UCONN

EVERSOURCE
ENERGY CENTER

Annual Report 2024

Contact

Eversource Energy Center

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Welcome

DEAR FRIENDS,

Fiscal 2023–24 marked one more milestone year for the Eversource Energy Center, during which the funding accumulated by the Center over the eight years of its existence exceeded $65 million. As a partnership of the University of Connecticut and Eversource Energy, the Center represents an unprecedented alliance of a state university and a leading electric utility. Together, we are confronting the great resilience challenges faced by the energy industry at the intersection of weather extremes, climate change, and clean power infrastructure. Today the Center is better positioned than ever to continue and expand that work around energy safety and adaptation to future climate extremes.

Located at the UConn Tech Park's Innovation Partnership Building, the Center enables Eversource and other energy providers to tap into the university's exceptional resources—its internationally recognized faculty, its outstanding students, and its state-of-the-art facilities—to innovate, develop new technologies, and establish advanced science-based solutions, while providing needed data and analytical support for effective decision making in managing the risks of extreme weather and security events. By obtaining considerable ongoing funding from the electric utilities and regional system operators, private industry, and federal sources listed under Sponsors and Strategic Partnerships on our Milestone pages below, the Center is meeting its goal of becoming a hub for innovation in the economical and reliable distribution of power through interdisciplinary research, teaching, and workforce development.

This year's annual report presents a great many research projects. Among them are the extension of the Center's outage prediction model to utility service territories in other states and the identification of winter storms across the country, as well as the forecasting or observation of snowfall, wind gusts, and tree failures. Also presented are projects that reduce risks to powerlines from roadside forests through better understanding of vegetation health and management and the creative application of cutting-edge remote sensing technologies. Center researchers are working to quantify and find ways to head off the growing risks to the electric grid posed by wind, flooding, and vegetation. And our Center continues its development of exciting new technologies to harness the wind, the sun, and other innovative renewable energy resources and to meet the challenges presented by threats to cybersecurity, the need for energy adequacy through integration of sustainable forms of energy, and other aspects of the transition to and maintenance of a modernized grid.

We report, too, on our continuing commitment to the future of people as well as technology. We provide an update on the progress of the students participating in our Power Grid Modernization Certificate Program and on our efforts to support interdisciplinary workforce training and provide experiential learning and research experience to undergraduate students.

We hope you will find the research summaries and other information in this report both useful and illuminating of the many ways in which our active collaborations with representatives of academia and industry are producing the next generation of technologies and software. Our work is generating transformative commercial products and services and advances in storm preparedness, grid resilience, and grid modernization. The partnerships that make it possible are driving innovation, and we invite you to join us in building the grid of the future, today.

Emmanouil Anagnostou
Director, Eversource Energy Center

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Who We Are

We are a hub for innovative and progressive thinking to build the electric grid of the future, today.

The **Eversource Energy Center** is a leading U.S. partnership between an energy utility and a university. With its high expertise in energy, it advances research and technology to ensure reliable power during extreme weather and security events. Through a consortium approach, the Center fosters partnerships, develops next-generation technology, and collaborates to address current and future energy needs.

Our Center originated from a partnership between Eversource Energy and the University of Connecticut, with the purpose of enhancing electric utility preparedness, hardening infrastructure, and embracing the grid of the future: intelligent, interactive, automated, reliable, and safe! The Center comprises experts at universities, state organizations, and the electric utility industry, collaborating within the framework of a Center of Excellence. Marshaling the expertise of these various stakeholders through an integrated analytical approach enables us to advance forecasting tools, proactively manage risk landscapes, and embrace new technologies, yielding strategies and actions to manage severe weather hazards. Importantly, research at the Center features a dynamic vision: it accounts for climate evolution, as well as the changes in exposure and vulnerability to extreme weather events associated with different societal activities and demographics.

Our Team

Principal Investigators

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Craig Tremback, Scientific Consultant, RAMS & WRF

Peter Watson, Scientist, Los Alamos National Lab

Feifei Yang, Adjunct Assistant Research Professor

Milestones 2024

KEY INITIATIVES

Several projects funded by federal agencies and by industry partners were awarded in FY2024 to faculty affiliated with the Eversource Energy Center. Our faculty also continued to work on projects awarded in previous years, as well as on the Eversource projects started in 2023.

EVERSOURCE PROJECTS

Eversource Energy supported 20 projects in FY2024, covering five thematic areas:

- Grid Resilience in a Warming Climate
- Grid Reliability in a Changing Demand Environment
- Renewable Energy Integration
- Cyber-Physical System Security
- Workforce Training, Outreach, and Policy

SUSTAINABLE CLEAN ENERGY SUMMIT

On September 23, 2024, the University of Connecticut and Eversource hosted the third annual Sustainable Clean Energy Summit. More than 300 UConn students and faculty participated, along with attendees from the Connecticut state government, organizations, and industry. Gene Rodrigues, the U.S. Department of Energy Assistant Secretary for Electricity, delivered the keynote address. The summit featured thought-provoking panel discussions, announced the establishment of the Connecticut Sustainable Energy Institute at Avery Point, and marked the signing of a new three-year memorandum of understanding between the university and Eversource to implement energy efficiency upgrades across all UConn campuses. The Clean Energy and Sustainability Innovation Program (CESIP) award was conferred upon graduate students Zhiqing "Lucy" Li, Steven Matile, and Meshach Ojo for their research, "Potential Micro-Hydropower Retrofits at Municipal Wastewater Treatment Plants," and they will receive additional funding from Eversource to continue their work.

GRID MODERNIZATION CERTIFICATE

In 2024, the Grid Modernization Certificate Program, offered to early-career engineers by the Eversource Energy Center at the University of Connecticut's College of Engineering, enrolled six new students and graduated two.

OUR SPONSORS

Eversource (principal sponsor)

Avangrid

Connecticut Department of Energy

Connecticut Department of Energy & Environmental Protection (DEEP)

Connecticut Department of Public Health

Dominion Energy

Electric Power Research Institute (EPRI)

Enel

Excelon

Federal Emergency Management Agency (FEMA)/Puerto Rico Electric Power Authority (PREPA)

Goeppert

Google

Housatonic Valley Association

Hydro One

ISO New England

Johnson & Johnson

Lenovo

National Academy of Engineering

National Aeronautics and Space Administration (NASA)

National Geographic Society

National Oceanic and Atmospheric Administration (NOAA)

National Science Foundation (NSF)

National Science Foundation (NSF)/ U.S. Department of Defense (DOD)

New York City Housing Authority

New York State Energy Research and Development Authority (NYSERDA)

New York State Energy Research and Development Authority (NYSERDA)/ TRC Companies

Schmidt Futures

Schneider Electric

Sloan Foundation

Sony

South Central Connecticut Regional Water Authority

Town of Lenox Madison County, New York

Travelers

United Illuminating Company

U.S. Department of Agriculture (USDA)

U.S. Department of Defense (DOD)

U.S. Department of Energy (DOE)

U.S. Department of Homeland Security (DHS)/Federal Emergency Management Agency (FEMA)/ Connecticut Department of Emergency Management and Homeland Security

U.S. Department of the Interior (DOI)/United States Geological Survey (USGS)

U.S. Environmental Protection Agency (EPA)

Weather and Marine Engineering Technologies

Woodwell Climate Research Center

Strategic Partnerships

The Center is continuing its collaboration with Bay State Wind Energy, the Electric Power Research Institute, and the University at Albany Atmospheric Research Center in the areas of offshore wind energy, water conservation, and grid vulnerability and the operations of the newly established NSF Industry-University Cooperative Research Center (IUCRC) on Weather Innovation and Smart Energy and Resilience (WISER). The Center is also continuing its partnership with Exelon for developing an outage prediction model and estimating the effectiveness of grid resilience initiatives for southeastern Pennsylvania, southern New Jersey, Maryland, Delaware, the District of Columbia, and Illinois. In addition, we have developed institutional partnerships with the National Renewable Energy Laboratory (NREL) and Lawrence Berkeley National Laboratory (LBNL) that will facilitate joint appointments for UConn faculty in these national labs.

