Using this model, a study estimated wildfire risk at an electrical substation in the wildland–urban interface of Valparaíso, Chile[60].	60,74 ,75
Farsite[6]	US Forest Service	2D deterministic fire growth simulation	Huygens, combines models for surface, spot, crown fires, wave dissemination models	Combines multiple fire models, generates fire propagation maps, essential for forest fire extinction decision-making.	Lacks dynamic wildfire simulation, lower crown fire accuracy, unreliable evaluation, poor estimation of spatial fuel and features distribution, needs multiple layers (unavailable inputs)	A study Incorporates power flow analysis to quantify exposure, risk, and vulnerability of power grid components[61].	61,76 –78
FSPro	U.S. Forest Service	Estimating fire spread probability from a known ignition location	Monte Carlo simulations, probabilistic fire spread maps, embedded within the Wildland Fire Decision Support System (WFDSS).	Assesses potential fire growth under various conditions, producing a range of possible fire spread scenarios.	High computational cost, results can be less precise due to probabilistic nature	No	79–82

[2] https://technosylva.com/

[3] https://www.canadawildfire.org/burn-p3-english

[4] Eulerian Level set Model of FIRE spread: https://elmfire.io/

[5] https://www.firelab.org/project/flammap

[6] https://www.fs.usda.gov/research/treesearch/27413

FSim[7]	U.S. Forest Service	Probabilistic quantitative wildfire risk analysis	Physics-based model, simulates wildfire growth using geospatial data on fire history, weather, terrain, and fuel conditions.	Comprehensive risk analysis, probabilistic simulations	Complex to use, requires detailed input data	No	83–85
BehavePlus[8]	U.S. Forest Service	Deterministic fire management applications	Raster-based, simulates surface fire spread and effects based on user inputs.	Flexible and user-defined simulations	Requires detailed input data, may be complex to use	No	86
SiroFire[9]	CSIRO	Deterministic fire spread prediction in graphical environment	Huygens, Graphical user interface, GIS-derived databases, wave dissemination models	Graphical user interface, accurate fire spread prediction, simulates wind velocity, relative moisture, and temperature variation.	Runs from 9 am to 9 am next day, requires GIS data, unresolved fire edge issues, needs advanced GIS skills for input preparation, complex fuel layers.	No	62
WRF-Fire[10]	UCAR	Wildland surface fire simulation platform within the Advanced Research WRF (ARW) dynamical core	Physics-based model, coupled atmosphere-fire model, surface fire, data assimilation, Rothermel's ROS, realistic wildfire propagation.	Combines weather data with fire modeling, data assimilation (input of additional data while the model is running)	Complex setup, high computational cost, requires detailed input data	No	63
FIRETEC[11]	Los Alamos National Laboratory	3D two-phase transport model for deterministic fire behavior	Physics-based computational fire model, coupled fire–atmosphere interaction (the wind's impact on the fire and vice versa), Large Eddy Simulation (LES) approach.	3D modeling, Coupled fire–atmosphere model, high accuracy	Requires detailed input data, high computational cost	No	64
WFDS	NIST[12]	Numerical simulation of smoke and heat transport	Physics-based fire model, Navier–Stokes equations, wildland fuel sub-models.	Numerical simulation of smoke and heat transport	Early stages for full-scale wildfires, ongoing validation, requires detailed input data.	No	65
FIRESTAR	University Aix-Marseille	2D Simulate wildfires at a large scale	Physics-based computational fire model, implicit solver, combustion reaction rate calculation	Large-scale wildfire simulation, includes various fuel particle types in the same grid cell	Large-scale simulation may be complex, requires detailed input data	No	65

3. Interaction Between Wildfire and Power Systems

Wildfires can significantly damage electric infrastructure, causing widespread blackouts, while the electric infrastructure itself can also ignite wildfires, impacting human life, infrastructure, and society. Fig. 3 illustrates these complex interactions, emphasizing climate change's role in creating conditions like high wind speeds, dry fuels, low humidity, and a high fire potential index, which increases wildfire activity. This section explores past blackouts caused by wildfires, the electric infrastructure at risk, and wildfire ignition sources within the power system, highlighting the history of wildfires ignited by electric infrastructure.

3.1. Wildfire Impacts on Power Systems and Wildfire-Induced Blackouts

Overhead power lines span vast areas of flammable forests and grasslands, making them both ignition sources and vulnerable infrastructure during wildfires. Studies have shown a notable increase in powerline failures causing fires over the past 71 years due to inadequate maintenance and grid expansion[87]. Wildfires can cause both temporary and permanent damage to electric power infrastructure, leading to significant blackouts globally. For instance, the Australian fires between December 2019 and January 2020 caused over 80,000 outages across the National Electricity Market[88]. In 2007, the Tatong bushfire in Victoria, Australia, cut power to 620,000 households, causing

[7] https://firelab.org/project/fsim-wildfire-risk-simulation-software

[8] https://www.firelab.org/project/behaveplus

[9] https://www.iklimnet.com/hotelfires/fire_modelling_software_17.html

[10] https://unr-wrf-fire.readthedocs.io/en/latest/

[11] https://www.lanl.gov/orgs/ees/ees16/FIRETEC.shtml

[12] https://www.nist.gov/el/fire-research-division-73300

A$234 million in economic losses. Similarly, in 1985, a brush fire in southern Florida left 3.5 million people without power for hours[89]. In 2023, a brush fire in Argentina led to a significant power outage affecting large sections of the country, including the capital, when it impacted transmission lines near a nuclear power plant, causing the plant to go offline[90]. That same year, forest fires in Quebec, Canada, left 500,000 customers without power when three transmission lines became unavailable[91].
Transmission and distribution lines are particularly vulnerable as they often pass through flammable areas. Wildfires affect the power system in various ways[49,57,66,69,71,92–95]:

