Sandia National Laboratories

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WILDFIRE ELECTRIC GRID SECURITY

Mitigate Electric Grid Ignitions and Major Wildfire Consequences

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Manager – Electric Power Systems Research

SAND2025-03917PE

Goal 1: Mitigate grid caused wildfires

Goal 2: Mitigate consequence from wildfire to grid and critical infrastructure

WILDFIRE AND THE ELECTRIC GRID NEXUS

WILDFIRE IMPACTS

- Impacts to society, property, and *loss of life*
- Damage to critical infrastructure
- Business impacts (utility business impacts)
- Supply chain impacts for replacement infrastructure
- Insurance
- Lawsuits
- and much more

Lawsuits: hundreds of millions for wildfire impacts. For example:
- 2017 Thomas Fire,
- 2018 Camp Fire,
- 2020 Archie Creek Fire,
- 2020 Zogg Fire,
- 2021 Dixie Fire.

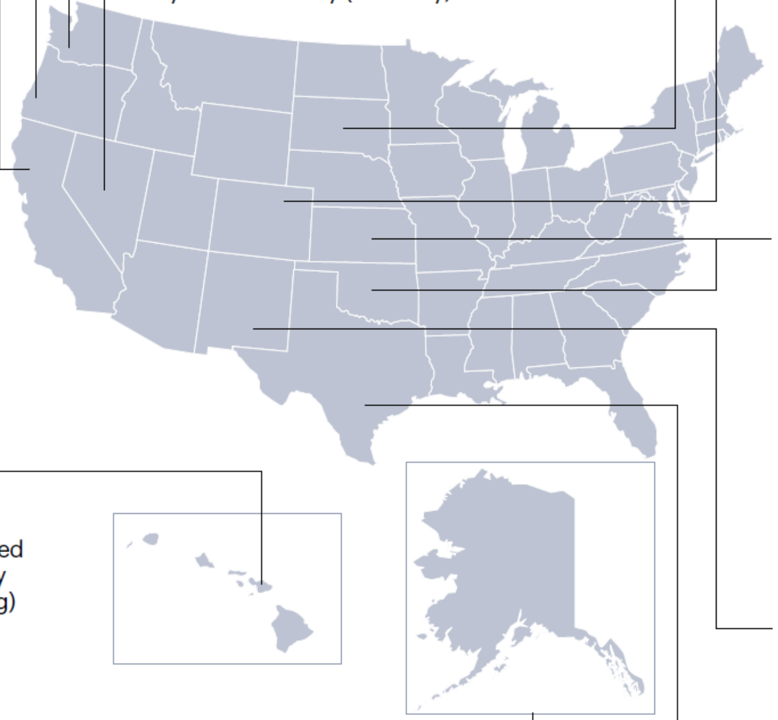
Oregon
- **Buzzard Complex in 2014:** Nearly 400,000 acres burned, costing $11 million, caused by lightning (14 July to 11 Sep)

California
- **Dixie Fire, 2021:** Second-largest, nearly 0.97 million acres burned, $637 million cost, caused by PG&E power line (13 July to 23 Oct)
- **August Complex, 2020:** The largest wildfire, nearly 1.03 million acres burned, $116 million cost, 1 death, caused by lightning (17 Aug to 11 Nov)
- **Camp Fire, 2018:** Deadliest and most destructive, 154,000 acres burned, $120 million cost, 85 deaths, caused by PG&E power line (8–25 Nov)
- **Mendocino Complex, 2018:** Largest in state history until the Dixie Fire in 2021, 459,000 acres burned, $220 million cost, 1 death, caused by a hammer spark and under investigation (27 July to 18 Sep)
- **Thomas Fire, 2017:** Seventh-most destructive, 270,000 acres burned, $124 million cost, 23 deaths, caused by downed power lines from Southern California Edison (4 Dec 2017 to 12 Jan 2018)

Hawaii
- **Hawaii fires, 2023:** Deadliest US wildfire in over a century, nearly 17,000 acres burned, 101 deaths, $5.5 million cost, possibly caused by downed power lines, exacerbated by dry conditions and high winds (14 June to 6 Aug)

Washington
- **Okanogan Complex, 2015:** Largest wildfire on record, 304,000 acres burned, 3 deaths, 120 homes destroyed, $44.5 million cost, caused by lightning (15 Aug to 19 Sep)
- **Carlton Complex, 2014:** Nearly 260,000 acres burned, 2 deaths, $68 million cost, caused by lightning (14 July to 28 Sep)

Nevada
- **Martin Fire, 2018:** Largest in Nevada's history, 436,000 acres burned, $10 million cost, caused by human activity (5–21 July)



Alaska
- **Lime Complex Fire, 2022:** Nearly 865,000 acres burned, $12 million cost, caused by lightning (15 June to 26 July)
- **Old Grouch Top Fire, 2019:** Nearly 307,000 acres burned, $61,000 cost, caused by lightning (5 June to 1 Aug)
- **Ruby Area Fires, 2015:** Nearly 422,000 acres burned, $2 million cost, caused by lightning (2 June to 4 Aug)
- **Tanana Area Fires, 2015:** Nearly 500,000 acres burned, $14 million cost, caused by lightning (14 June to 6 Aug)

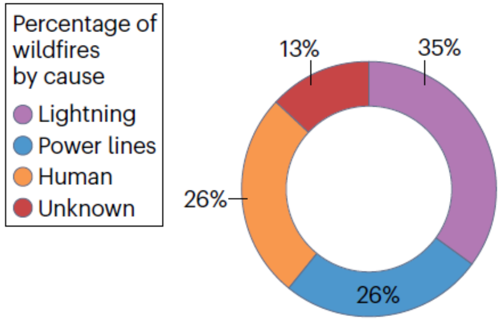
South Dakota
- **Legion Lake Fire, 2017:** Third-largest in state history, nearly 54,000 acres burned, $2.2 million cost, 2 deaths, caused by a tree falling on a Black Hills Energy power line 11–13 Dec)

Colorado
- **Marshall Fire, 2021:** Most destructive in terms of buildings destroyed, about 6,000 acres burned, 2 deaths, $2 million cost, cause unknown (30 Dec 2021 to 1 Jan 2022)
- **Cameron Peak Fire, 2020:** Largest wildfire in state history, about 209,000 acres burned, $133 million cost, cause unknown (13 Aug to 4 Dec)
- **Spring Creek Fire, 2018:** Third-largest in state history, about 108,000 acres burned, $35 million cost, caused by human activity (27 June to 6 Dec)

Oklahoma and Kansas
- **Northwest Oklahoma Complex, 2017:** Impacted parts of Kansas and Oklahoma, largest wildfire in Kansas history, nearly 800,000 acres burned, 6 deaths, thousands of cattle killed, $3.2 million cost, cause unknown (7 March to 24 April)
- **Anderson Creek Fire, 2016:** Impacted parts of Kansas and Oklahoma, the second-largest wildfire in Kansas, nearly 370,000 acres burned, $1.75 million cost, sparked by a vehicle (23 March to 4 April)

New Mexico
- **Hermits Peak Fire, 2022:** Largest and most destructive wildfire in state history, nearly 342,000 acres burned, $330 million cost, caused by human activity (7 April to 20 Oct)
- **Black Fire, 2022:** Second-largest fire, nearly 325,000 acres burned, $60,000 cost, caused by human activity (13 May 10 Nov)

Texas
- **Smokehouse Creek Fire, 2024:** Largest wildfire in Texas history, nearly 1 million acres burned, $4.6 million cost, 2 deaths, caused by downed power lines (26 Feb to 14 March)



Soroush Vahedi, Junbo Zhao, Brian J. Pierre. 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.

*this slide may not have the most up to date information.

POC: Dr. Brian J. Pierre

WILDFIRE ELECTRIC GRID SECURITY PROGRAM

Mitigating Electric Grid Initiated Wildfires and Protecting our Critical Infrastructure from Wildfires

Wildfire Electric Grid Security: Planning / Monitoring

Sandia National Labs

ELECTRIC GRID IGNITED WILDFIRES

- Conditions and drivers that led to the ignition event.

Drivers

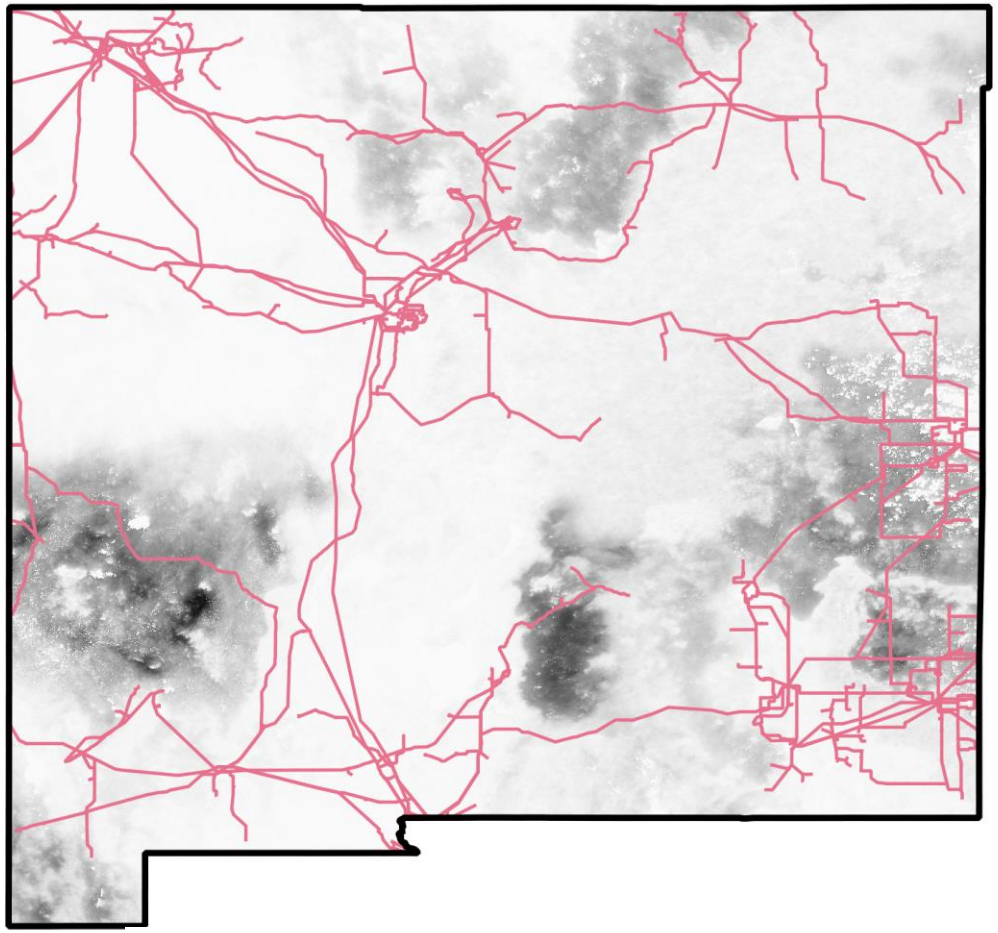
	Smokehouse-Creek, TX	Maui Fires, HI	Hermit's Peak, NM	Marshall Fire, CO	Caldor Fire, CA	Dixie Fire, CA	Camp Fire, CA	Woolsey, CA	Carr Fire, CA	Tubbs Fire, CA	Atlas Fire, CA
Ignition Cause		TBD	Rx								
Ignition Date	Feb '24	Aug '23	Apr '22	Dec '21	Aug '21	Jul '21	Nov '18	Nov '18	Jul '18	Oct '17	Oct '17
High Winds											
Low Humidity	40%	40%	7%	12%	16%	15%	11%	5%	21%	4%	12%
% of Avg. Snowpack	na	na						na		na	na
Live Fuel Moisture	70%	unknown	73%	96%	108%	75%	95%	51%	114%	56%	56%
Dead Fuel Moisture	4%	6%	2%	8%	3%	3%	5%	7%	3%	4%	4%
Dry Grasses											
Tree Mortality											
Drought											
Unusual Heat											
Acreage											
Cost to Utility	TBD	TBD	NA	TBD	NA	$45m	$13.5B	$2.2B	NA	$415m	$415m
Suppression Cost	TBD	TBD	$968 per acre	$333 per acre	$1220 per acre	$661 per acre	$667 per acre	$588 per acre	$691 per acre	$2703 per acre	$1156 per acre
Total Cost	$0.5B	$5.5B	$4.0B	$2.0B	$1.2B	$1.2B	$16.5B	$6.0B	$0.8B	$9.6B	$3.3B