Avangrid

Avangrid serves more than 3.3 million customers across the New York and New England regions. It co-sponsors with NYSERDA a project to develop and demonstrate an outage prediction model for power outages caused by rain-wind, thunderstorm, and snow-ice events across the New York service territory. The Center collaborates with the University at Albany Atmospheric Research Center on this project.

Electric Power Research Institute

The Electric Power Research Institute (EPRI) is an independent, nonprofit organization in the public interest that conducts research on electricity generation, delivery, and use in collaboration with the electricity sector, its stakeholders, and others focusing on electric power safety, reliability, and affordability and the nexus between electric power and the environment. In 2020, the Center established a research collaboration with EPRI to provide complete and accurate information on the vulnerability of the electric grid to weather extremes and assess trends in power outages and efforts needed to maintain reliable energy delivery. After demonstrating our methodology over the northeastern United States, for which our team holds many years' worth of outage and electric infrastructure data from Eversource Energy and the United Illuminating Company, we have been working to extend this effort nationwide.

Exelon

Exelon Corporation, with its 10 million customers across six states, is the largest regulated electric utility in the United States. Exelon owns six subsidiaries: Atlantic City Electric, Baltimore Gas and Electric (BGE), Commonwealth Edison (ComEd), Delmarva Power, PECO Energy Company (PECO), and Potomac Electric Power Company (Pepco). In 2023, BGE sponsored a project for performing research on weather and resilience analysis and for developing and piloting the UConn OPM for outage forecasting and resilience improvement assessment in the contiguous Exelon territories along the North Atlantic Coast. In 2024, ComEd sponsored a project to conduct outage prediction modeling research in their Illinois service territory.

Lawrence Berkeley National Laboratory (LBNL)

LBNL is a federally funded research and development center in the hills of Berkeley, California. Established in 1931 by the University of California, the laboratory is sponsored by the U.S. Department of Energy and administered by the UC system. The mission of Berkeley Lab is to bring science solutions to the world. The research conducted there has four main themes: discovery science, clean energy, healthy earth and ecological systems, and the future of science. The Center has initiated a project with LBNL under a DOE grant for assessing and mitigating wildfire risk to power transmission systems. The two partners also began to collaborate on analyzing and mitigating the impact of electric vehicle (EV) integration into the grid.

National Renewable Energy Laboratory (NREL)

NREL is a research and development center funded by the U.S. Department of Energy and operated by the Alliance for Sustainable Energy, located in Golden, Colorado. It is home to the National Center for Photovoltaics, the National Bioenergy Center, and the National Wind Technology Center. The UConn-NREL Partnership for Clean Energy Innovation and Grid Resilience will leverage scientific knowledge and state-of-the-art facilities to solve complex, multidisciplinary challenges in energy efficiency and resiliency, renewable energy technologies, and smart grid innovation.

University of Albany Atmospheric Sciences Research Center

The Atmospheric Sciences Research Center (ASRC), of the State University of New York at Albany, was established in 1961 by the Board of Trustees of SUNY as a systemwide resource for developing and administering programs in basic and applied sciences related to the atmospheric environment. In 2020, ASRC and the Eversource Energy Center submitted a proposal to the National Science Foundation for a planning grant to form an Industry-University Cooperative Research Center (IUCRC) for Weather Innovation and Smart Energy and Resilience (https://wiser-iucrc.com/). Following the awarding of the grant, planning activities took place between 2021 and 2022. The WISER Center was established in 2023 and is supporting research in the areas of renewable energy, outage management, grid resilience, and climate change.

Center by the Numbers

Publications and Patents 2016-2024

Peer-reviewed papers	268
Patents	5

Expenditures

FY2016	$998,059
FY2017	$2,158,683
FY2018	$2,423,839
FY2019	$2,454,938
FY2020	$2,156,234
FY2021	$2,366,012
FY2022	$3,508,000
FY2023	$3,418,186
FY2024	$3,426,085

Awarded Amounts

2016-present	$65,913,354
Proposals pending	$39,064,442

Students

Undergraduates	4
Graduates	56

Storm Readiness

Eversource Energy Center researchers continue to make impressive progress in their efforts to minimize the effects of bad weather on the electric grid. Through ever more accurate predictions of the weather and its consequences, the Center enables utilities both to prepare for storms and restore service afterwards.

Type	Utility	APE_50	MAPE	CRMSE	R.2	NSE
Rain-wind	Eversource	44%	62%	906	0.50	0.33
Rain-wind	Exelon	31%	55%	454	0.88	0.81
Rain-wind	Avangrid	30%	34%	164	0.65	0.59

Note: Updated data for the Dominion Energy OPM are not yet available.

Evaluating the performance of outage prediction models for different utility companies. The models are assessed using various accuracy measures, including median error (APE_50), the middle value of prediction errors; mean error (MAPE), the average prediction error; mean squared error (CRMSE), a measure of the average squared differences between predicted and actual values; R-Squared (R.2), an indicator of how well the model's predictions match the actual data; and predictive accuracy (NSE), overall effectiveness of the model.

OPM Advances

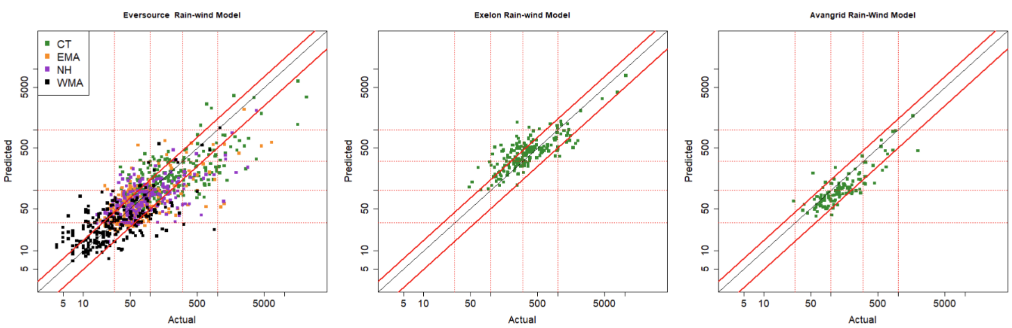
Potential and Thrilling Discoveries

Ten years after it was first conceptualized by researchers at the Eversource Energy Center, the University of Connecticut's Outage Prediction Model has become more than a model. It has evolved into an OPM strategy that simulates the complex relationship among the weather, land surface conditions, electrical infrastructure, surrounding vegetation, and outages and ensures reliable power during extreme weather and security events.