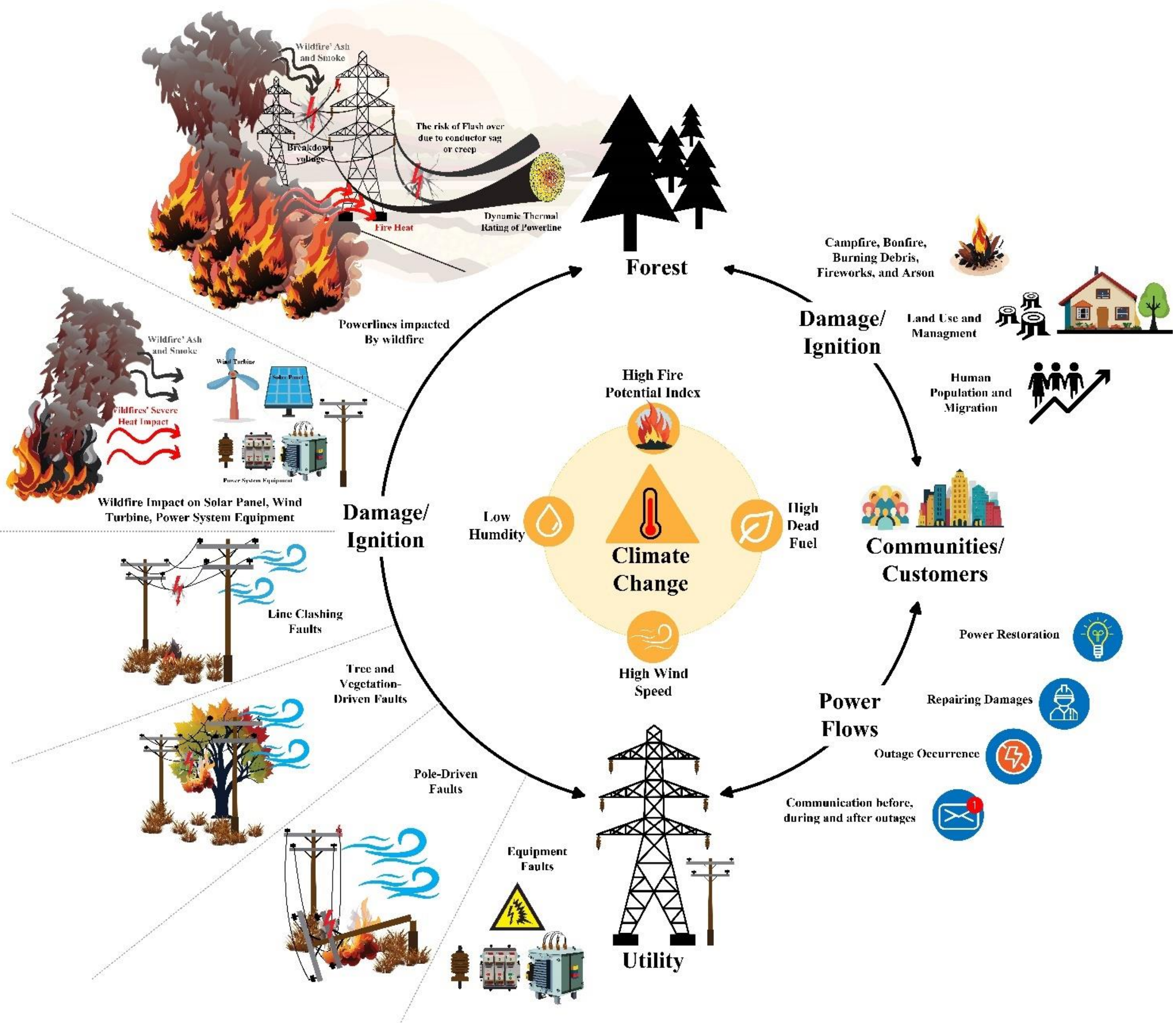

Fig. 3: Wildfire and Power system Interaction. This demonstrates the interaction between wildfire, power system, and customers, combining some subfigures illustrating how wildfire impacts power system operations and infrastructure, how the power system ignites wildfire and impacts wildfire response. It highlights human activities, like campfires and debris burning, that increase wildfire risk, and the impact of outages on communities, including power restoration efforts.

Powerlines: Wildfires can damage powerlines through exposure to smoke, ash, and high heat. Burning wooden poles/towers can collapse transmission and distribution networks[49]. Radiant heat can raise conductor temperatures, reducing their thermal ratings, causing sag and creep, and increasing flashover risk. Conductor annealing may necessitate line replacement[71,96]. Ash on insulators can create conductive paths, causing shutdowns and reducing breakdown voltage[96]. Smoke can ionize air, causing arcing and outages, potentially igniting new fires[70,97]. Research is needed to develop fragility curves for smoke, ash, and temperature impacts[98].

Solar PVs: Wildfire smoke can reduce the output power of PV solar panels by decreasing visibility and irradiance levels, affecting grid stability[94,95,99,100]. The impact varies depending on the solar cell material[95]. The "Wiggle Effect," caused by smoke, jeopardizes grid stability[99]. Understanding this impact and developing mitigation plans is crucial. Future work could predict the smoke impact on PV generation using weather data and satellite image processing-based models[101]. Ongoing research aims to develop a wildfire smoke surrogate model to estimate changes in Aerosol Optical Depth from increased smoke[102].