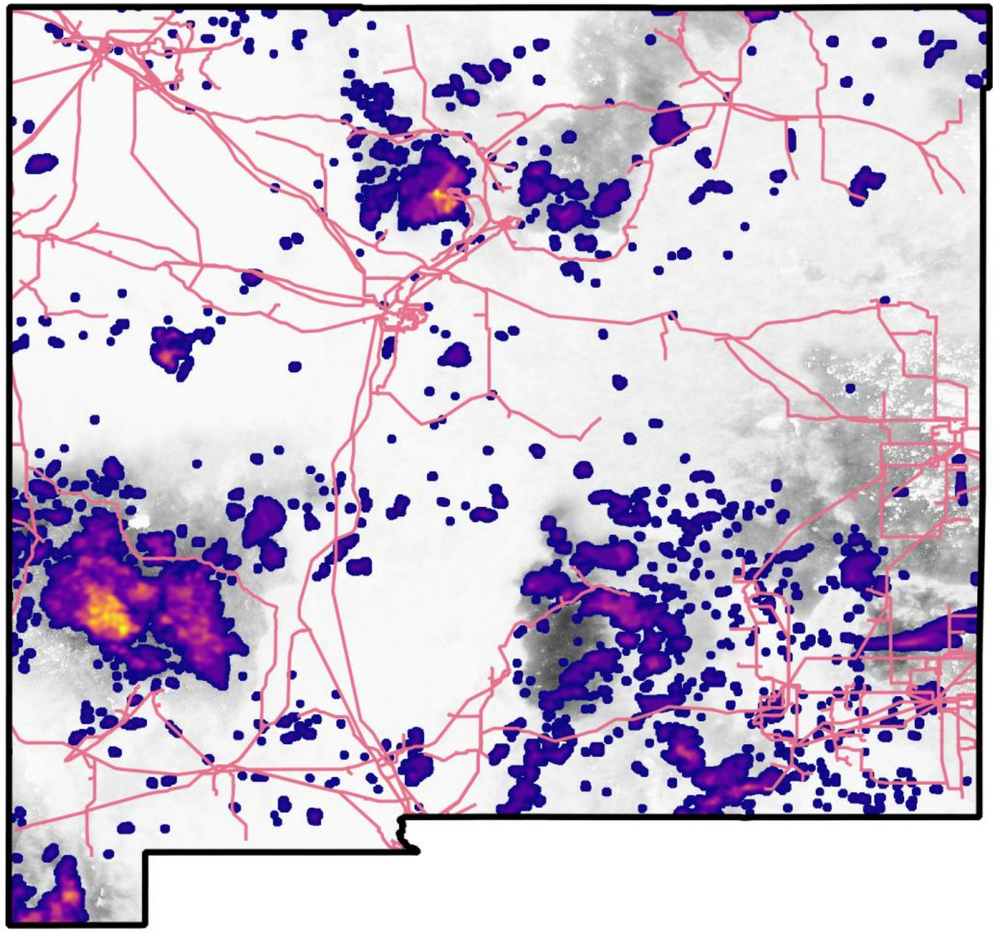
Live Fuel Moisture Content Scale
- 30-50% : Treat as dead fuel
- 50-80%: Yellowing / curing
- 80-100%: Green color pales
- 100-200%: Mature foliage
- +200%: Fresh foliage, growing

US Drought Monitor Scale
- Abnormally Dry (D0)
- Moderate Drought (D1)
- Severe Drought (D2)
- Extreme Drought (D3)
- Exceptional Drought (D4)

▪ = 10k Acres

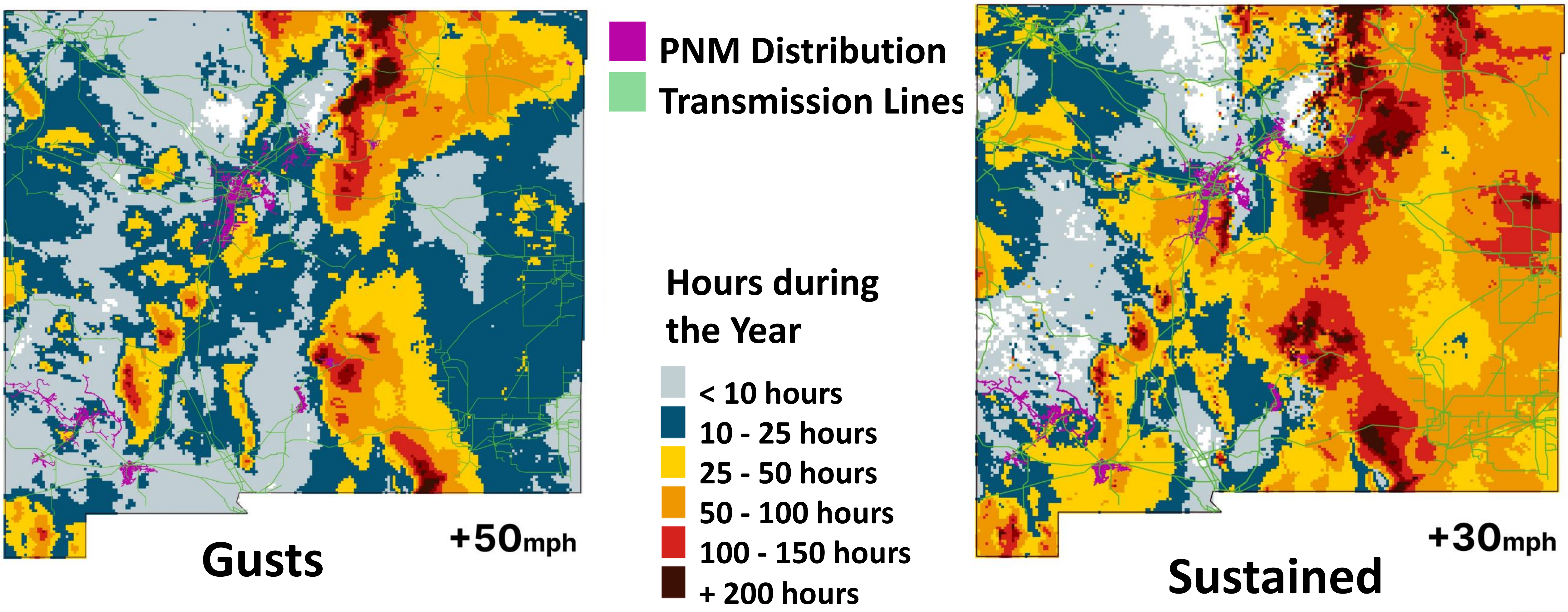
WILDFIRE RISK: NEW MEXICO





GUSTS AND SUSTAINED WINDSPEED | NEW MEXICO 2023 DATA

Wind obviously has a major impact on wildfire risk, especially spread rate, which can often lead to the largest wildfires



Vegetation Classification for Fire Spread Modeling

Problem:

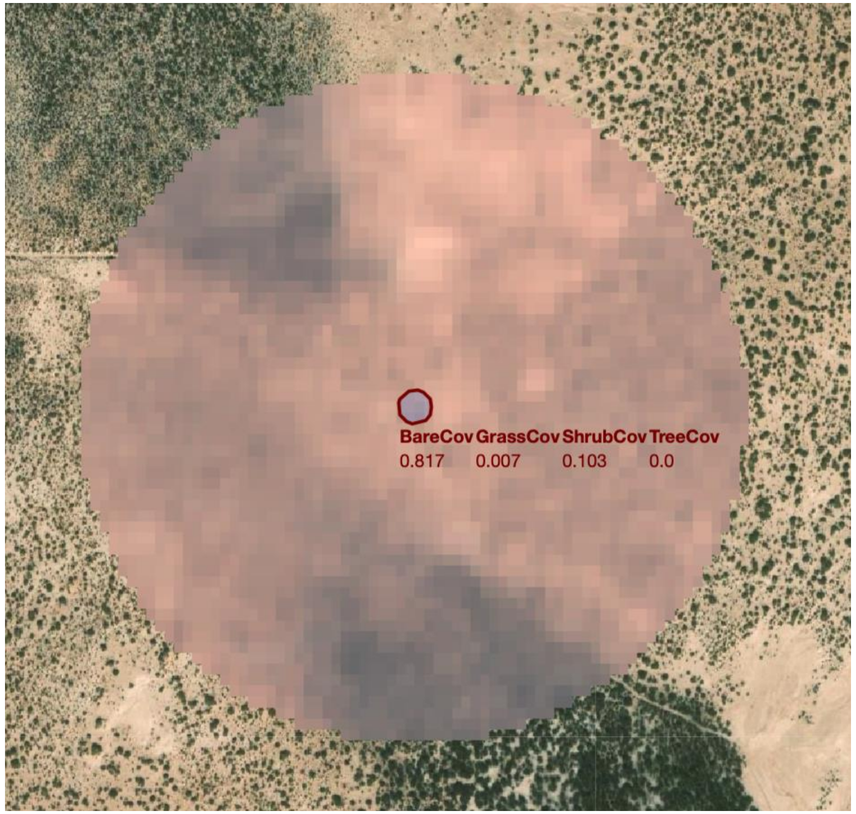
- Utilities require accurate up-to-date fire spread models to safely and efficiently distribute mitigation resources.
- Accurate modeling of wildfire spread requires detailed and up-to-date input data on the vegetation conditions such as amount of biomass, vegetation cover type and flammability characteristics.