Severe weather impacts are among the leading causes of power outages that have affected businesses, vital government services, and the lives of millions of electric utility residential customers, resulting in billions of dollars in economic losses. The OPM project provides quantitative estimates of system damage in the overhead electrical distribution network by utilizing a variety of high-resolution datasets to build separate machine learning–based predictive models for different storm types across several major utilities and their service territories: Avangrid in New York; Dominion Energy, covering Virginia and North Carolina; Eversource, covering Connecticut, Massachusetts, and New Hampshire; and Exelon, covering the mid-Atlantic. These models are capable of forecasting outages up to 120 hours before a storm begins, allowing utilities to plan and allocate resources for efficient power restoration.

Customizing the OPM in this way is difficult and complicated. Since the accuracy of the predictive models for the same types of storm events can differ in the different utility service territories, merely training them with available predictor variables across utilities is insufficient. The issue for the energy industry is the development of tools that are not only accurate in predicting outages but that incorporate key differentiating storm event characteristics at service or regional geographical locations. Only this level of prediction will benefit emergency managers at electric distribution utilities who need to estimate the impacts of weather on their infrastructure networks when communicating with customers and regulators and making decisions that forestall weather-related grid damage.

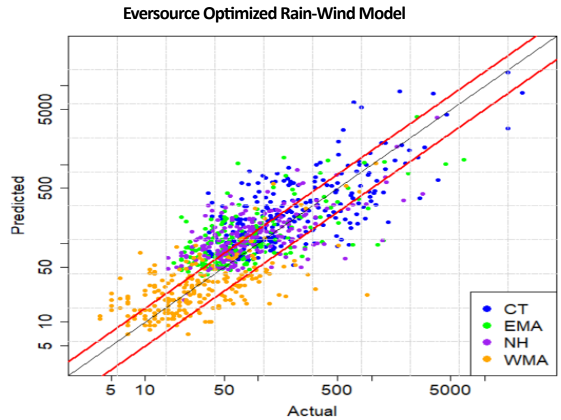
Our goal, then, is to build machine learning tools for different storm types that are profitable for multiple utilities. To do so, we harness weather parameters and infrastructure, vegetation, and land cover diversities across utilities through a comprehensive feature selection procedure that tailors the OPM to each utility's territory characteristics, modeling, and optimizations. This approach removes any systematic bias from the predictions and ensures reliable OPMs.



Note: Updated data for the Dominion Energy OPM are not yet available.

Scatterplots showing the accuracy of outage predictions for different companies during storms: Eversource, 929 storms; Exelon, 183 storms; Avangrid, 118 storms. The black line represents perfect predictions, while the red lines show a range of acceptable predictions (within 50 percent of the perfect line). Points outside the red lines are less accurate. This helps us understand how well the prediction models work for making decisions during storms.

This research will support the optimization of operational performance metrics for various utilities and will explore ways to improve these metrics across the board. The next steps promise to uncover exciting new insights and innovations, paving the way for more efficient and effective utility management. The journey ahead is full of potential and thrilling discoveries.



Note: Updated data for the Dominion Energy OPM are not yet available.

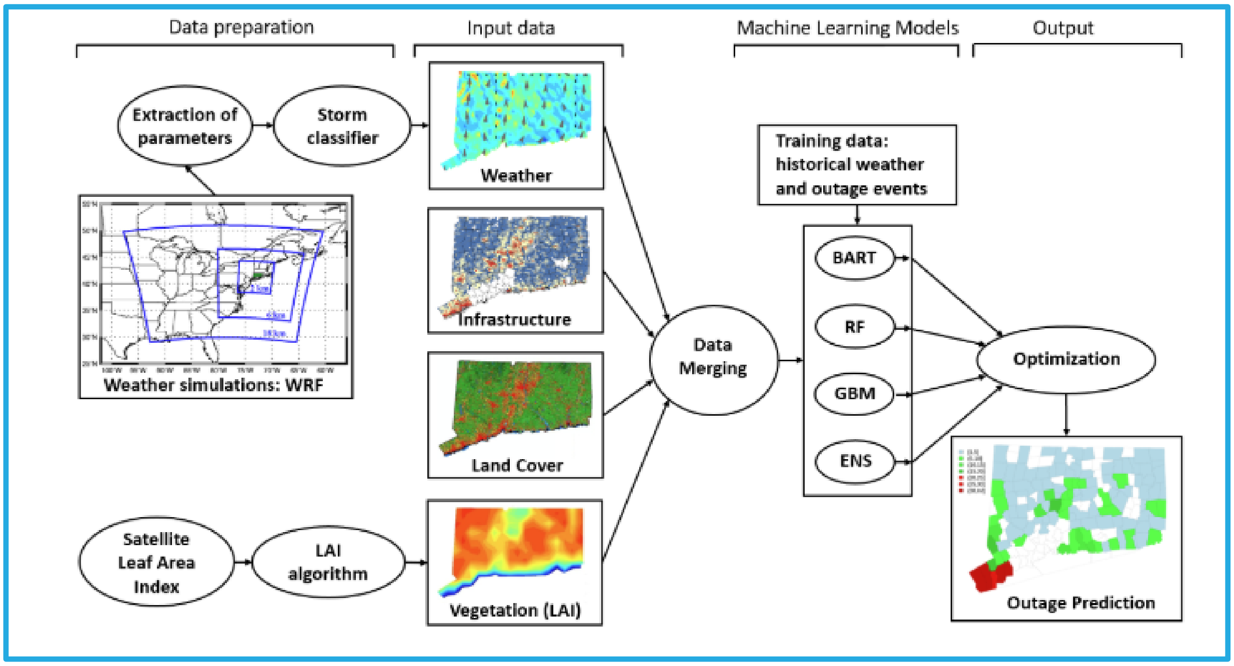
Scatterplot showing the results of testing optimized rain-wind outage prediction model for 929 storms. Each dot represents a comparison between actual and predicted trouble spots. The black line shows perfect predictions, while the red lines mark a range of 50 percent above and below perfect. Dots outside the red lines are either overpredicted or underpredicted.