Wind Turbines: Wildfires can destroy wind turbines and reduce their efficiency by depositing soot or ash on blades, decreasing their smoothness and power output[94]**.** Further research is needed to examine interactions between soot, ash, and turbine blades[103].

Power Equipment: Wildfire heat can soften plastic insulation[104], fracture ceramic insulators, and damage components like transformers, switches, clamps, bushings, capacitors, and surge arrestors[105]. High temperatures can cause explosions and accelerate insulation aging in transformers, increasing failure risk[106]. Extreme heat also accelerates chemical reactions, heightening the risk of malfunctions such as arcing and loss of control signals.

In summary, wildfires impact power systems in various ways, both immediately and in their aftermath. A comprehensive model must consider the fault probability of different system components, the impact on distributed energy resources, reserve allocations, and electric demand. Considering probability density functions of weather factors and fuel types across scenarios can help utilities make optimal operational and planning decisions[49,67,107].

3.2. Wildfire Ignition by Power Systems

Power lines and equipment can ignite wildfires through downed lines, conductor slaps, recurring faults, and component failures[19,108]. These ignitions account for 10% of the acres burned by wildfires in California[109] PG&E reported that the electricity grid caused 414 wildfires in California between 2015 and 2017[110]. Distribution lines pose nearly three times the ignition risk compared to transmission lines due to vegetation for distribution and animal interactions for transmission. In Texas, power lines caused over 4,000 wildfires between 2010 and 2014, costing hundreds of millions of dollars[111,112]. Notable wildfires in California caused by power grid infrastructure include the 2018 Camp Fire and 2007 Witch Fir[48]. In Alaska, major fires caused by power lines include the 2014 Tyonek Fire, 2015 Twin Creeks Fire, and 2019 McKinley Fire[113]. A downed power line likely caused the Maui Fire in Hawaii in 2023[114].

The prevalence of severe fire weather, defined by factors like temperature, moisture, vegetation, and wind, along with increased load on power lines and aging infrastructure, contribute to fire ignitions from power systems[105]. High wind conditions are particularly crucial, especially during droughts and hot weather[105,115–117]. At least five of the 20 most destructive wildfires in California were caused by power systems[118,119].

Tree and Vegetation-Driven Faults (Indirect Wind-Related Faults): These are significant causes of issues in power systems. In California, vegetation contact causes 53.5% of power utility ignitions[120]. Faults occur when a conductor breaks and contacts the ground, leading to high-temperature arcing, a common cause of wildfires in Texas[121]. Broken trees or limbs falling on power lines can result in single-phase-to-ground faults, while high winds can cause conductors to swing into nearby vegetation, leading to earth or phase-to-ground faults[122,123]. High-impedance faults, where high voltage current passes through vegetation without exceeding protection device thresholds, pose significant detection challenges and ignition risks[124–126].

Conductor Clashing Faults (Direct Wind-Related Faults): These occur when two bare conductors contact due to high winds, causing current flow between them. This can heat the lines to the point of melting and potentially eject heated particles or molten droplets that can ignite fuels upon contact with the ground[1]. Thermal expansion from high temperatures leads to conductor sagging[94,127,128]. To prevent ignitions during extreme conditions, utilities in California have implemented Public Safety Power Shutoff (PSPS) events.

Pole-Driven Faults: Wildfires can be caused by pole issues, particularly in the distribution network[105,108]. Common failure modes include corrosion and various pole component issues[129]. Breakdown mechanisms of insulators, framing configurations, and environmental contamination contribute to pole fire incidents[130]. Wooden poles are particularly susceptible to pollution-induced leakage currents[131,132]. Mitigation plans include using new metallic structures with insulation coordination gaps, fully bonded structures, modified insulators, regular maintenance practices, and replacing equipment with fiberglass alternatives[130]. Steel poles, though more resistant, are costly and susceptible to corrosion[103]. High winds and car accidents can also cause aging distribution poles to fall, leading to line clashing or vegetation-driven faults[108]. There is a gap in research on the role of preventive maintenance in preventing wildfires caused by aging power pole infrastructure.

Equipment Faults: Transmission and distribution transformers, as well as failures of switches, breakers, bushings, clamps, capacitors, or surge arrestors, can initiate wildfires through overheating, arcing, or explosion[133–135]. Transformers are increasingly causing fires due to their inability to handle new strains in the North American power grid[105]. For example, a transformer malfunction in Killeen, Texas, sparked a fire that destroyed 50 acres of land[136], and the Thomas Fire started from a transformer explosion[137]. Older transformers with degraded insulation are more prone to failures. Replacing oil-immersed transformers with dry-type equivalents is one mitigation method, but the risk of transformer explosions during wildfires persists[105,138]. Research in power transformer explosions is still in its early stages.

In summary, wind significantly impacts powerline-related wildfires, either by directly interacting with lines or indirectly causing foreign objects to interact with them[1]. Transmission conductors are vulnerable to wind hazards, which are expected to worsen due to climate change. Analysis of San Diego Gas & Electric's data shows outages are ten times more likely with every 25 km/h wind speed increase[117]. The American Society of Civil Engineers advocates for adaptive infrastructure to mitigate the adverse effects of powerline-induced ignition[139]. California utilities use PSPS events to prevent ignitions but must balance the risks of wildfires and blackouts[140]. Research is needed on preventive maintenance to reduce wildfire risks from aging power infrastructure and other fire-causing components.