Approach:

- Leverage machine learning (ML) with frequent revisit multiband satellite imagery to predict vegetation coverage for accurate up-to-date fuel model generation.
- ML model down-selection and optimization.
- Run fire spread simulations against historic wildfires to validate fuel model generation.

Impact:

- Increase the accuracy and reliability of fire spread models with On-the-fly fuel model generation from up-to-date satellite data.

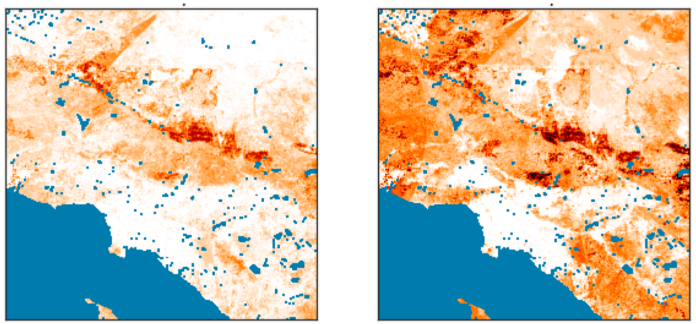


Predicted Vegetation Coverage *Pixel* (inner circle) from ML model trained on BLM labelled data. Outer circle is an RGB stacked 10m satellite image representing a fraction of the model input.

POC: Dr. Michelle Bester, Tomas Moore

WILDFIRE MODELING

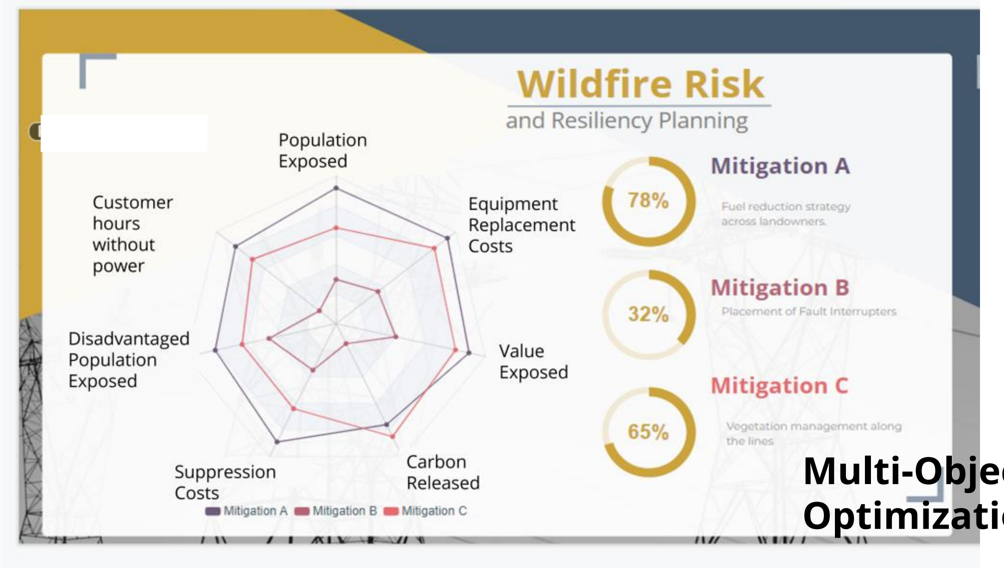
1. Data-driven Dynamic Wildfire Risk Maps
   - Satellite imagery, dynamic accurate ML-derived vegetation characterization, weather station data
   - Wildfire spread modeling



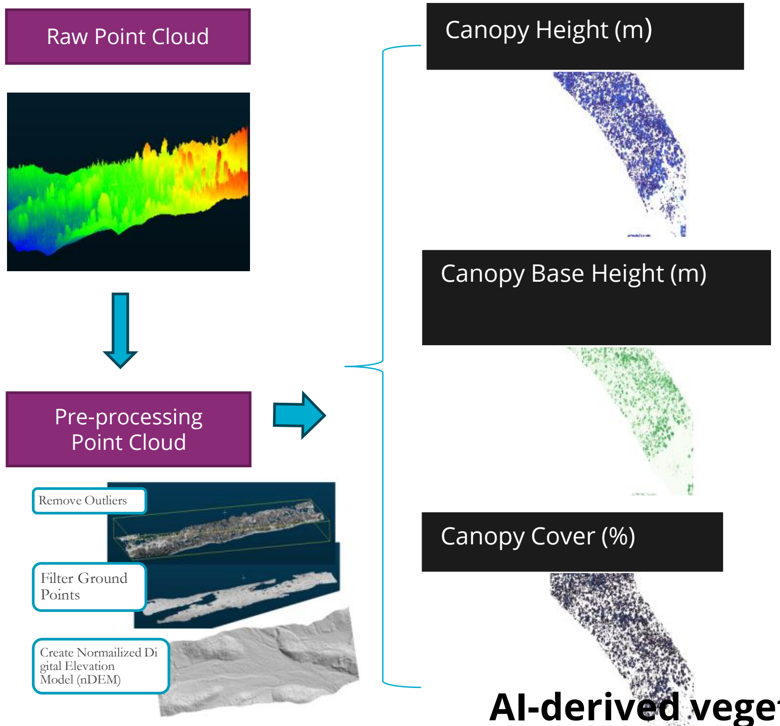
Dynamic Wildfire Risk

2. Dynamic Monitoring for Grid Vulnerability to Fire
   - Wildfire risk – electric grid impacts, possible cascading failure.

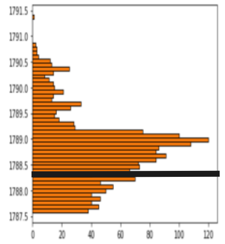
3. Optimized Vegetation and Resiliency Treatments to Reduce Wildfire Threat

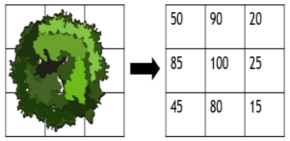


Multi-Objective Optimization



Field measurements as ground truth data for AI training





AI-derived vegetation characterization from satellite imagery

POC: Dr. Michelle Bester, Dr. Jubair Yusuf, Dr. Lauren Wheeler

Future Burn Probability: Next Fire Season Impacts to Electric Grid

Problem:

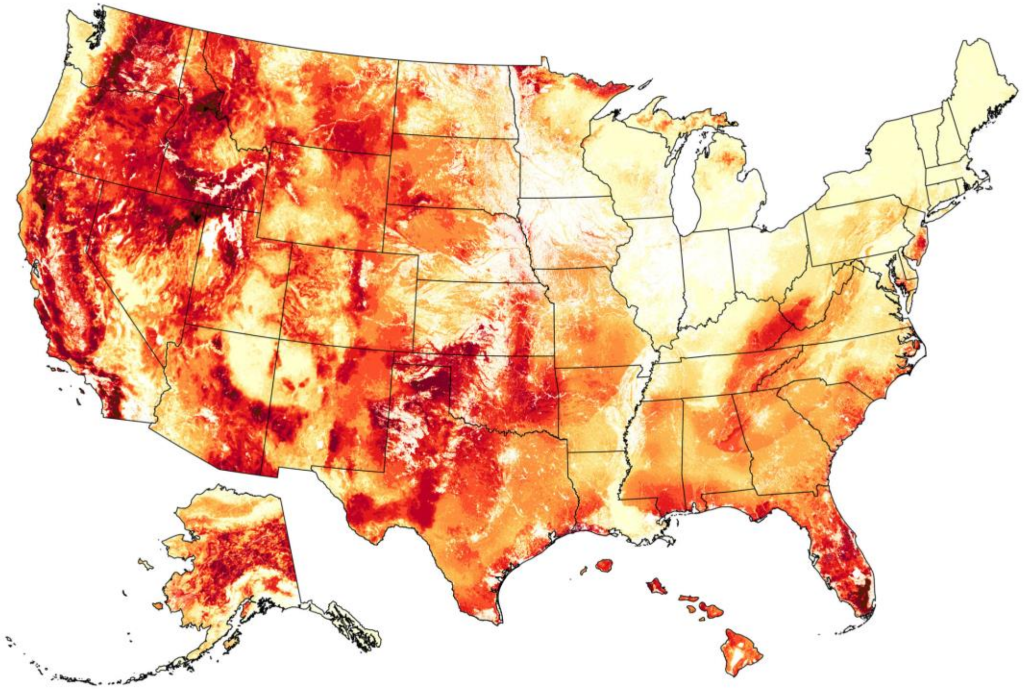
- Utilities need to plan months in advance
- Fire weather and burn probability forecasts are often short term (next 7-days), there is a need for mid-term (months ahead) forecasts

Approach:

- Use **machine learning** methodology with satellite imagery and field data to **predict vegetation growth** 6 months ahead
- Downscale **seasonal forecasts**
- Run WRF-SFIRE fire simulations with **long-term weather forecast** data and forecasted vegetation data
- Ensemble runs and overlay with GIS data of electric grid assets
- Back-test on historic fire seasons

Impact:

- Forecasting wildfire risk for the upcoming fire season increasing preparation and enables fast response in the event of a wildfire
- Partnering with utilities, USFS, and companies to beta-test the tool and align with utility operator needs



Burn Probability: Mapped burn probability for the United States mapped in 2022 by the USFS.