The University of Connecticut Outage Prediction Model

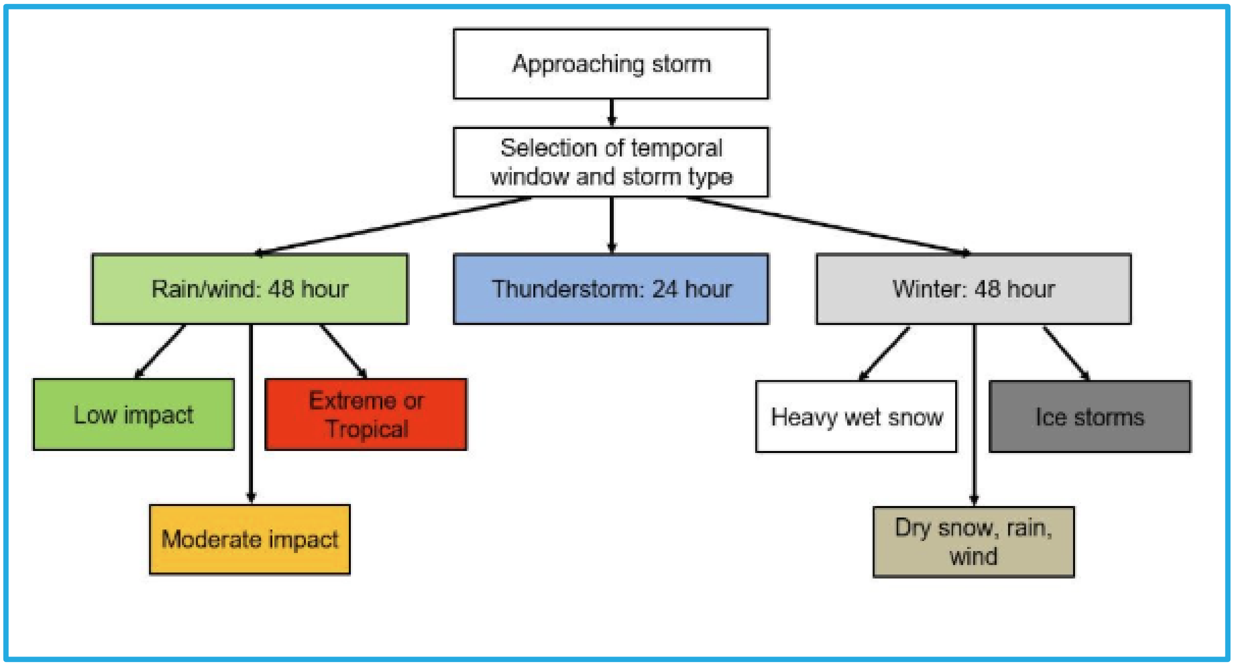
The OPM is a framework developed by researchers at the Eversource Energy Center that integrates weather predictions with infrastructure, land cover and vegetation characteristics, and historical power outage data to predict, through the use of machine learning models, the number and locations of storm power outages across utility service territories. Predictive modules of the OPM—some of which are discussed in this report—are developed separately for different types of storms and different utility service territories.

The OPM framework was first developed for Eversource's service territory in the northeastern United States, using data from that region. OPMs are now being developed for the service territories of other utility companies, beginning with Avangrid, in New York State, and Dominion Energy, headquartered in Richmond, Virginia.

OPM Architecture



OPM Storm Classifier



Outage Prediction with Neural Networks

An especially thorny problem in power outage prediction is creating a model that can accurately forecast the widespread and extreme disruptions from severe storms, such as hurricanes, without compromising the precision of predictions for smaller storms and routine weather events. The ability of a model to predict both high- and low-impact events ensures it can be used effectively across a wide range of weather scenarios, providing utility companies with a versatile tool for outage management.

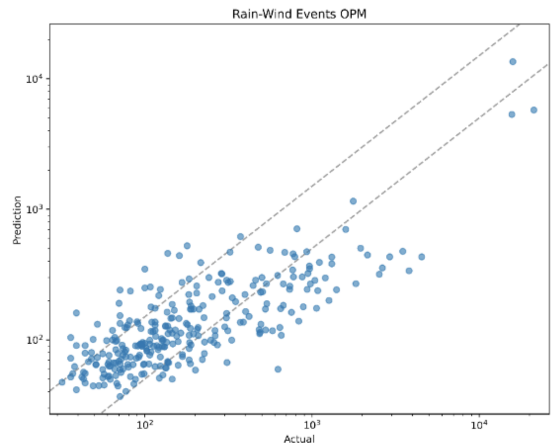
Researchers at the Eversource Energy Center are working to create such a tool by developing advanced outage prediction models that make use of cutting-edge machine learning techniques, particularly graph neural networks. A GNN is a form of artificial intelligence that predicts outages by understanding how different parts of the power grid are connected and affected by storms. A graph convolutional network (GCN), a type of GNN, analyzes these connections in layers, helping utility companies anticipate which circuits are most vulnerable during severe weather events. Our GCN model improves outage prediction accuracy at the circuit level, enabling proactive grid management and resilience planning.

The novelty of this approach lies in the incorporation of newly developed features that capture the intricate interactions among weather conditions, infrastructure characteristics, and environmental factors, such as tree proximity, and integrate the information to predict how various circuits will be affected by storms. By combining it with GNN architectures, we have succeeded in enhancing the prediction of outages resulting from both extreme and routine weather events at the circuit level. This allows utility companies to minimize disruptions by deploying resources and initiate preemptive interventions, such as tree trimming or temporary reinforcement of infrastructure, more effectively. The identification of circuits that are consistently vulnerable to outages also allows them to prioritize upgrades that increase grid resilience.

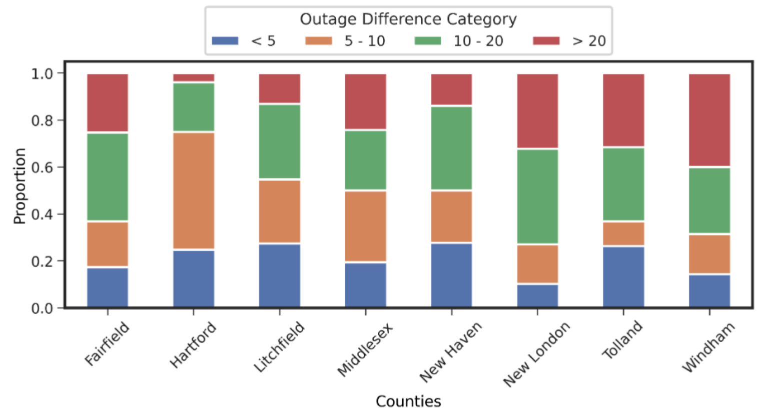
The circuit-level OPM holds great potential for future applications, including relicense studies, where it can be used to assess the long-term reliability of grid infrastructure under various climate scenarios. As we continue to refine the model and incorporate additional features, it will become indispensable for improving power grid performance and mitigating the impacts of severe weather.

__Machine learning__ is a branch of artificial intelligence (AI). It involves developing algorithms that allow computers to identify and learn from patterns in sample (training) data, based on which they can make predictions whose accuracy increases as they learn.

AE q50	APE q50	MAPE	CRMSE	R2	Nash
48.59	43.09	47.59	1183.0	0.84	0.57



Accuracy of outage predictions made by the GCN model. This figure shows a scatter plot of predicted outages versus actual outages for weather events from 2005 to 2023. Each blue dot represents a single event, with its position indicating the predicted outage count (y-axis) relative to the actual outage count (x-axis). Points closer to the diagonal line represent more accurate predictions, highlighting the model's effectiveness across both high- and low-impact weather events.



Predicted circuit errors based on historical data from Hurricane Irene in 2011, broken down by counties in Connecticut. This figure shows a stacked bar plot illustrating the proportion of circuits (y-axis) within each error category, based on the difference between the GCN model's predictions and actual outages for Hurricane Irene in 2011. The x-axis represents counties, and the bars are color coded to indicate the magnitude of outage differences. This visualization highlights the model's consistent performance across counties, with most predictions falling into the smallest error category, indicating high accuracy statewide.

After the Storm

In line with the Eversource Energy Center's mission to enhance power system reliability and resilience, our research team has made significant strides in developing an advanced agent-based model (ABM) for optimizing power restoration efforts in the aftermath of storms. The model incorporates key lessons from events like tropical storm Isaias—which caused extensive damage and widespread outages in Connecticut in 2020—applying cutting-edge technologies to the improvement of disaster management and restoration capabilities.