4. Wildfire Risk Management: Proactive, Real-Time Mitigation Response, and Recovery Plans

Wildfire risk management in the context of electric grid operations can be split into three aspects: Proactive plans to mitigate long-term risk, real-time response to high-risk events, and recovery after the fire and/or high-risk event has passed. These aspects are summarized in table 2, which provides an overview of the current wildfire risk management strategies and categorizes them into proactive, real-time mitigation response, and recovery plans. Each method, technology, principle, and its associated advantages and challenges are discussed in detail in the following subsections.

Mitigating electric grid-caused wildfires has been of utmost importance to utilities. Utilities understand the importance of reducing electric grid-initiated wildfires and reducing wildfire impacts on humanity. Utilities also have seen significant lawsuits[10] related to electric grid-ignited wildfires. For example, PacifiCorp's settlement for the 2020 Archie Creek fire in Oregon and PG&E's large settlements for the California fires, 2018 Camp Fire, 2020 Zogg fire, and 2021 Dixie Fire[48].

Table 2: Wildfire Risk Management

Category	Methods and Technologies	Advantages	Challenges	References
Proactive Plans	**Line Undergrounding and Covered Conductors**: Replacing bare wires, prioritizing high-risk areas	Reduces faults and ignitions, protects lines from fire	Extremely expensive, changes in electrical/mechanical properties	50,141,142
	Protection Equipment: Fuses, relays, circuit breakers, FCLs	Timely detection and fault prevention	High-impedance faults challenging to detect, costly	105,143–145
	New Technologies: REFCL, GFN, ASC, machine learning algorithms	Reduces fault energy, predictive fault detection	Implementation costs, requires extensive planning	146,147
	Asset Management: UAVs for inspection, digital monitoring, transformer aging calculation	Prevents faults, improves reliability	Requires advanced technologies and expertise	138,148–150
	Vegetation Management: Trimming encroaching vegetation, using LiDAR and UAVs for inspection	Reduces risk of ignitions, cost-effective long-term	Requires ongoing maintenance, high initial costs	50,151,152
Real-Time Mitigation Response Plans	**Situational Awareness and Forecasting**: Remote sensing, IoT, advanced wildfire simulation tools	Real-time risk management, improved decision-making	Data integration challenges, requires advanced technology	116,152–154
	Proactive De-energizations: EPSS, PSPS	Reduces wildfire risk during severe weather	Public disruptions, economic impact	3,147,155,156
	Proactive Protection and Operation Strategies: Adjusting reclosers, circuit breaker settings	Reduces ignition risk, improves safety	Longer outages, increased tripping frequency	49,66,69,71,157
	Firefighting Methods: UAVs for early suppression, efficient tactics	Effective suppression, operational in hazardous environments	Requires coordination, high operational costs	158–160
Recovery Plans	**Recovery Logistics**: Resource mobilization, strategic stockpiles, PSSSP	Efficient recovery, optimized resource use	Limited research specific to wildfires, complex planning	161–165
	Microgrids & Emergency Power: Mobile generators, power storage, DER-based microgrids	Ensures electricity supply to critical facilities	High costs, regulatory challenges	166–169
	Financial Recovery Strategies: Self-insurance, commercial insurance, catastrophe bonds	Ensures financial stability and recovery	Lack of literature on effectiveness, complex financial planning	170–172

4.1. Proactive Plans

Proactive plans are essential for utilities to reduce wildfire ignition risks. While utilities cannot control the fire threat from the surrounding landscape, they can focus on mitigating ignition risks through various proactive measures. These measures include vegetation management, equipment upgrades, grid design improvements, system hardening, and the adoption of advanced technologies for better risk assessment, asset management, and situational awareness. Comprehensive mitigation plans ensure safety and cost efficiency[60]. Utilities can enhance system resiliency through grid design and system hardening.

Line Undergrounding and Covered Conductor: Undergrounding power lines is highly effective in reducing power line faults and preventing wildfire ignitions, improving reliability, and protecting lines from fire. However, it is prohibitively expensive on a large scale. For example, PG&E in California increased electricity rates by an average of 13% primarily to fund wildfire mitigation efforts[142]. For smaller electric cooperatives, the cost of undergrounding, especially in rural areas, may be too high. An alternative is using covered conductors, which replace bare wires with conductors covered in insulating material to reduce ignition probability[141]. PG&E prioritizes replacing conductor segments of transmission circuits in High Fire Threat District regions to further decrease the risk of asset failure-triggered fires[50]. However, the insulating material may alter the electrical and mechanical properties of the line and could be susceptible to burning.

Protection Equipment and Wildfire Ignition Mitigation Strategies: Timely detection of faults capable of causing fires, voltage reduction, and limiting fault current is essential to prevent wildfires[19]. Fast detection is critical, as low impedance faults with high amplitudes can ignite wildfires but are detectable by fuses, relays, fast circuit breakers, and fault current limiters. High-impedance faults, however, are challenging to detect due to their low current amplitude and are a major driver of large-scale wildfires caused by power grids[105]. Current practices focus on detecting faults once they occur[105,143,144], but there is a research gap in predicting these faults to enable proactive prevention. Novel protective relays using traveling wave technology with machine learning techniques are under development to significantly reduce arc fault time, directly reducing fire ignition probability[145]. These new protection algorithms can detect low-impedance faults in less than a quarter cycle and high-resistive faults in less than a cycle. Moreover, expulsion fuse retrofits with non-expulsion fuse designs can reduce ignition chances due to less molten particle emission[141]. However, the reliability and potential peripheral ignition concerns of these replacement technologies need to be proven over time.