POC: Dr. Laura Wheeler, Dr. Michelle Bester

PUBLIC SAFETY POWER SHUTOFF (PSPS) OPTIMIZATION FOR WILDFIRE RESILIENT GRID OPERATION

Investigating the best strategies for PSPS operations by combining optimization models and data-driven PSPS forecasts

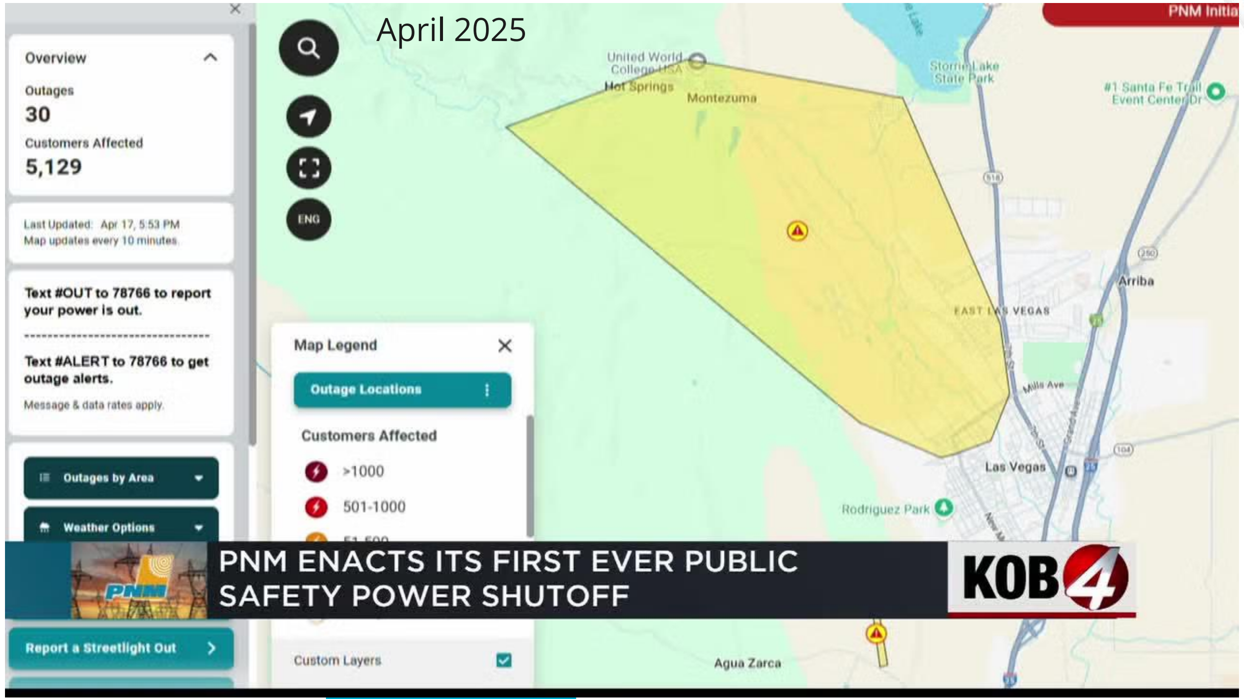
Problem: It is challenging to achieve both safety from wildfire and reduce the number of customers impacted by PSPS. PSPS action may severely impact critical loads and leave the grid network vulnerable to additional contingencies in post-PSPS periods.

Approach:

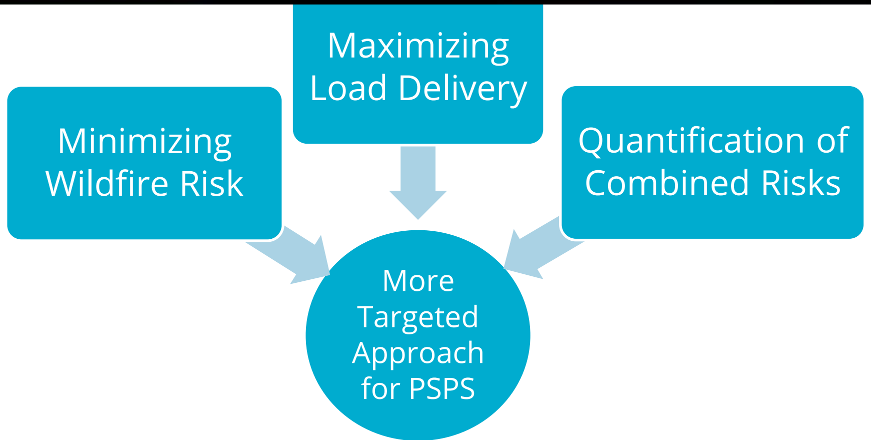
- Development of optimization models to minimize load-shedding and impact on customers without compromising wildfire risk
- Ensuring more critical loads getting served in PSPS events
- Leveraging the PSPS forecasts to complement the optimization model and help utilities select the best PSPS strategy.

Expected outcome and impact:

- Assist utilities in identifying optimal deployment of PSPS, to minimize wildfire risk, maximizing service to customers especially critical loads, and minimizing the impact to the bulk electric grid security (e.g. a “weakened” state possibly leading to cascading outages).



Thank you KOB4 for reporting



POC: Dr. Jubair Yusuf

PyroKit: Wildfire Risk and Mitigation Planning Tool

Problem:

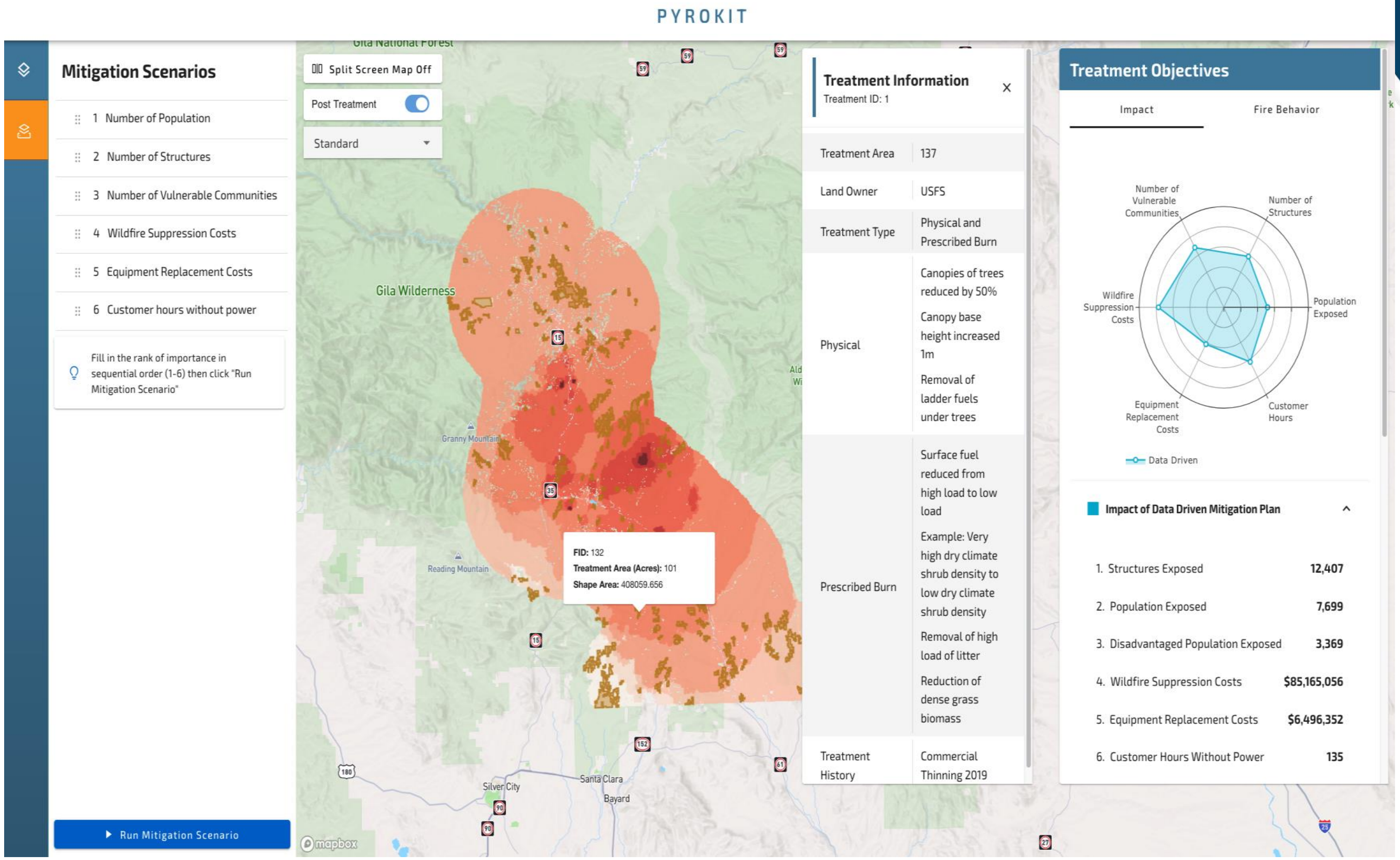
- Assessing current conditions and risk is critical to avoid electric-equipment started fires and to be prepared for encroaching wildfire.

Approach:

- Leveraging previous R&D investments at Sandia National Labs, we will use machine learning algorithms trained on satellite imagery and weather station data to determine wildfire risk and mitigation effectiveness.
- Data models include:
  - Dynamic utility wildfire risk maps
  - Burn Probability
  - Red Flag Warning
  - Customizable Public Safety Power Shutoff (PSPS) calculator
  - Contingency Analysis
  - Mitigation Scenarios / Solutions

Impact:

- Provide decision makers with an interactive map which shows fire risk and then allows the user to run mitigation scenarios based on user input management objectives.



POC: Phil Kay

WILDFIRE TOOLS

- Many tools to be aware of to assist in wildfire modeling, characterizing wildfire risk, spread modeling, forecasting, wildfire behavior analysis.

