EVERSOURCE ENERGY CENTER





RESEARCH INITIATIVES
Grid Resilience, Security and Modernization

January 2020 – December 2022

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Outage Prediction Modeling and Emergency Response

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HIGHLIGHTS

- Continue improving the UConn Outage Prediction Model for all weather caused outages (rain/wind, blizzards, ice events, hurricanes, thunderstorms, etc.)
- Develop a procedure to incorporate weather fore casting uncertainty in the UConn outage prediction system.
- Develop integrative tools to support optimal restoration strategies based on outage forecasts and optimal restoration strategies.
- Support emergency managers and grid operators training based on simulated catastrophic weather-outage scenarios.

Background

Severe weather is the major cause of damages to electric distribution networks and resultant power outages in the United States. Outage prediction models, based on weather forecasts and other information such as geographical data and attributes of the electrical system, are used to predict a storm's impact many days in advance. To use these outage predictions effectively in decision making, models must exhibit acceptable accuracy in the spatial distribution of estimated outages for all storm types. The Outage Prediction Model (OPM) developed at UConn for the New England area, currently uses more than 200 simulations of different weather events (thunderstorms, nor'easters, snow/ice and rain/wind events and hurricanes), which combined with detailed geographical and electrical system attributes and associated outage reports has demonstrated a good performance across the various storm types. In this project we aim at capitalizing on successes and unique aspects of our previous research to help utility emergency operation and planning with: (i) predicting the likely storm impact (total number of expected outages), (ii) show where damage/outages are likely to occur according to weather, infrastructure and vegetation patterns, (iii) enhance awareness of storm severity and restoration practices. Additional application include providing information about resilience, such as quantifying the value of tree trimming or other power grid hardening activity.

Needs

- Continue enhancing UConn OPM capabilities to forecast distribution network outages from winter storms, extreme weather events and thunderstorms.
- Pilot novel procedures to incorporate weather forecasting uncertainty in the outage prediction system.
- Demonstrate modularity and transferability of the outage forecasting system across the different Eversource service territories.
- Develop restoration support tools based on weather and outage forecasts and optimal restoration response strategies.
- Develop tools for emergency managers and grid operators training and facilitate drill exercises of catastrophic weather-outage scenarios across New England.
- Provide resiliency insights, such as quantifying the value of vegetation management and other network hardening investments in terms of storm outage reductions.

Outage Prediction Modeling and Emergency Response continued...

- Provide projections of outages and outage durations under climate change projections (e.g. future storms, snow/ice events, hurricanes, sea level rise)
- Provide operational support of Eversource incidence control managers through our on-line outage forecasts communication system.

Expected Deliverables

- This work will consolidate current research that has developed methods for combining historical weather forecasts with utility-owned, or freely-available, data layers (e.g. geography, system hardening activities, electric grid attributes and outage reports) to advance the state of the art in outage modeling that provides critical information for storm recovery.
- Deliverables from the new integrated project will include:
- Enhanced OPM for winter (snow and ice) storms, severe weather events (including hurricanes) and thunderstorms.
- Probabilistic OPM predictions by incorporating weather forecasting uncertainty.
- A system to transfer OPM calibration from the data rich CT to less data rich MA and NH Eversource service territories.
- A restoration optimization model that predicts restoration plans and restoration times.
- A training restoration tool for emergency managers.
- What-if scenarios quantifying impact of vegetation management on outage reduction.
- A new operational outage forecast communication system that incorporates the probabilistic OPM output.
- Training utility engineers on the use of these data.
- Operational production of OPM and dissemination to Eversource managers.