The ABM simulates the intricate process of power restoration by creating virtual "agents" representing repair crews. These agents navigate a simulated post-storm environment, complete with damaged infrastructure and blocked roads. As the simulation progresses, the model continuously updates its strategy based on factors like elapsed time, crew fatigue, and the number of affected customers.

Our ongoing research has yielded several key enhancements to the ABM, significantly improving its capabilities. One enhancement is the implementation of a dynamic multi-agent probability system. This system allows the model to adapt to the severity and progression of a given storm, optimizing the deployment of both individual and team-based repair crews throughout the restoration process.

Another significant advancement is the incorporation of a sophisticated system for predicting and adapting to road accessibility issues. This feature dynamically adjusts restoration strategies based on evolving ground conditions, addressing one of the major challenges faced during events like Isaias, in which restoration efforts were impeded by blocked roads.

Based on historical data, our model now provides proactive recommendations for crew arrangements and resource allocation before a storm hits, improving the ability of utility companies to prepare for incoming weather events. Furthermore, we've developed a time-based approach that evolves as the restoration process unfolds. In the initial hours, the model simulates the prioritization of nearby outages, mimicking response to critical situations. As time goes on, it shifts focus to high-impact repairs affecting larger numbers of customers. This temporal strategy helps balance the competing priorities of customer restoration with municipal "make safe" requests.

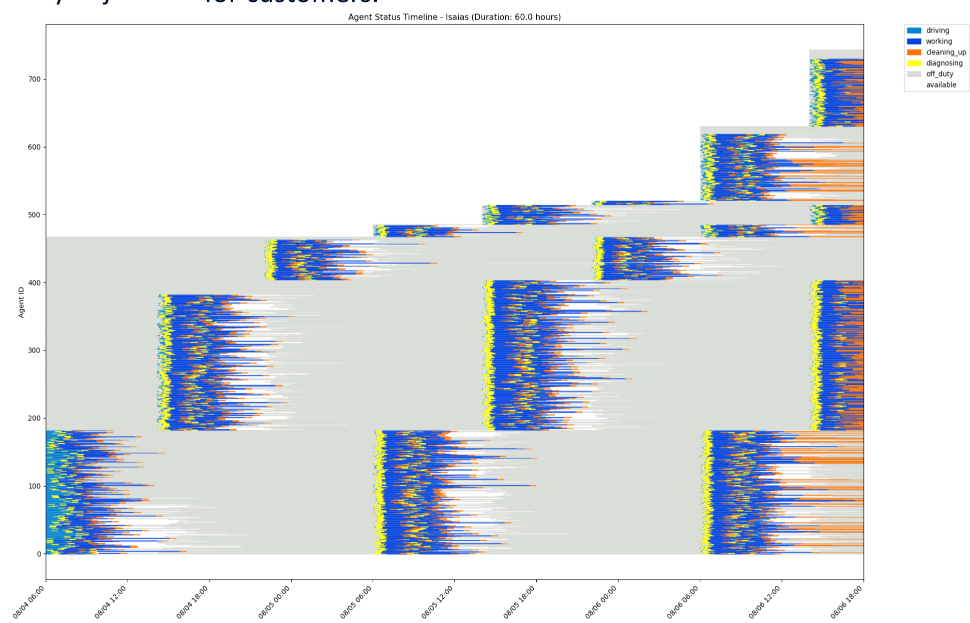
__Agent-based modeling__ is a computational technique that simulates human decisions while also representing technical conditions. The ABM under development at the Eversource Energy Center provides a virtual environment where utility managers can test their restoration decisions before implementing them. The model can also be used in real time to provide an estimate of the time to restoration, given available resources.

Damage to powerlines from tropical storm Isaias. *wtnh.com*

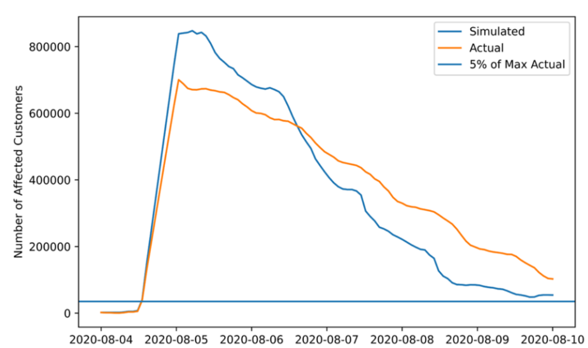
Altogether, preliminary results from simulations based on storm data show potential to reduce overall restoration time by up to 20 percent compared to traditional methods. This improvement could translate to substantial savings and significantly reduced disruption for customers.

The future of our project includes exploring integration of our model with the UConn Outage Prediction Model to test and enhance the ABM's capabilities further. We also plan to make use of machine learning and generative artificial intelligence to create and simulate future scenarios, including events more severe than Isaias and the Category 3 Hurricane Sandy that devastated the Atlantic coast in 2012.

In short, by learning from past events and continuously incorporating new data and technologies, our ABM stands at the forefront of power restoration modeling. It will help utility companies navigate the challenges of increasingly severe weather events, ultimately leading to more resilient power systems and reduced outage times for customers.



Agent statuses over time for tropical storm Isaias.



Comparison of actual affected customers with simulated affected customers for tropical storm Isaias.

Improving Extreme Weather Forecasting, Phase II

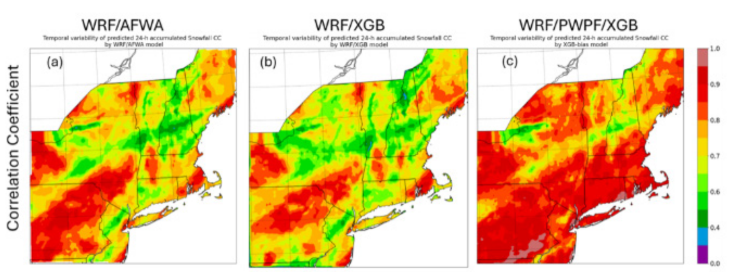
Between 2020 and 2023, researchers at the Eversource Energy Center identified challenges in forecasting tropical storms, snowstorms, and wind gust, all of which significantly affect the reliability of the power outage predictions that are issued by the Center and used directly by managers at Eversource Energy. In 2023, a new project—Improving Extreme Weather Forecasting Capabilities in Support of Power Outage Prediction Activities—commenced as the continuation of our previous three-year project.

The goals for this second phase are, first, to develop two operational products for improved wind gust and snowfall forecasts based on the previous exploratory machine learning work and, second, to quantify the influence of these weather conditions on power outage predictions. During the first year of phase II, we quantified the uncertainty of gust predictions with an evidential deep learning model; we developed a methodology to predict wind gust for input into the UConn Outage Prediction Model; and we explored additional machine learning algorithms and probabilistic data for the prediction of snowfall.

__Deep learning__ is an artificial intelligence method that teaches algorithms to process data in complex ways, as the human brain does.

We are currently finalizing an automated operational system to download National Weather Service products so we can investigate how official NWS predictions differ from our in-house storm forecasts, using maps and frequency distribution plots for wind, snowfall accumulation, and temperature. This task will give us an efficient real-time knowledge of the variability between our predictions and the official ones, which will inform the power outage forecasts we provide to Eversource Energy managers.