- Examples of other lab risk tools:
  - RADR-Fire (PNNL)
  - AHA (INL)
  - WildfireGPT (ANL)
  - Wildfire Tool Inventory and Evaluation (EPRI)

ELMFIRE	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 forec quantifies fire ri exposure
FlamMap	US Forest Service	Deterministic fire behaviour prediction and landscape analysis under constant conditions.	Physics-based model, produces raster maps, integrates multiple fire models, provides environmental condition data	Detailed fire be maps, compreh analysis
FARSITE	US Forest Service	2D deterministic fire growth simulation	Huygens, combines models for surface, spot, crown fires, wave dissemination models	Combines mult fire models, ge fire propagatio maps, essential forest fire extin decision-makin

S. Vahedi, J. Zhao, B. Pierre, et. al., "Wildfire and power grid nexus in a changing climate," Nature Reviews Electrical Engineering, March 2025.

Table 1 | Wildfire model comparisons

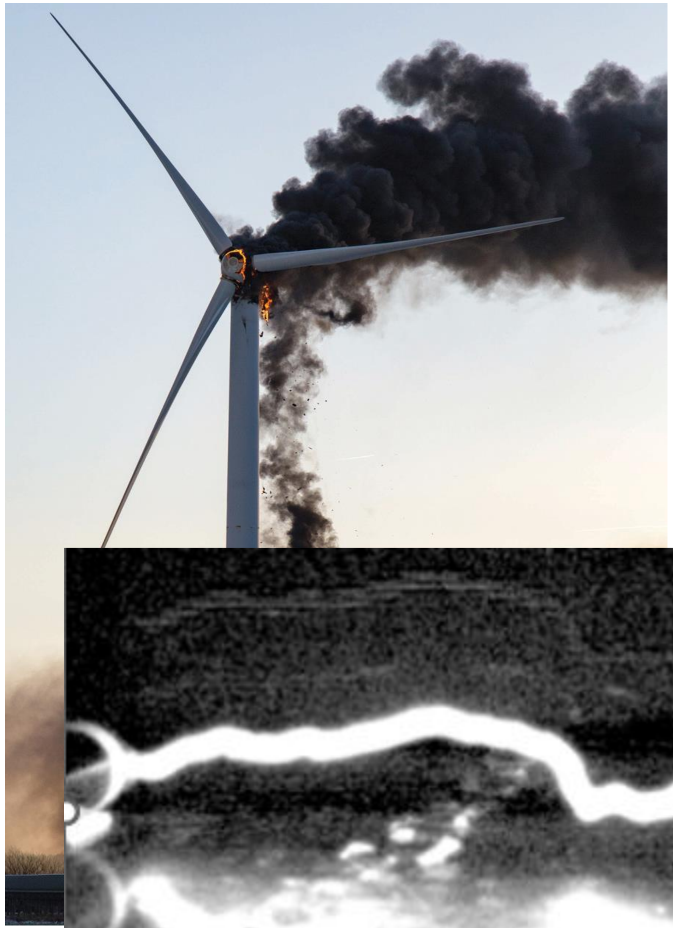
Wildfire model	Developer	Primary application	Key features	Benefits	Limitation	Used in PSRA
FireSim	Technosylva	Deterministic and probabilistic modelling, real-time fire behaviour prediction	Physics-based wildfire models, initial attack assessment, impact analysis, urban encroachment algorithms, real-time data calibration	Quickly determines fire path and impacts, all-in-one platform: wildfire risk forecasting, spread predictions, risk mitigation and fire behaviour analysis	May not capture all complexities of fire behaviour, not free for use	Used by PG&D, SCE, San Diego Gas & Electric, Xcel Energy, Bear Valley Electric Service, Liberty for wildfire mitigation plan
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	Using IFTDSS, they provided a wildfire characterization package enabling proactive decision-making for the wildfire mitigation plan
Solid Fire Model	NA	1D/2D flame model for deterministic/probabilistic wildfire risk modelling, fire management, firefighting	Physics-based approach, detailed fire behaviour 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 such as ignition probability, intensity, spread rate, temperature and severity affect the failure likelihood of power system components
MTT	US Forest Service	Underlying model for FlamMap and FSim	Physics-based prediction for fire perimeter expansion, calculates MTT across a 2D network of landscape nodes	Approximates complex fire behaviour models at low computational cost (makes it well suited for running many wildfire simulations), predicts fire behaviour 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[54]
Burn-P3	Natural Resources Canada (NRCan)	Landscape-scale wildfire simulation	Physics-based model that uses Prometheus model, evaluates fire characteristics and produces burn probability maps	Detailed predictions, supports planning, open source	Extensive input data, computationally intensive	No

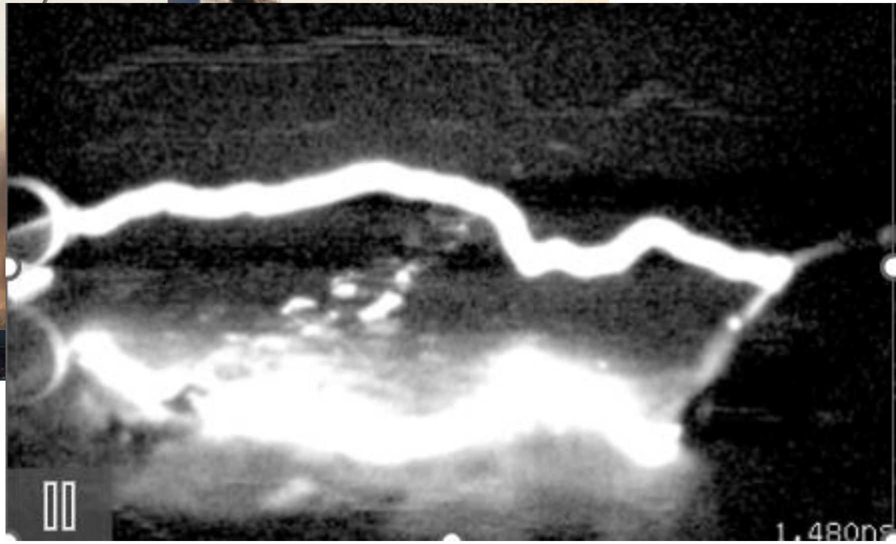
Wildfire Electric Grid Security: Ignition / During Wildfire

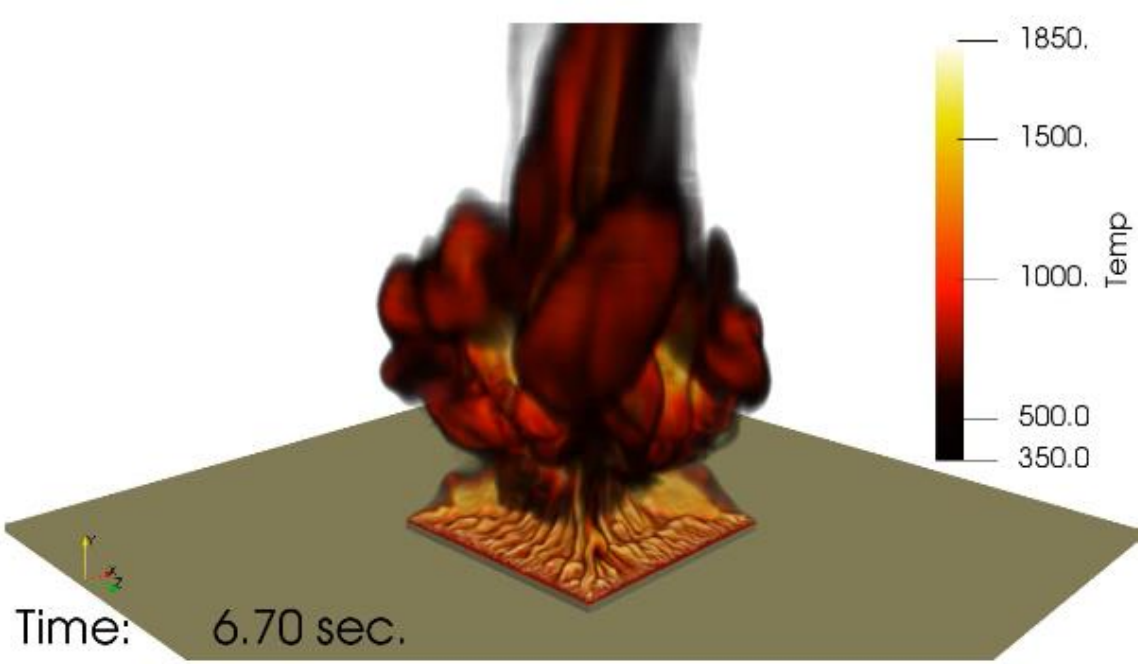
Sandia National Labs

LIGHTNING MODELING

1. First principles of wildfire ignition by lightning
   - Better understand probability of lightning ignition given different situations to inform wildfire response.
   - Create an experimentally-driven computational model to understand the predictability of lightning-ignited fire using Sandia's lightning strike lab capabilities for testing.





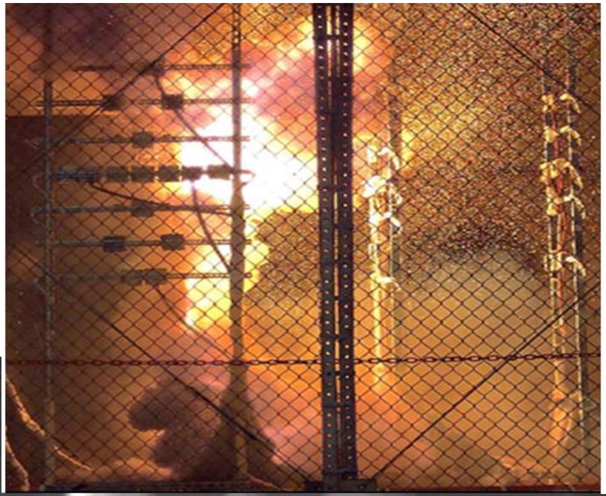


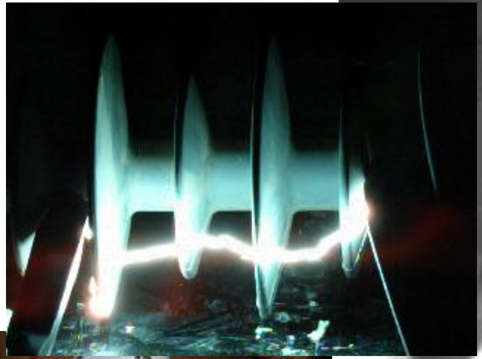
2. Novel lightning monitoring of critical assets for wildfire risk assessment
   - Develop a novel lightning monitoring system that provides total lightning current (and energy), to predict ignition by lightning.