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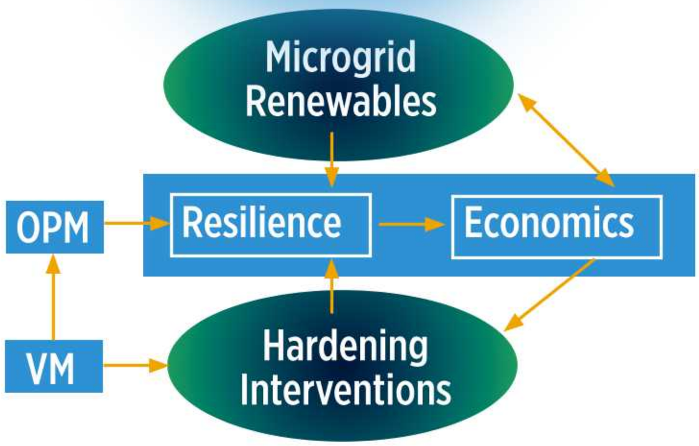
Resilience System Modeling and Economic Effects



Conceptual framework for economic analysis bridging the gap between OPM, system resilience, renewables, etc., and possible interventions

HIGHLIGHTS

- **Continue improving the UConn System**
- **Performance Model for all parameter interplays (weather scenarios, hardening options, local wind and soil conditions, etc.)**
- **Develop linkages between intervention techniques and economic analysis.**
- **Perform analysis for savings for the utility company, and long-term state and regional economy.**

Background

Current efforts in weather and system resilience predictive models provide forecasts of adverse weather by locale and expected electricity infrastructure damages and outage durations. Economic literature generates likely economic costs by duration but is not industry specific by locale. There is a need to tie databases on industry locales to above vulnerable locales and supplement economic estimates with industry specific cost impacts. Relevant questions are:

- Can such estimates be based on current expected costs without industry reference or surveys?
- Are vulnerable firms wholly or partially off-set by back-up capacity?
- If back-up generation is made available, its capital and operating costs are needed as well as its capacity to avoid outage costs by duration, industry and locale.
- Can we estimate outage costs of firms with no or insufficient backup?
- Can we estimate cost savings due to resil-ience interventions?

Therefore, it is critical that Eversource be able to make the economic argument that the in-vestments in resiliency will pay off in ways that translate into a more competitive economy and defend those choices--as they imply rate increases at least in the short-run--to PURA. The Connecticut Center for Economic Analy-sis (CCEA) uses the REMI model, which is a dynamic forecasting and policy analysis tool (referred to as an econometric model or a com-putable general equilibrium model). The model forecasts the future of a regional economy, and it predicts the effects on that same economy when the user implements a change.

The data REMI can draw is the OPM-driven system projections on disruption (as well as, if desired), pole breakage, expanded renewables, etc. with detailed county-level economic data to bridge the technical resiliency to recommen-dations for interventions.
To that end, work on System Resilience Mod-eling will continue to update and augment fragility curves by incorporating correlation of parameters, such as soil, weather, wind, pole conditions, and vegetation status. This will al-low the development of multivariable fragility curve (i.e. response surface -- fragility surface).

Resilience System Modeling and Economic Effects continued...

Statistics of scenario-based extreme parameters will be used for outage predictions and time-series of weather events and outages will be predicted by the OPM team and will inform system model predictions as time-series of power outages under different interventions or conditions scenarios.

- Comparisons of different intervention techniques will inform economic analysis (performed over 5 year periods or more). This analysis will be based on counterfactual modeling vs. pre-post analysis. Results generated by counterfactual scenarios will be compared against the observed reality (or paired factual model). The relevant metrics for comparison will be power outages or economic indicators without ETT or other interventions.
- Analysis will provide a) the cost of savings for the utility company, and b) how this might affect long-term state and regional economy (societal effects, loss of business and loss of revenue).
- Date for outages from 2005 to present will allow the analysis of several 5-year window scenarios including the reference (2005-2009) that had no trimming. For the economic analysis outage duration will be provided by the OPM team including shorter than 5 minute outages (likely a noisy data-set). Eversource data on customer type for outages will also be needed.

Needs

- Improve the UConn System Performance Model to incorporate all parameter interplays (weather scenarios, hardening options, local wind and soil conditions, etc.).
- Develop fragility response surfaces that capture all these parameter interplays.
- Implement REMI approach and develop linkages between intervention techniques and economic analysis.
- Perform counterfactual analysis of power outages or economic indicators without ETT or other interventions.
- Analyze savings for the utility company, and long-term state and regional economy.
- Provide operational support of Eversource incidence control managers through training to use our system modeling system.