Our next steps will involve the assessment and correction of biases in winter weather temperatures and continuation of the development and evaluation of the gust and snowfall prediction systems, using physical models and machine learning algorithms that we will be deploying operationally.



Improvement of the correlation of snowfall accumulation with observations from the default weather model (left) to the first machine learning model (WRF/XGB, middle) and a second machine learning model that includes probabilistic snowfall information (WRF/PWPF/XGB, right). Higher correlation is indicated in red.

Let It Snow
An IMPACTS Campaign Update

Winter brings a variety of challenges when it comes to forecasting the weather. Small changes that are often not observed in detail allow precipitation to range from significant snowfall to ice accumulation to heavy rain and wind. Matters are further complicated by local topography, which plays an important role in determining what type of precipitation is seen at the Earth's surface. The result is a degree of uncertainty in forecasting that hinders preparations by utility operators for winter storms. In 2021, the Eversource Energy Center began collaborating with the National Aeronautics and Space Administration on NASA's Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) field campaign, whose objective was to collect a variety of observations from winter storms in the northeastern United States. At two locations at the University of Connecticut, twenty instruments were installed to make measurements from the surface and lower atmosphere. Ground instruments recorded characteristics related to falling precipitation, including amount and intensity, temperature, humidity, and wind speed. Above the ground, instruments sensed the location and intensity of precipitation and clouds.

Although IMPACTS ended in March 2023, NASA continued its partnership with the Center, with the instruments returning during the winter of 2023–24 to continue collecting observations. In addition, the Center began working with Oklahoma State University, which brought to UConn the Unmanned Aerial Weather Measurement System. The WxUAS, a drone outfitted to observe precipitation in winter conditions, measures temperature, humidity, and pressure in the lowest levels of the atmosphere. These data can be combined with the ground observations from NASA to explain more about the physical processes occurring.

Researchers at the Eversource Energy Center have now begun to explore the observations collected over the past three years. One question is how these measurements compare to those produced by different model simulations of winter weather, the answer to which is important to gaining an understanding of

An overview of the different instruments at UConn: (a) Deployment of instruments in winter of 2022–23. (b) Deployment of instruments in winter of 2023–24. (c) Deployment of instruments in winter of 2023–24, with WxUAS in foreground.

the configuration of weather model that will best capture the right amount and type of precipitation—information that can be used to improve the UConn Outage Prediction Model. Future research will analyze observations related to snow size, speed, and density to determine whether the model accurately replicates observed snow characteristics. Improvements to simulations of snow processes not only will make the models more accurate when representing snowfall but can improve their ability to predict snow density, a characteristic of winter storms especially pertinent to the prediction of power outages.

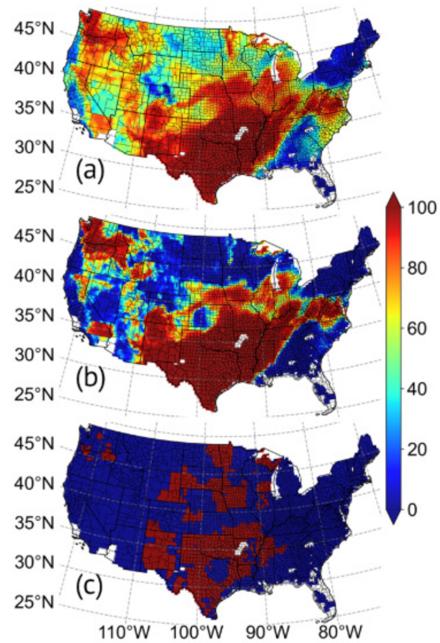
Where? When? How Big?

Better Prediction of Winter Storms

Winter storms are unique in that they envelop a large variety of atmospheric conditions, which increases the uncertainty of predicting them and the difficulty of estimating their impacts. Precipitation types alone can vary greatly, even within the same storm, to include freezing rain (water droplets that freeze upon contact), sleet, and snow. Compound hazards, such as blizzards, can result in large amounts of heavy snow being carried by high winds.

For the UConn Outage Prediction Model, the outages from winter storms remain among the most challenging to predict, as a result not only of the complexity of atmospheric conditions but of the unique interactions between weather conditions and the environment. Ice and wet snow, for example, which tend to be more adhesive, accumulate on branches, making them heavier and more likely to break and strike grid infrastructure. Accumulation on electrical circuit components leads to device malfunctions and even catastrophic failure. Moreover, the impacts are not limited to power outages. The effects of winter weather events can range from local school closings to transportation service delays and cancellations, unprecedented heating demands, extensive property damage, and human injury and loss of life.

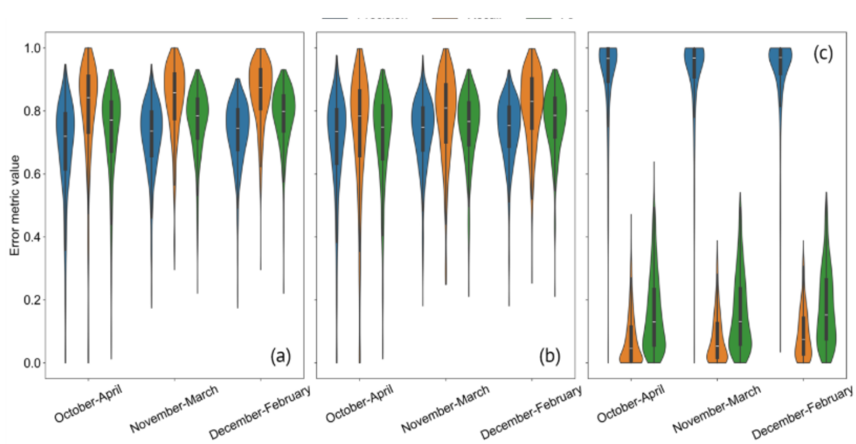
State-of-the-art tools deployed by agencies like the National Weather Service (NWS) to improve winter storm preparedness by issuing watches, advisories, and warnings to the public are highly computationally demanding, which limits their capacity to provide continuous estimates. They also rely on regional parameters that might introduce systematic bias in their results, while their rigid architecture does not allow for a seamless integration of datasets other than those on atmospheric conditions that have customarily been utilized. To support efforts to improve such tools and create new ones, researchers at the Eversource Energy Center have developed a framework based on machine learning techniques that combines weather and climatological data, information about topography and modifications of the environment induced by human development, and reports from onsite observers to improve prediction of the locations, timing, and extent of winter storms that may have significant impacts.



Examples of winter storm occurrence likelihood estimates obtained by Eversource Energy Center researchers from two machine learning models (a and b), compared to observer reports (c) from February 15, 2021, at midnight (that is, corresponding to the Great Texas Freeze).

Our work has been a success: although an evaluation of results using assimilated snowfall data found evidence that onsite observer reports may be inconsistent, our models performed well in capturing the associated winter weather patterns.

The implications are twofold. First, the new framework allows modelers to exclude instances of non-severe winter weather. This contributes to the creation of more balanced datasets for winter storm impact assessment studies, such as the estimation of power outages. Second, it can serve as a guidance tool that enables society's response well before imminent winter storms, not only across Connecticut but the nation and, potentially, other parts of the world. The study has been completed and submitted as part of a scientific journal article. Looking ahead, we plan to operationalize our findings, particularly in the context of supporting the prediction of outages caused by winter storms.