POC: Dr. Julia Tilles

ARC MODELING

- Testing arc probabilities
- Testing arc ignition probabilities




Nuclear Energy

“There was a failure of the main contacts of a 25 year old 4.16 kV breaker to close fully, causing a HEAF event… the fire persisted for three hours until water was applied.” ~San Onofre Nuclear Generating Station

Insulator Flashover from Wildfire Contaminants

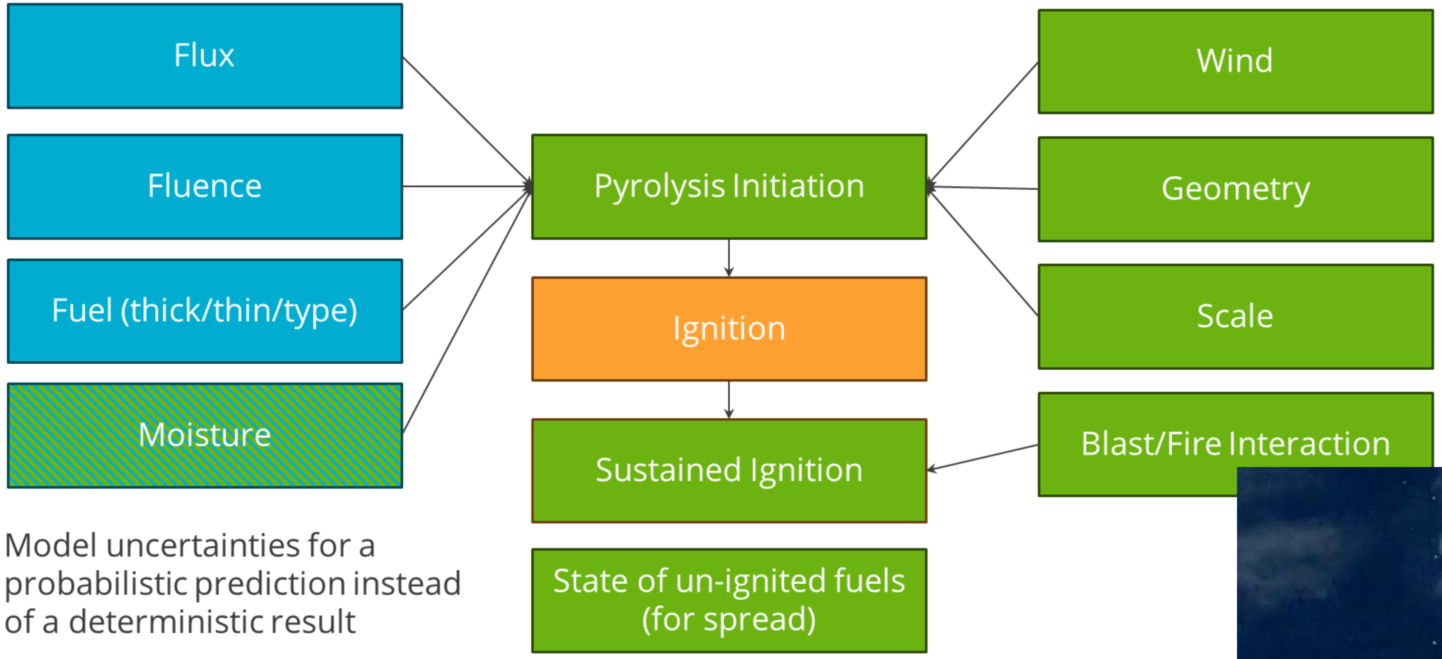
- High voltage breakdown testing of clean vs. contaminated/aged insulators
- Define risk metrics for contamination and aging at which point risk of failure / faults increase
- Develop failure thresholds and tracking criteria (working with wildfire propagation projects at Sandia) that can be used for grid health predictions in response to wildfires.

POC: Dr. Julia Tilles, Dr. Kenneth Armijo, Dr. Alex Brown

LEVERAGE IGNITION MODELING FROM OTHER SOURCES

Existing Models:

Potential New Phenomenology:



Model uncertainties for a probabilistic prediction instead of a deterministic result

5-year testing campaign, conducted high-flux exposures at Sandia National Thermal Test Facility.

Leveraging ignition models from other sources.

- Identified missing physics in most existing models:
  - Wind effects on ignition
  - Geometry effects on ignition
  - Effect of scale on ignition

POC: Dr. Kenneth Armijo, Dr. Alex Brown

Protective Relaying To Reduce Wildfire Risks and Possibly Reduce Public Safety Power Shutoff (PSPS) Events

- New power system protection methods and new technologies can reduce wildfire grid ignitions significantly.
- Sandia protective relaying R&D efforts to significantly reduce future wildfire risks

Protection Planning for Faults

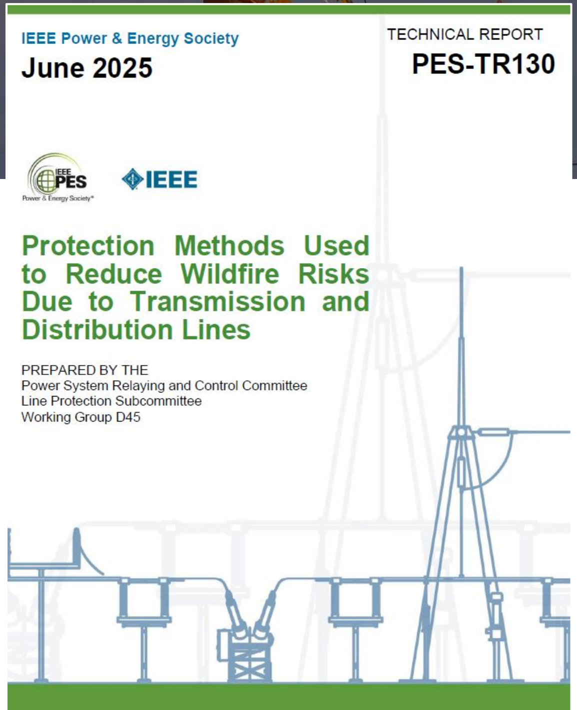
1. Rapid Earth Current Fire Limiter (RECFL)

Preemptive Protection Response

2. Adaptive Settings – Fast Sensitive Trip, No Reclose
3. Incipient Failure Detection

Fast Fault Clearing

4. AI-Based Traveling Wave Relay
5. Communication-Assisted Fast Protection


IEEE Power & Energy Society

June 2025

TECHNICAL REPORT

PES-TR130

PES IEEE

Protection Methods Used to Reduce Wildfire Risks Due to Transmission and Distribution Lines

PREPARED BY THE
Power System Relaying and Control Committee
Line Protection Subcommittee
Working Group D45

POC: Dr. Matthew Reno

AI-BASED TRAVELING WAVE PROTECTION SCHEME FOR DISTRIBUTION SYSTEMS

Use fast fault location to quickly detect and isolate an incident before it leads to a wildfire

Problem: The potential for fire ignition is proportional to the duration of the arc, and current protection schemes **generally take around 100 milliseconds** to a second to operate

Solution:

- Develop fast, local, bi-directional, data-driven fault detection and location schemes for distribution systems, including DER high-penetrations, that operate in **less than 2 milliseconds**
- Use high-frequency (1 MHz) **traveling wave** methods combined with physics-informed **Artificial Intelligence** can learn correlations to determine the fault location – Ability to detect fault location in the distribution system within 100 meters

Conventional protection

<15.36 kHz sampling rate → Measurements' processing and protection functions' calculation → Trip logic → >16.66 ms operation time
Often much greater (100ms+)

Fast, AI data-driven protection

> 400 kHz sampling rate → Advanced signal-processing and feature creation → Machine-Learning model → **1.4 ms operation time**

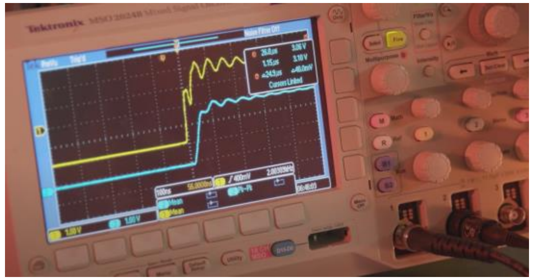
Machine-Learning model: Trained on past faults and simulated faults

Wildfire ignition risk decrease!

POC: Miguel Jimenez Aparicio and Dr. Matthew Reno

AI-BASED PROTECTION – TECHNOLOGY VALIDATION EFFORTS AND DEMONSTRATIONS

Kirtland Air Force Base, Albuquerque, NM (2023)



Link to YouTube demonstration video

Portales, NM (2024-2025)

NuGrid

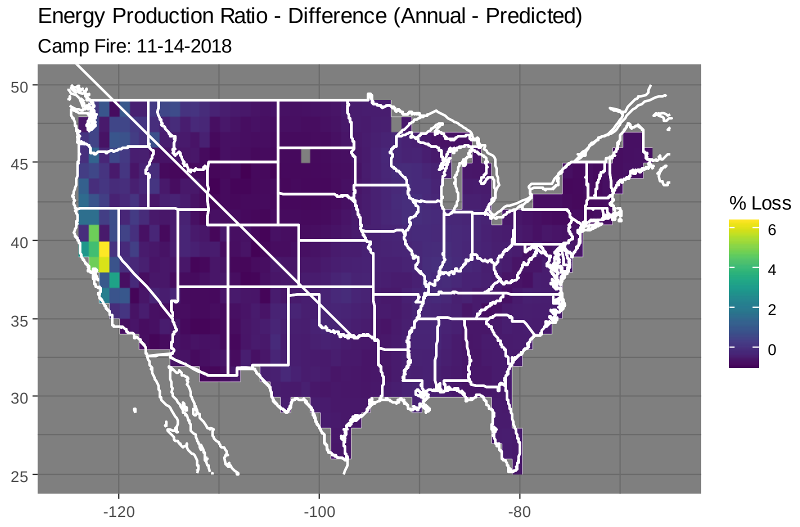
Roosevelt County Electric Cooperative

Risks/challenges to investigate:

- Integration with MV commercial sensors
- Impacts of system model accuracy

POC: Miguel Jimenez Aparicio

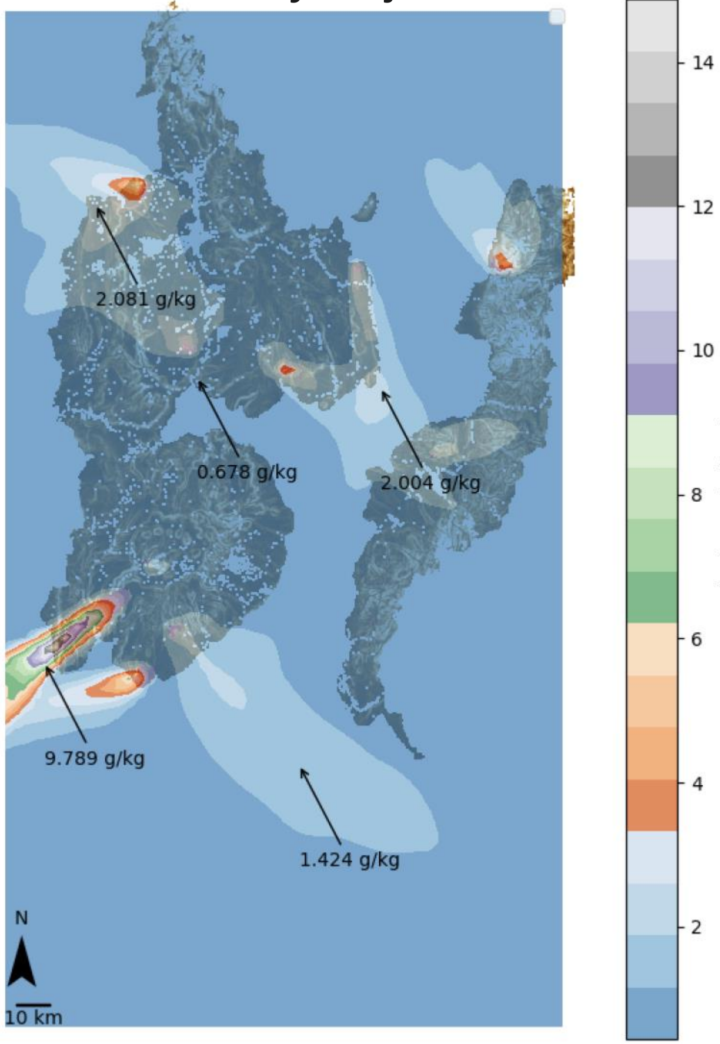
SMOKE MODELING



Custom WRF-Fire code and LANDIS-II running on Sandia HPC environments

Smoke plumes from many major fires simulated

- Developed a coupled landscape, weather, wildfire, smoke modeling platform.
- Wide-scale future smoke impact across the U.S. (plum modeling).
- Help forecast future smoke impact to energy systems, primarily solar power.
- Smoke impact to military installation mission assurance.



Project SMOKEWISE

POC: Dr. Dan Krofcheck and Dr. Joe Crockett

VISUALIZING UNCERTAINTY: PSPS AND EVACUATION

Decision making for Public Safety Power Shutoffs and Evacuations.

Design choices, visualizations, impact decision making. How should data be presented to a grid operator to make the optimal decisions.

State uncertainty is uncertainty about the current or future state of some phenomenon

- Very common in weather forecasts, hazard maps, AI/ML outputs

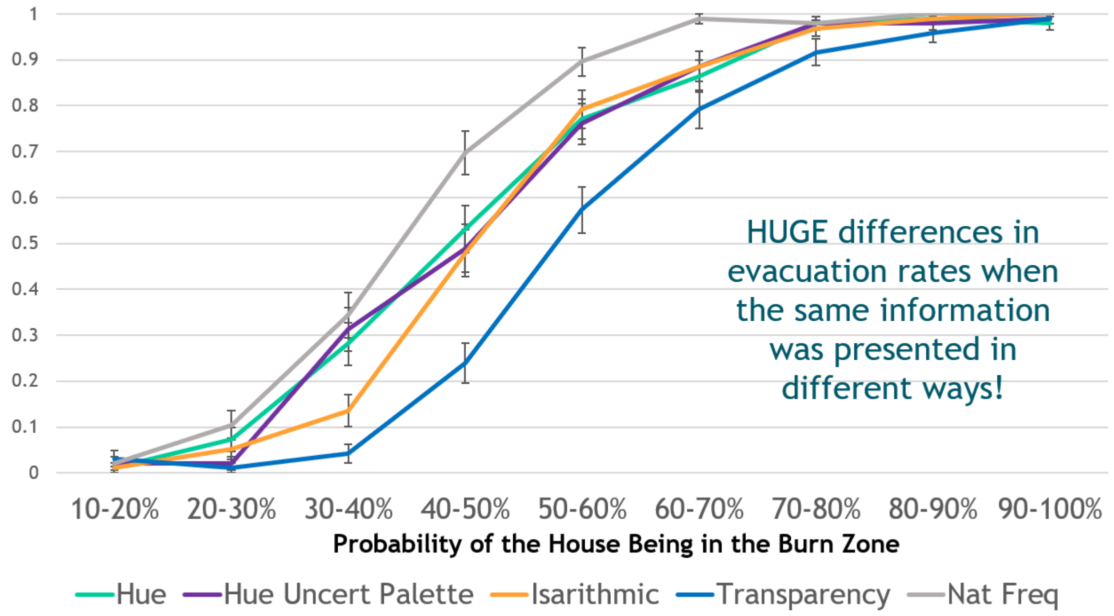
Humans are notoriously bad at understanding state uncertainty and probability

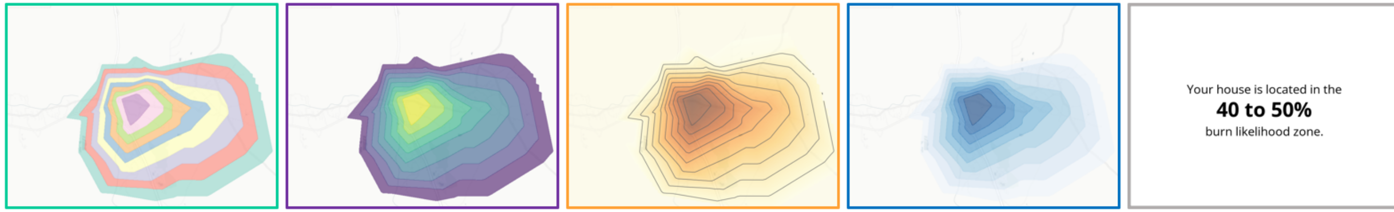
- Prior research suggests that **different representations of uncertainty can lead to different patterns of decisions**, but we don't yet know when and why this happens.

Grid operations (and modeling) involve complex, heterogeneous, uncertain information

- **How should that data be presented to support optimal decision making?**

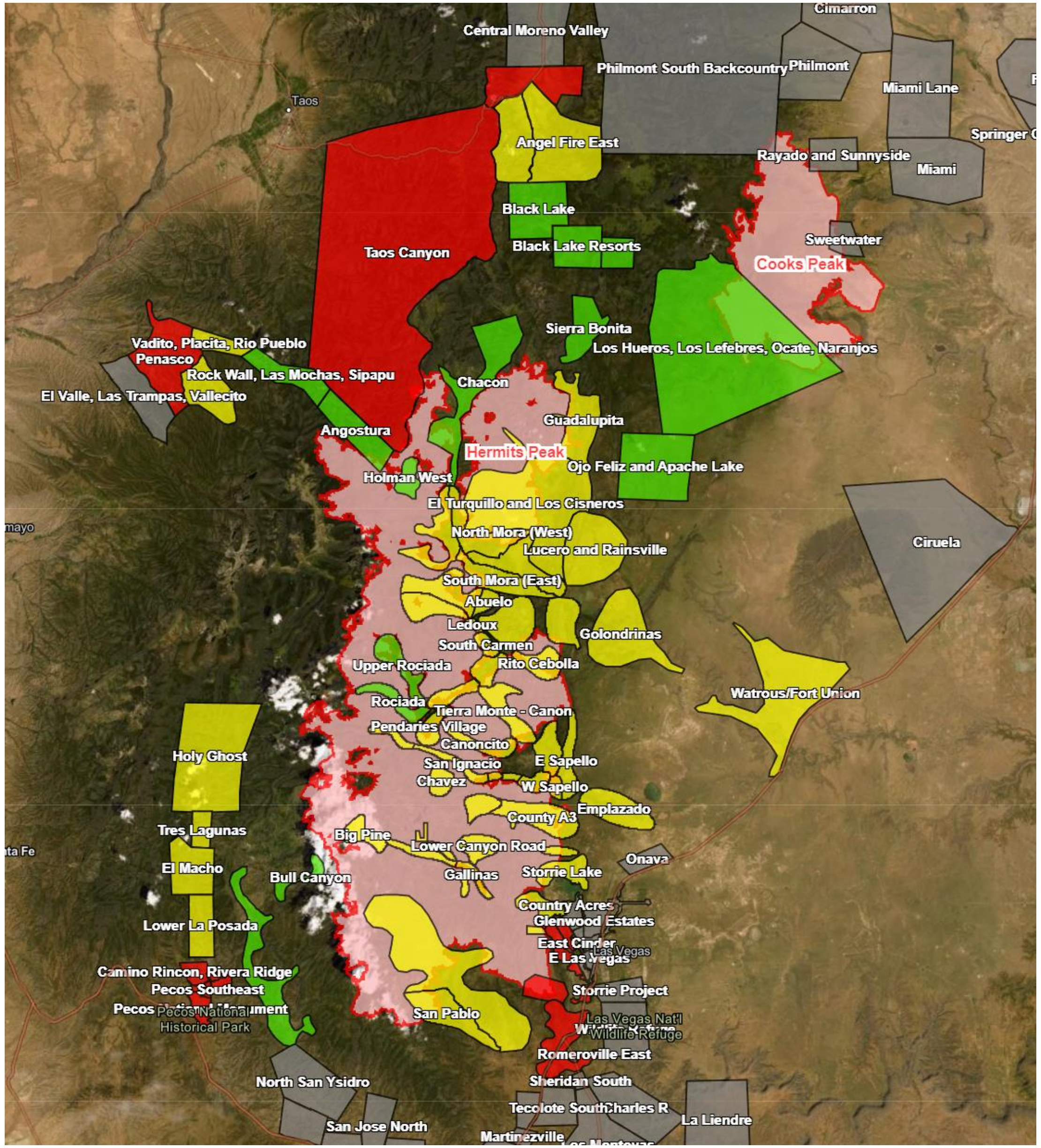
Wildfire evacuation decision dependent on how the information is presented





POC: Dr. Laura Matzen

THESE CHOICES MATTER



New Mexico wildfire evacuation material from long ago.