Expected Deliverables

- This work will consolidate current research on system performance modeling that has developed methods for combining weather forecasts with electric grid components via fragility curves and link to short- and long-term economic analysis. Deliverables from the new integrated project will include:
- Multivariable response surface -- fragility surface with correlation of parameters (soil, weather, wind, pole conditions, vegetation status).
- Linkage between OPM predicted time-series of weather events and outages with system model predicted time-series of power outages under different interventions or conditions scenarios.
- Linkage between different intervention techniques and economic analysis.
- Counterfactual analysis of power outages or economic indicators without ETT or other interventions.
- Analysis for a) the cost of savings for the utility company, and b) how this might affect long-term state and regional economy.
- Multiple 5-year window scenarios for economic analysis.
- Production of economic forecast and dissemination to Eversource managers.

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Improving Vegetation Management Effectiveness with Remote Sensing, Outreach, and Forest-Science

Highlights

- Enhance geospatial support tool for prioritizing treatment areas for vegetation management programs (Stormwise and tree trimming).
- Develop methods for mapping and forecasting forest health and tree mortality.
- Improve vegetation risk models by incorporating corrected power line maps and forest health factors.
- Evaluation of the effect of Stormwise and tree trimming on tree failure and stability.
- Identification of socioeconomic barriers and mitigation strategies for implementation of vegetation management programs.
- Develop spatial predictions of stakeholder receptivity to vegetation management programs.

Background

Mitigating vegetation-related risks to infrastructure is a major challenge to utilities in forested regions and vegetation management is one of the largest recurring expenses to utilities across North America. Vegetation management programs can be made more efficient and effective with the help of decisions support systems incorporating relevant geospatial and socioeconomic data as well as knowledge of the effectiveness of alternative vegetation management approaches. This program seeks to develop methods and collect data to 1) improve targeting of treatment areas with ongoing remote monitoring of vegetation conditions using ground-, air- and space-borne sensors, 2) understand socioeconomic barriers to treatment implementation and develop outreach strategies to mitigate these barriers, and 3) assess the impact of different vegetation management options on tree failure and stability. The proposed tasks would expand on previous Eversource Energy Center research to provide a more complete and operational decision support for managing vegetation to reduce power outage occurrences.

Needs

- The silvicultural literature suggests that the Stormwise vegetation management program, developed through Eversource Energy Center research, will be an effective long-term solution for reducing power outages in rural forested areas. However, there is currently no data available to provide empirical support for the program's effectiveness. Analyses to date have shown that Enhanced Tree Trimming (ETT) is effective in reducing total numbers of outages but it remains unclear whether ETT has any effect on reducing physical damages which are often associated with tree failures occurring outside the utility protection zone. Furthermore, the tree biomechanics literature suggests that the drastic crown alterations and tree removals, a common result of ETT, can lead to reduced tree stability and potential for increased risk of whole tree failures. Finally, socioeconomic issues can make Stormwise and ETT programs challenging to implement across broad areas. The tasks below aim to address the challenges associated with the implementation of vegetation management programs.

- Prioritizing treatment areas for vegetation management programs:
- Enhance web-based geospatial support tool for prioritizing treatment areas for vegetation management programs including Stormwise and Enhanced Trimming.
- Improve vegetation risk models using updated power line maps and incorporating forest health and structure risk factors.
- Develop procedures for assessing forest health and mapping current tree mortality using remote sensing.
- Develop predictive models of future tree mortality.
- Site suitability analysis for Stormwise applications.

Evaluating the impact of vegetation management programs on tree failure and stability:
- Multi-temporal mapping of tree failure events in Stormwise treatment and control areas derived using unmanned aerial system and ground-based monitoring.
- Multi-temporal mapping of tree crown symmetry, stand species composition, and stand structure and density at Stormwise treatment and control areas.
- Continued monitoring of tree sway in the three existing Stormwise tree biomechanics research sites.
- Implementation of new tree biomechanics research sites focused on monitoring sway characteristics for ETT and SMT sites.