Rapid Earth Fault Current Limiters (REFCL), Ground Fault Neutralizers (GFN), and Arc Suppression Coils (ASC) can reduce fault energy and wildfire ignition probability. REFCL technology in Victoria, Australia, has reduced fire starts by 30-35% over ten years through mitigation risk plans, including digital monitoring systems, smart meters, and REFCLs. SCE has tested many of these technologies and summarized their findings[146]. Utilities like PG&E have implemented further protective measures such as installing animal and bird guards, clearing poles, and replacing non-exempt equipment[147]. These actions add another layer of protection in comprehensive wildfire mitigation programs but are costly and require extensive multi-year planning and regulatory approval.

Asset Management and Inspection: Efficient asset management and preventive maintenance can prevent fire-causing faults. Indirect wind-related faults, line clashing, pole-driven, and equipment faults pose wildfire risks. Transformer explosions are a known risk with preventive studies[138,148,149], but gaps remain in addressing aging infrastructure. PG&E developed transformer failure inspection by incorporating transformer oil temperature and aging calculations[50]. Unmanned aerial vehicles (UAVs) and digital cameras are cost-effective for power line inspection, with vision-based analysis using machine learning and deep learning methods[151]. However, challenges include limited data, computational efficiency requirements, and complexities in detector performance[151]. Developing robust real-time detectors is crucial. PG&E uses aerial and intrusive inspections for comprehensive pole inspection (CPI) to prioritize repairs. SCE improves grid safety and reliability with the Deteriorated Pole and Pole Loading Program[51], enhancing pole resilience with fire-resistant composite poles. SCE's Long Span Initiative uses LiDAR to identify conductor clash risks, remedying them with line spacers and covered conductors.

Vegetation Management: As discussed in the subsection "Tree and Vegetation-Driven Faults," indirect wind-related faults are a substantial issue in power systems. Utilities and cooperatives worldwide invest significantly in vegetation management, a key strategy to mitigate wildfire ignition. This entails extensive vegetation trimming, particularly in high-fire threat areas, to decrease costs and lower fire ignition risk. LiDAR is used to determine tree height and predict power outages along utility lines[152]. High-resolution imagery from UAVs and LiDAR can be fused to calculate tree clearance anomalies[173] predict tree incursion, and forecast tree growth, delineated by species, to time trimming cycles. Image segmentation and deep learning algorithms such as UNet detect tree mortality[174] and can further predict treefall interactions with power lines. Integrating data from drone and satellite inspections with advanced models improves the identification and timing of vegetation management practices.

4.2. Real-time Mitigation Response Plans

While proactive plans address long-term wildfire risk mitigation, this section focuses on adopting forward-looking strategies during high-risk periods and risk-informed strategies during actual wildfires to efficiently manage resources and minimize damage[1,2,19,116,116,147]. This includes weather-driven responses like Enhanced Powerline Safety Settings (EPSS) and PSPS to prevent ignitions and adaptive grid operations to minimize damage during wildfires. Key areas examined include situational awareness and forecasting, proactive power line shutdowns, firefighting methods, wildfire monitoring systems, and emergency management procedures for power grids during wildfires.

Situational Awareness and Forecasting: Situational awareness and forecasting are vital components of Mitigation Response Plans, enabling utilities to continuously predict, monitor, and manage wildfire risks in real-time through advanced technologies and data analysis[116]. This approach includes wildfire detection, prediction, and tracking using advanced simulation tools, remote sensing, and IoT. Integrating meteorological data and vegetation conditions, wildfire prediction models assess risk effectively[153]. High-resolution satellite sensors and UAVs enable detailed observations, aiding in wildfire tracking, severity mapping, and assessment[166]. Fire severity mapping, achieved through advanced algorithms analyzing satellite imagery, offers efficient estimations of fire extent and severity[168]. Programs like the New South Wales Fire Extent and Severity Mapping (FESM) and the Monitoring Trends in Burn Severity (MTBS) utilize remote sensing for comprehensive fire severity assessments[179,180]. For example, the Bootleg fire in Oregon (2021) severity map was derived from MODIS and Landsat imagery (Fig. 4), and classified into severity levels using the USGS threshold. Overlaying this map with power lines provides a further assessment of risks to infrastructure[107,116]. Remote sensing technologies identify fire hazards near infrastructure and assess power grid vulnerability[115]. Advanced techniques, like the coarse-to-fine approach using public airborne LiDAR data for preliminary analysis and drone LiDAR for detailed inspections, enhance risk evaluation along high-voltage power lines[181]. Indices such as the Fire Potential Index (FPI) and the Fosberg Fire Weather Index (FFWI) evaluate fuel characteristics and wildfire risk, informing decisions like PSPS[116,147]. Monitoring fuel moisture content (FMC) through satellite observations is also crucial[154] in this context.

Wildfire detection, achieved by fusing MODIS, GOES, and VIIRS thermal satellite imagery, is visualized for situational awareness during events. These detections serve as ignition inputs for wildfire spread models, forecasting fire extent and direction[173]. The commercial development of thermal satellite constellations aims for higher resolution, with 50m resolution images expected by 2026 at a 15-minute revisit rate[182]. Researchers emphasize predicting wildfire scales using meteorological data and neural networks[183], employing Poisson regression models for fire activity predictions based on satellite data[184], adaptive neuro-fuzzy inference systems[185], IoT-fog-cloud frameworks[186], and combining fault probability with vegetation ignition likelihood[187].