POC: Dr. Laura Matzen

Wildfire Electric Grid Security: Recovery / Post Wildfire

Sandia National Labs

ACCELERATED GRID RECOVERY POST WILDFIRE

Problem: Electrical outage time due to wildfires needs to be minimized.

Approach: Today, linemen are frequently stationed in areas affected by wildfires. They await safety approval to access damaged areas and then they proceed to assess and repair the affect grid infrastructure.

Expected outcome and impact: In partnership with PNM/SCE, this approach will manage key information that can accelerate grid recovery

- Document existing capabilities
- Created an optimization method enabling an accelerated recovery decision process

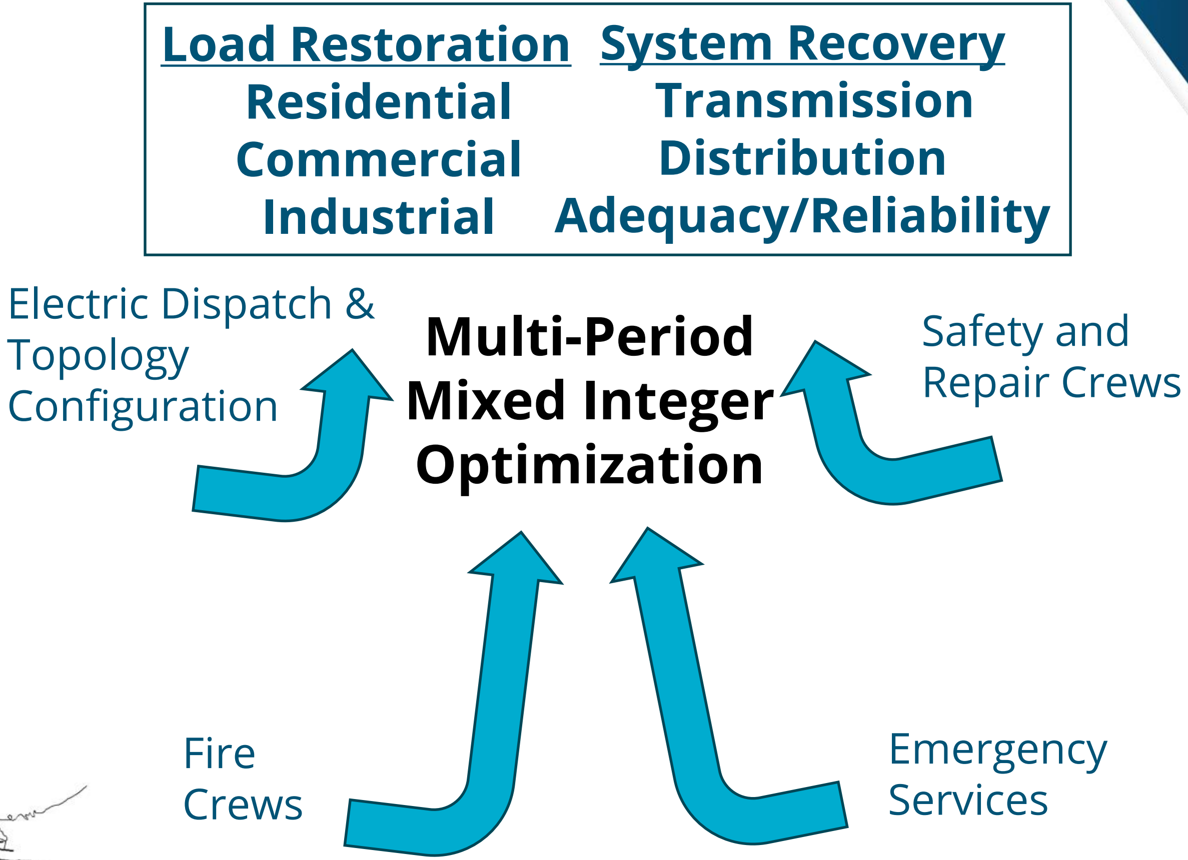
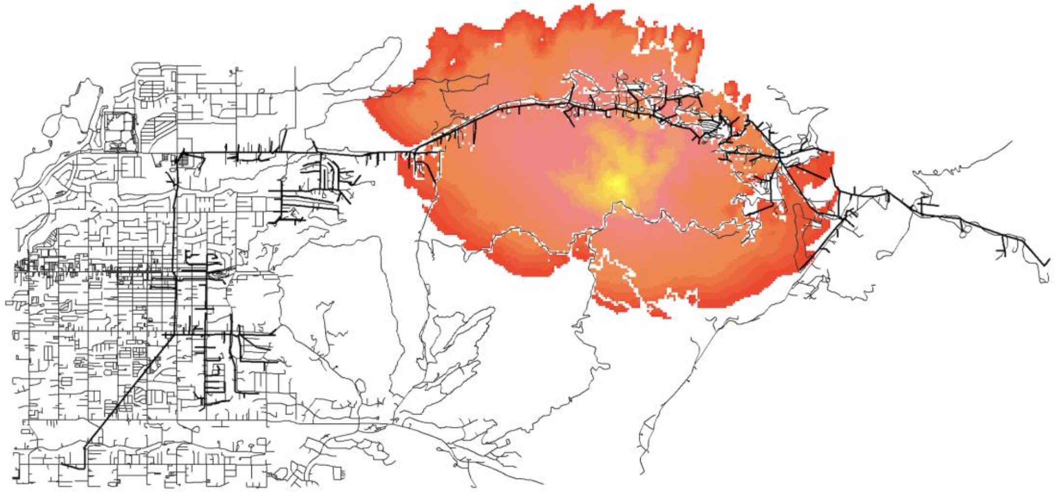


Figure: Optimal Recovery of Wildfires for Electric Utilities

FlamMap fire progression coupled with grid and transportation infrastructure



POC: Ross Guttromson and Dr. Brent Austgen

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DOE CESER Natural Hazards Program

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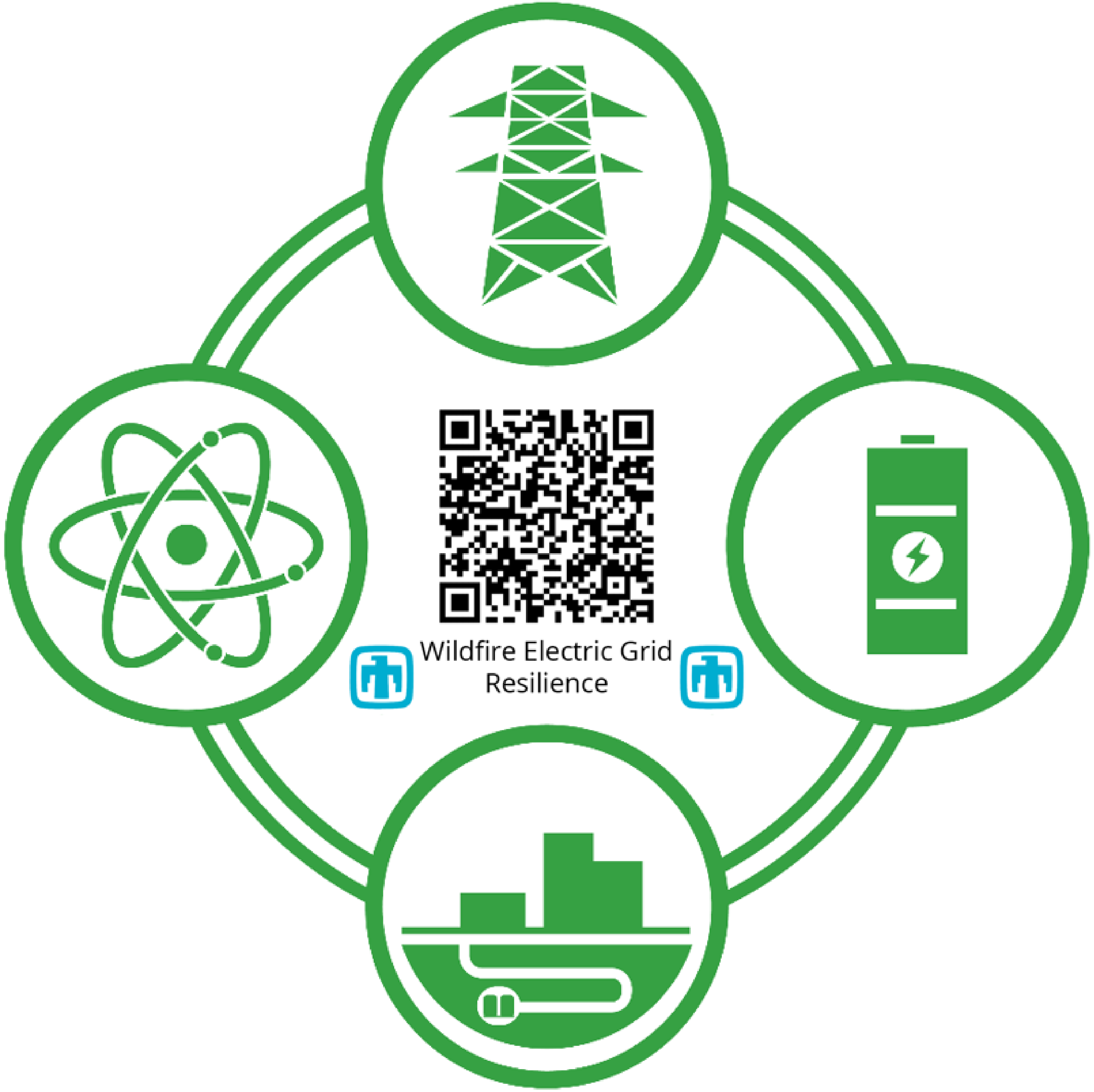
U.S. DEPARTMENT OF ENERGY

Office of Cybersecurity, Energy Security, and Emergency Response



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