Socioeconomic barriers and mitigation strategies for implementing vegetation management programs:
- Identify socioeconomic barriers and opportunities to implementation of vegetation management programs.
- Develop outreach methods to overcome social barriers to implementation.
- Develop geospatial predictions of perceived receptivity of communities to Stormwise and other vegetation management programs to support treatment area prioritization.

Expected Deliverables

This research will create the following products:
- Web-based geospatial decision support tool to help in prioritizing treatment areas for vegetation management including Stormwise and enhanced trimming.
- Geospatial datasets mapping: forest health and mortality, predictions of future forest health and mortality, predicted receptivity to vegetation management programs.
- Report on Stormwise treatment effectiveness.
- Report on the effects of Stormwise, ETT, and SMT on tree stability.
- Report on outreach activities and socioeconomic barriers to Stormwise and tree trimming as well as proposed outreach strategies for mitigation.

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Renewable Energy and Grid Integration

HIGHLIGHTS

- **Modeling of transmission-distribution grid on the Eversource Energy Testbed.**
- **Impact assessment of deep integration of distributed energy resources (DERs, e.g. PVs, wind, fuel cells, hydro, storages) on grid stability, resilience and security.**
- **Integrate EPVA and D2NDZ software tools for accurate hosting capacity mapping and unintentional islanding evaluation.**
- **High-resolution mapping of renewable energy sources**
- **Optimal integration of renewable DERs and storage options for current and future load scenarios.**

Background

The penetration level of renewable DERs in the New England States, e.g. in CT and MA, is expected to reach 40% and 50% by 2030, respectively. Deep integration of renewable DERs will lead to several planning and operation problems, including stability issue, resilience concern, data security, coordination problem, optimal design, etc. This project will contribute a set of model, evaluation methods, and software tools to enable high penetration of renewable DERs in New England States while maintaining grid security and reliability.

Needs

- Co-model transmission-distribution grid on the Eversource Testbed.
- Build model libraries for DERs, utility scale storages and controls, and new loads (e.g. heat pumps, programmable loads)
- Integrate EPVA and D2NDZ software tools for accurate hosting capacity mapping (based on power flow, transients, stability, and security analysis).
- Study impact of deep integration (40%, 50%,...,100%) of renewable DERs (including aggregated DERs, virtual power plants, microgrids) on grid stability, resilience and safety.
- Assess renewable energy sources (PV, hydro, wind) potential based on high-resolution reanalysis data and hydrologic model simulations.
- Evaluate the potential of different storage options (battery, heat-pumps, hydro-pump storage, fuel-cells) and their economic benefits.
- Develop a model to predict current load patterns and that will be able to simulate future load patterns.
- Develop a framework that will provide the optimal integration of renewable DERs and storage options under current and future load/climate scenarios.
- Establish a real-time analysis and nowcasting system of solar energy generation potential in the distribution network.