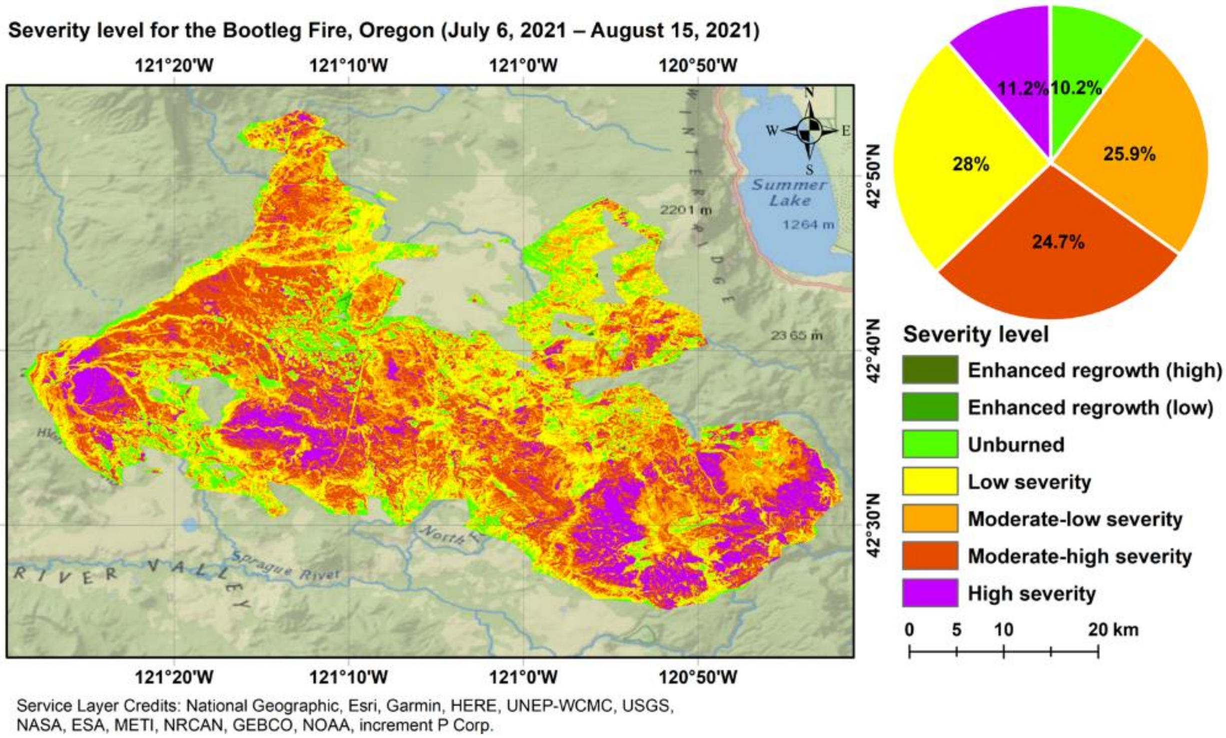

Fig. 4 Wildfire Severity Map for the Bootleg Fire, Oregon (July 6, 2021 – August 15, 2021)

Proactive De-energizations: Selective de-energization of power lines, like EPSS and PSPS, reduces wildfire risk during severe weather. EPSS, an enhanced PSPS by PG&E[147], rapidly detects faults and shuts off the power, while PSPS is a last resort measure during severe weather. Despite their effectiveness, they can disrupt public life, as seen in California's 2019 PSPS affecting nearly a million customers for a week[155]. The research aims to maximize power delivery while minimizing wildfire risk[156]. PSPS triggers vary but often include wind speed, fuel conditions, humidity, and temperature. Integrating engineering solutions with socio-economic sciences is crucial for future PSPS studies[3,116]. EPSS criteria include adjusting device sensitivity, utilizing fire-risk mapping, and responding promptly to outages[147]. Utilities like PG&E explore options like providing backup batteries to susceptible customers to reduce PSPS and EPSS impact, though cost remains a concern. Recent research comprehensively reviewed PSPS, suggesting the need for integrated solutions[3].

Proactive Protection and Operation Strategies: Grid operations during wildfires focus on mitigating distribution network impacts[157], estimating conductor temperature[49,66], assessing vulnerability[66], optimizing grid operations[49,66,67], optimizing grid operations[57,68,72], evaluating insulator performance[188], enhancing resilience[68], studying reliability[69,71], developing early warning systems[70], and analyzing rate impacts[49,57,71]. Proposed optimization frameworks assess wildfire dynamics to help operators strategize before fires reach distribution lines[56]. Reinforcement learning approaches enable proactive power system operations by providing setpoints for power generation resources[189]. Geographical data correlates wildfire risk with power network models, demonstrating that microgrid-equipped systems can sustain operations during severe fires, reducing overall outages[190]. Studies analyze power line aging due to forest fires[69], develop line outage models based on air gap voltage breakdown and wildfire prediction[71], and propose combined outage probability models[70]. Settings for reclosers and circuit breakers can be adjusted to reduce wildfire ignition risk. Disabling reclosers, reducing reclose attempts, or increasing reclose time after a fault during high-risk conditions can reduce fire risk but may result in longer outages. Adjusting circuit breaker time-over-current settings can also reduce fire risk but may increase tripping frequency. Implementing both adjustments can improve protection but may lead to more frequent and longer outages, potentially affecting customer satisfaction.