Error metrics obtained from the evaluation against assimilated snowfall, over the entire contiguous United States and three different overlapping periods, for the estimates of two machine learning models (a and b), as well as observer reports (c). F1 is a combination of precision and recall. They jointly quantify the quality of estimates in a classification setting.

Tree and Forest Management

Science and nature meet where Eversource Energy Center researchers explore ways to reduce the risks to powerlines from roadside trees. Their broadening understanding of forests and the people who manage them supports development of a variety of strategies to prevent outages while preserving the beauty of the landscape.

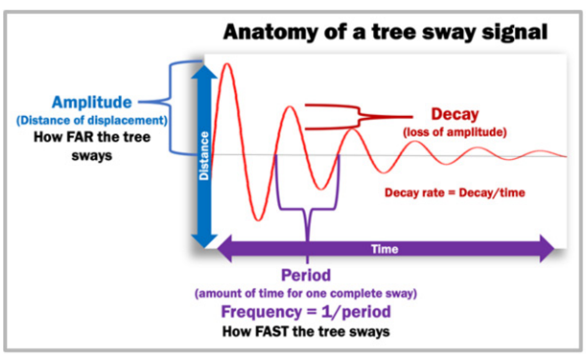
Dynamic Sway

Enhancing Tree Stability and Forest Resistance to Storms

Trees and forests along roads provide substantial benefits, including shade, protection for water and wildlife, noise buffers, aesthetic value, and a sense of place to the local community. Because of their position at the forest edge, however, roadside trees are particularly vulnerable to storms and high winds, which, with climate change, are increasing in both frequency and severity. Fallen trees may obstruct roads when emergency services are needed during storms and can cause major damage that results in loss of heat or power to essential infrastructure, such as hospitals. While tree trimming efforts have helped reduce outages associated with minor events, such as branch failures, they have not been as effective in strong wind events that bring down many branches at once and, often, entire trees.

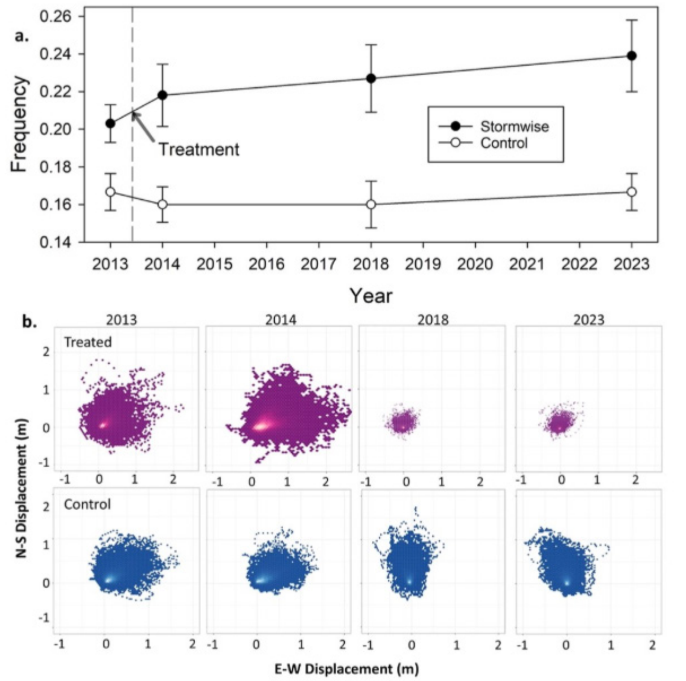
Researchers at the Eversource Energy Center initiated the Stormwise program to mitigate the risk posed by roadside trees through vegetation management. Stormwise management seeks to alter characteristics of the forest canopy to promote changes in the structure of trees that should increase their stability in the face of storm wind conditions.

One way to understand the risks associated with roadside trees and how the trees may be affected by storms is to study the way they sway in the wind and how it changes over time. The Tree Biomechanics and Stability project currently underway investigates the sway response of roadside trees to wind in terms of both amplitude and frequency of movement and the effects on this phenomenon of the Stormwise management protocol. Dynamic sway characteristics serve as a proxy for tree stability because they shift as the tree develops wind-firm characteristics, with reduced amplitude and increased frequency of movement reflecting the smaller, more rapid sway motions that are associated with stability.



Metrics describing tree sway include amplitude—or distance moved from a resting position—and frequency, representing the timing associated with repeated movement.

Our results to date indicate that tree sway characteristics in managed Stormwise sites (relative to paired control sites) have shifted in a way that is indicative of the potential for these

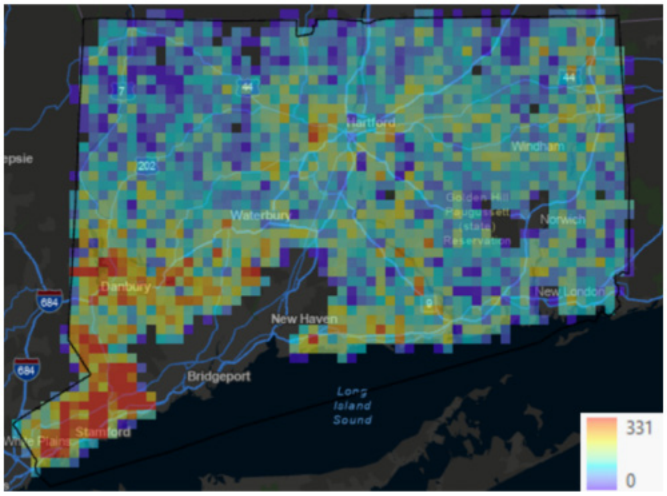


The effect of Stormwise management on tree biomechanics: (a) change in sway frequency over time for trees in Stormwise and control units and (b) bole positions of individual trees in the Stormwise management and control areas, illustrating change in displacement over time. Plots represent all measured bole locations in three-hour periods during leaf-on conditions in June and July, where wind averaged 3.8–4.0 m/s and maximum gust was ~10.0 m/s and wind direction was consistent (all 5°–25°).

treatments to increase tree stability. Following Stormwise forest management, tree sway frequency generally has increased; and, after a period of increase immediately after the treatments and before tree structural response, sway amplitude has decreased. These changes likely reflect increased stability and may indicate that the forest has become more resilient to the impact of storms.

Future work in the area of tree biomechanics and stability will focus on modeling the relationship between forest characteristics and storm resilience across the landscape and studying the effect that widespread implementation of Stormwise management could have on tree failures, outages, and grid resilience.

Stormwise *is the Eversource Energy Center's innovative and multifaceted forest management and public education initiative that aims to reduce the risk of power outages and other damage caused by wind-related tree failure, especially along wooded roadsides and electricity distribution lines. A combined forest management demonstration, outreach effort, and discipline-spanning research program, Stormwise applies what we know about growing trees to develop management strategies for more storm-resistant roadside woodlands that maintain the functions of forest ecosystems and preserve their beauty, while reducing or at least shortening tree-related outages and extending intervals between trimming or management treatments.*



Numbers of outages caused by trees, 2015–21.