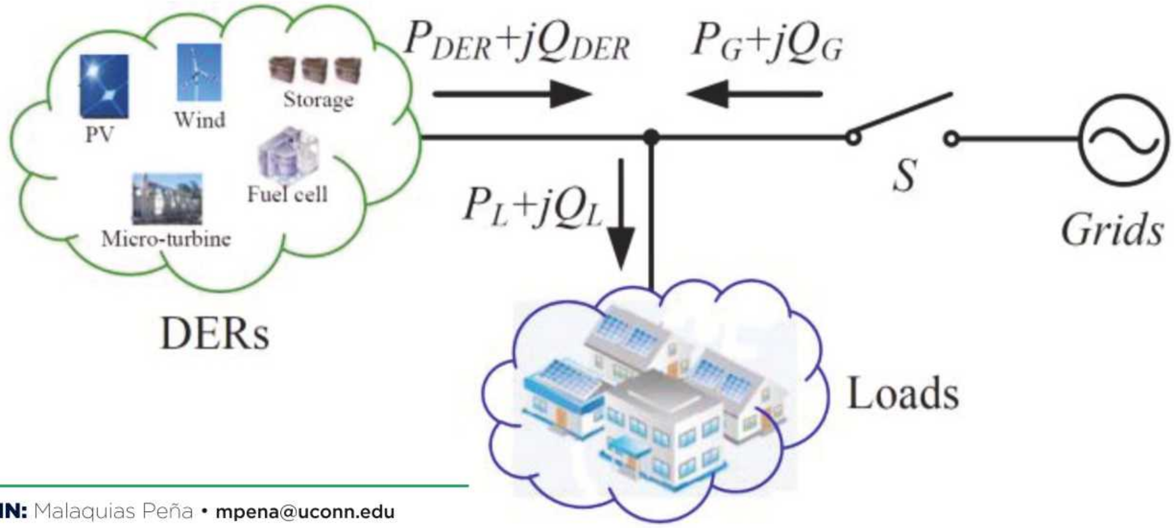
Expected Deliverables

Deliverables from the new integrated project will include:

- A tool for mapping host capacity in distribution feeders considering renewable DER inputs, network constraints and robustness/attack-resilience requirements.
- A report to evaluate the influence of system's stability and resilience due to the high penetration of renewables; identify special phenomena such as over voltages, small-signal and large disturbances.
- A software to integrate tools developed in previous projects, e.g. EPVA, D2NDZ, in Eversource's planning tools.
- High-resolution maps of capacity factors for different renewables at monthly, seasonal and annual scale.
- A tool for time-series analysis (e.g. trend analysis) of capacity factors for selected locations/areas.

Renewable Energy and Grid Integration continued...

- A robust predictive model for load patterns at different scales (county, state).
- A report on the potential of existing water infrastructure to be used as pumped hydro storage and comparison (cost-benefit) with other storage options (e.g. batteries).
- A report for grid side enhancement for reliable and secure integration of different renewable DERs and energy storages for improved renewable DER penetration.
- A software to display solar energy generation potential over the next 6 hours that refreshes every 30 minutes.



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Cyber and Physical Security

HIGHLIGHTS

- **Build dynamic models for typical Eversource Energy power networks on the cyber-physical Eversource Energy Testbed for cyber-physical security analysis purposes**
- **Develop a tool for detecting, localizing, and mapping potential power-botnet attacks and design defense mechanism for preventing remote control of power-bots.**
- **Ensure cyber-physical security in Eversource Energy transmission and distribution substations through Detect-Delay-Defend Security against cyber-physical attacks, air gap based substation attack detection, and formal verification to detect anomalies across IP-based substations against coordinated cyber-physical attacks.**
- **Develop a predictive model for future flood-inundation risk estimation of substations under climate change and sea-level rise.**

Background

Electric power networks in New England are critical infrastructures which have been targets for malicious, well-equipped, and well-motivated adversaries who aim to jeopardize their operations, trigger sustained outages, and delay network restoration after major disruptions caused by extreme events. Attackers may exploit vulnerabilities in substations, Internet of Things (IoT) devices, building and industrial management systems, distributed energy systems, microgrids, and distributed storage devices that are connected to the electric power networks. Once a significant number of such devices are compromised, attackers can collusively cause load fluctuations, stress power grids and deplete reserves, and lead to rolling or even uncontrolled blackouts, perhaps eventually resulting in cascading outages across regions. Moreover, CT substations are prone to flood vulnerabilities due to climate change and sea-level rise. Motivated by the above challenges, this project aims to develop cyber physical security technologies to improve the attack-resilient power networks for Eversource Energy and New England utilities. This project will achieve four major objectives:

(i) Build an integrated models in the Eversource Energy Testbed for cyber physical security analysis;
(ii) Detect, localize and mapping power botnet attacks and mitigate remote control of power-bots;
(iii) Improve cyber physical security in transmission/distribution substations through Detect-Delay-Defend security, air gapped attack detection and formal verification;
(iv) Develop a predictive model for future flood-inundation risk mapping for Eversource Energy substations.