Firefighting Methods: Aerial vehicles play a critical role in wildfire suppression due to their range and maneuverability, offering advantages over manned aircraft[19,116]. UAVs are effective for early targeted suppression, operating in smoky, hazardous environments[158]. Efficient wildfire suppression tactics are addressed in publications like the National Wildfire Coordinating Group's Wildland Fire Suppression Tactics Reference Guide[159]. Limited descriptive analytics of suppression operations have led to an increased focus on predictive analytics for decision-making support[19]. Recent work evaluates current suppression practices for large wildfires in Victoria, Australia, emphasizing the need for more research on efficient suppression tactics, especially concerning wildfires caused by power grids[160].

4.3. Recovery Plans

The role of recovery preparedness is crucial in enhancing system resilience and facilitating efficient recovery from wildfires. This section emphasizes comprehensive recovery logistics, energy contingency plans, disaster risk financing mechanisms, and community engagement for effective post-disaster recovery.

Recovery Logistics: Recovery logistics are vital in disaster risk management, encompassing personnel, equipment, transportation, inventory management, planning, and technology[19]. Utilities must proactively assess wildfire impacts, plan for resource mobilization, and maintain strategic equipment stockpiles. The research introduced the Power System Stochastic Storage Problem (PSSSP)[161], optimizing stockpiling and distribution of power system supplies to maximize power delivery during disaster recovery. Operations research in disaster logistics[162] and models for recovery logistics during hurricanes[163–165] can be adapted for wildfires, though specific research on wildfire recovery logistics is limited.

Microgrids & Emergency Power: Recovery from wildfires can take days to months, depending on infrastructure damage. Contingency plans to ensure electricity supply to critical facilities and vulnerable communities are essential. Long-term solutions include adopting microgrids to improve resilience[166,167], while emergency responses can involve mobile generators[168] and power storage units[169]. Research gaps exist in energy contingency planning for wildfires[19]. A study suggested an operational mechanism for restoring critical loads via microgrids and automatic switches, using a distributed multi-agent coordination model[191]. Another study used Monte Carlo simulations to assess microgrid impacts on power system resilience[192]. PG&E distributes batteries and subsidized generators to customers, but local generators pose hazards like air quality issues and fuel risks[166]. Transporting replacement fuel during wildfires is dangerous, prompting some sites to invest in large underground storage for enhanced resilience. Microgrid deployment is gaining traction globally as a solution against wildfires and extreme events. For example, the Blue Lake Rancheria microgrid in California, with 500 kW of photovoltaic (PV) power, a 1-MW/2-MWh battery bank, and a 1-MW backup generator, provides critical services during outages, demonstrating the value of microgrids in enhancing resilience. Additionally, PG&E and other utilities are encouraged to develop temporary mobile substation generator projects and community microgrid programs[166]. Programs in Australia, Canada, Hawaii, and Japan highlight the opportunities and challenges of using distributed energy resources (DER) and microgrids for resilience[166 ,215 195]. Designing an optimal DER portfolio against wildfires requires a robust methodology considering uncertainties. A proposed approach in the UK adopts a risk-based probabilistic techno-economic framework[196]. A practical DER design involves both preventive measures (such as upfront investments in DER equipment) and corrective measures (such as immediate and delayed actions) to mitigate the impact of wildfires[166].

Financial Recovery Strategies: The economic impact of wildfires can be destructive, threatening utilities' financial health and solvency[170]. Developing disaster risk financing strategies and integrating operational and financial preparedness is essential for resilient infrastructure[171]. Various disaster risk financing mechanisms[19,170,171] help utilities cover wildfire risks, including funded self-insurance, commercial insurance, catastrophe bonds, captives, risk pooling, and recovery bonds. Funded self-insurance involves setting aside reserves to cover losses, while commercial insurance spreads coverage costs to ratepayers[172]. Catastrophe bonds transfer risk to investors, and captives offer insurance to parent companies. Risk pooling shares risk among participants, and recovery bonds provide post-disaster financing for reconstruction. Combining these mechanisms ensures adequate coverage for different wildfire scenarios, though the literature on their effectiveness in power grid infrastructure resilience is scarce[170].

Community resilience: Community resilience and engagement are vital for wildfire readiness and recovery[19]. Enhancing community resilience involves five steps: reducing risk and addressing vulnerabilities, engaging communities in mitigation, building networks for resource mobilization, boosting social supports post-disaster, and promoting flexibility and effective communication[197]. Ongoing engagement by utilities and local governments is crucial for smooth recovery. Studies highlight the importance of social capital and community engagement in recovery[198]. For example, a study analyzing tweets during Hurricane Irma revealed high activity and coordination roles of local agencies in communication and mass care[199]. PG&E implements various programs to help communities prepare for and recover from wildfire-related power outages, offering resources such as portable batteries, generator rebates, backup power meters, online safety information, local resource partnerships, and meal replacements for impacted residents[147].

5. Outlook

Addressing the escalating challenges posed by wildfires and their impact on power systems requires a collaborative and comprehensive approach. Our Power System Resilience Roadmap against Wildfire (Fig. 5) outlines a structured pathway through three pivotal steps: Wildfire Resilience Foundation, Planning & Strategy Development, and Plan Adoption, Implementation, and Evaluation.

The foundation of wildfire resilience begins with understanding the geographic regions and infrastructures most at risk. This involves analyzing global and regional wildfire patterns, considering climate impacts, and developing a flexible wildfire model tailored to specific conditions. Visualization through maps and charts aids in understanding the scope and intensity of wildfire threats.