Needs

Cybersecurity testbed integration

- Interface RTDS real-time simulators with cyber security tools, network simulators, KMAX network emulator, and SDN switches;
- Co-model Eversource power transmission-distribution grid on the Eversource Testbed;
- Digital twin for analysis of EEC power distribution network dynamics under different types of attacks, by leveraging the RTDS testbed capability.

Power-bot communication and its mitigation

Design of defense mechanism to prevent direct communication from powerbot to attacker;

- Investigate a 'covert channel' allowing attacker to communicate with power-bots, but exploiting the power network itself;
- Investigate the capacity and limitations of the covert channel, and defense mechanisms designed to eliminate or reduce its effectiveness;

Cyber and Physical Security continued ...

- Automatic reactive mitigation action mapping for power-botnet attacks after attack detection and localization;
- Differential privacy preserving machine learning method based on distribution feeder dynamic data for attack detection.

Substation Cyber Physical Security

a) Modeling, analysis and mitigation of Detect-Delay-Defend Security against theft and sabotage:
  - Detect, Delay and Defend (DDD) for physical intrusion attacks with a focus on theft, sabotage and cyber attack, by algorithms to optimize use of existing cameras and deployment, analysis and algorithms to incorporate other surveillance devices, incl. mobile;
  - Detection of droid intrusions via machine-learning based detection of radar, radio and audio signals;

b) Air gap based substation security:
  - Monitor the physical behavior and component damages of transmission/distribution substations through air-gapped side channel measurements (cyber-secured low-frequency electromagnetic waves);
  - Enable remote monitoring of grid/substation status and remote detection of topological changes due to attacks;

c) Formal verifications to automatically detect and isolate errors and vulnerabilities in substation automation, protection and control to enable provably correct operations of new facilities.
  - Formal verification of substation automation operations and protection functions;
  - Formal overseer between substations and control center to detect inconsistencies and anomalies across IP-based substations against coordinated cyber-physical attacks.

Future projection (50 years) of substation flood vulnerability in the scenario of climate change and sea-level rise

a) Apply hyper resolution flood modeling to evaluate Eversource inland and coastal substation flood vulnerability to river and coastal flooding associated with future climate (2050) storms and sea-level rise.

b) Integrate surge, river flows, tides and sea level rise to compute worse case scenarios of flood inundation at substations

c) Use the modeling framework to derive 100-500 year return period flood levels and evaluate the vulnerability of current Eversource infrastructure.

Expected Deliverables

This work will extend ongoing research for modeling, analysis, and anomaly detection for enhancing the cyber secure Eversource Energy power distribution networks, and will leverage the newly established Eversource Energy Testbed for cybersecurity. Deliverables from the new integrated project will include:

- A functional cybersecurity Eversource Energy Testbed with a documentation for the cybersecurity testbed federation; an integrated Eversource transmission-distribution grid model on RTDS/PSAT
- A design of firewall-based defense mechanism for preventing remote control of powerbots.
- A hybrid system model to analyze the spatial-temporal characteristics and the interaction of the manipulated components with the normal components of the distribution network.
- A tool to automatically map actions after detecting and localizing power-botnet attacks, to assist human experts to mitigate the effects of power botnet attacks on the distribution network.
- A predictive model for future flood-inundation risk mapping at very high resolution (VHR, 1 m)
- A report on substation flood-inundation risk under climate change and sea-level rise
- A documentation of modeling, analysis and optimization of DDD systems, as well as the use of automated unmanned vehicles for DDD.
- A cyber-physical hardware device that perform air-gapped, remote, and verified detection for cyber-physical attacks in substations.
- A formal verification tool that automatically verify substation protection and switching functions, locate errors and cyber vulnerabilities in substation operating and protection devices to enable provably correct operations of substations.

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