Planning & Strategy Development focuses on proactive measures, mitigation responses, and recovery planning as detailed in section 4. This includes implementing proactive plans such as line undergrounding, advanced protection equipment, asset management, and vegetation control. Mitigation response plans emphasize situational awareness, forecasting, proactive de-energizations, and firefighting methods. The integration of real-time monitoring and remote sensing technology is critical, alongside enhancing grid operation optimization and emergency management procedures.

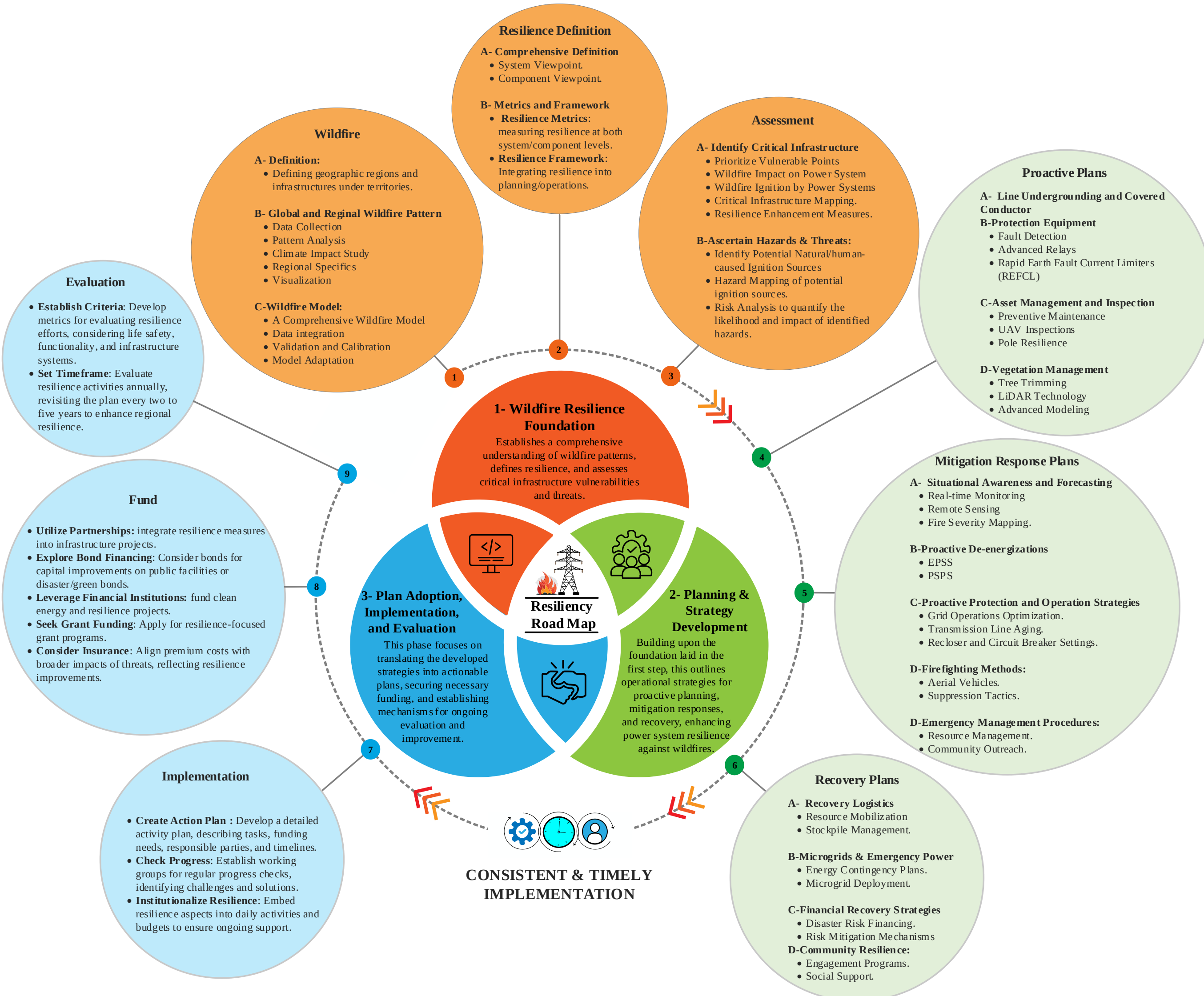

Fig. 5: Power System Resilience Roadmap against Wildfire.

The third step, Plan Adoption, Implementation, and Evaluation, ensures that strategies are effectively put into practice. This includes creating detailed action plans, checking progress through regular assessments, and embedding resilience into daily operations[200]. Funding is crucial, requiring partnerships, bond financing, and leveraging financial institutions. Evaluating the efficacy of these plans involves establishing criteria and setting timeframes for periodic reassessment.

A key emphasis of this roadmap is the proactive prevention of wildfires, especially concerning aging power infrastructure. Significant new investments in research and development are paramount to minimize the impacts of wildfires on power system resilience, safety, and security.

Future work will explore operational risks associated with electric power infrastructure during wildfires. Developing an Operational Risk Management System (ORMS) for real-time grid management will be a focal point, aiming to enhance the resilience of power systems by providing real-time data and decision-making tools to mitigate risks effectively.

In conclusion, the Power System Resilience Roadmap against Wildfire underscores the necessity of a multifaceted approach, combining proactive planning, strategic development, and diligent implementation and evaluation. Through collaborative efforts and targeted investments, we can significantly enhance the resilience of power systems against the increasing threat of wildfires.

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Competing interests

The authors declare no competing interests.

Author contributions

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Soroush Vahedi and Junbo Zhao conceived the article. All authors participated in the writing of the initial draft as well as discussions and finalization of the article.