Monitoring Roadside Tree Risks from the Sky

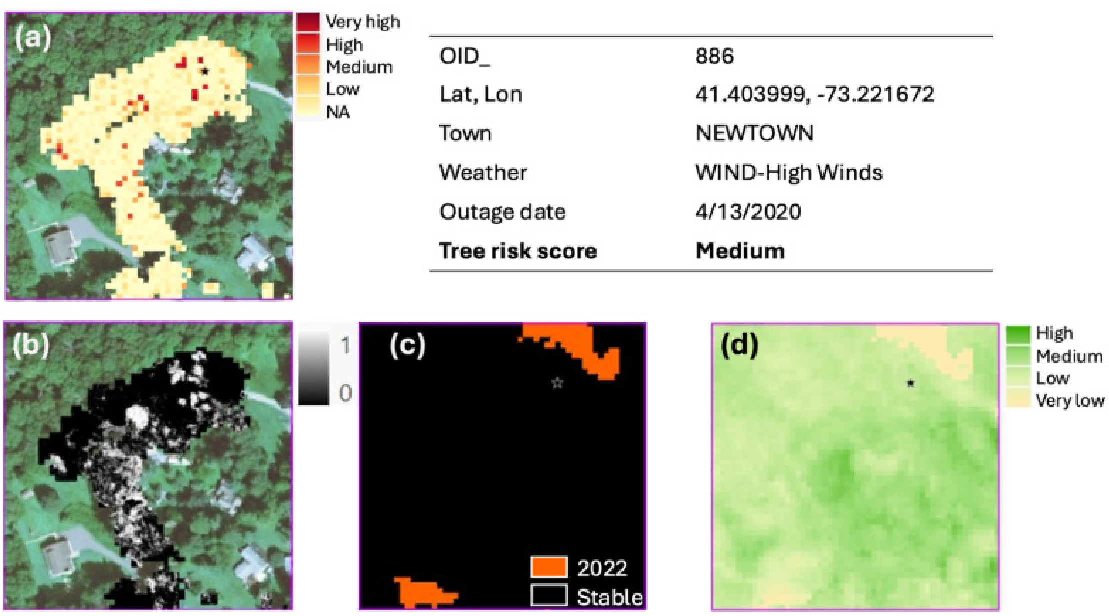
In recent decades, disturbances such as droughts and pest outbreaks have caused the health of New England forests to decline. As seen especially in southwestern Connecticut, the stressed and dead trees pose a serious threat to grid infrastructure. Identifying these hazardous trees through manual inspections is not feasible, though, given the vast areas involved and the dynamic nature of forest health.

At the Eversource Energy Center, the research team for a new project, Estimating Roadside Tree Risk to Grid Resilience and Reliability Using PlanetScope Time Series (GRR), has been working on improving grid resilience and reliability by using high-resolution satellite and aerial imagery to estimate roadside tree risk. The team created an analytical tool to assess at three-meter resolution the powerline risks that result from changes in forest conditions.

Using advanced machine learning models and time series analysis, we sought to predict the probability of tree-related outages by incorporating a range of input variables, including the probability of dead trees, the frequency and intensity of disturbances, forest resilience indicators, and the density of trees along roadsides and rights-of-way. By combining these data, we can now create maps that show tree risk in great detail, categorizing it into five levels—not applicable (NA), low, medium, high, and very high.

As the GRR project continues, we are working to refine current analyses that help us identify areas that may need attention so we can provide a timely assessment of tree-related risks. The first version of the tree risk map has been delivered to Eversource arborists for field validation, upon which it can begin to inform proactive tree trimming efforts to prevent outages. In addition, we are working to develop comprehensive data layers that integrate seamlessly with existing outage prediction models, further enhancing the accuracy and effectiveness of grid management strategies.

Our project demonstrates how the convergence of remote sensing, machine learning, and field validation can address complex environmental and infrastructure challenges, offering a scalable solution that can be applied to other regions facing similar risks.



OID_	886
Lat, Lon	41.403999, -73.221672
Town	NEWTOWN
Weather	WIND-High Winds
Outage date	4/13/2020
Tree risk score	**Medium**

Characterization of tree risk by the GRR project: (a) Roadside tree risk score map. A risk level is assigned to each three-meter pixel. For the site of a tree-caused power outage (highlighted as a black star), the model-predicted risk is medium. Detailed information about this site is shown on the side. (b) Probability of roadside dead trees, ranging from 0 to 100 percent. (c) Land disturbance map, in which orange represents the latest disturbed year, and black denotes stable surface. (d) Forest resilience map with four categories: very low, low, medium, and high resilience. Low resilience could relate to a decline in forest health. The background for (a) and (b) is provided by a true-color aerial image from the 2018 National Agriculture Imagery Program.

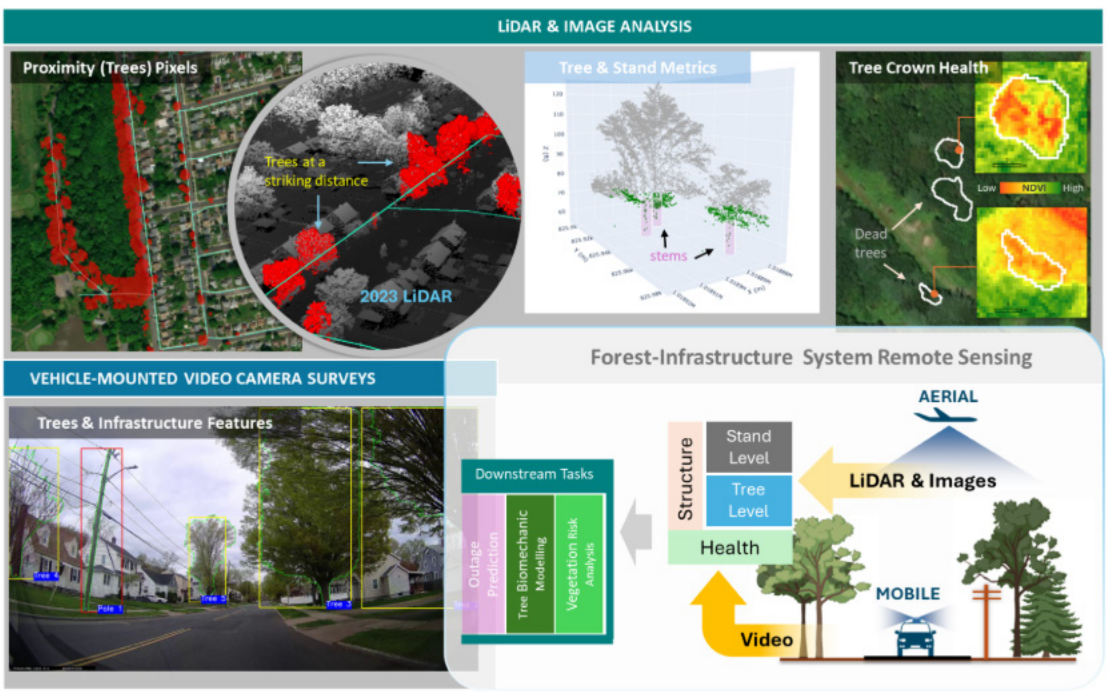
Remote Sensing of the Forest–Infrastructure System

Roadside trees account for nearly 90 percent of weather-related power outages in the forested northeastern United States. Accurately assessing the risk they pose to powerlines requires detailed and timely information on their physical structure and health. By combining data from aerial and satellite remote sensing with data—mainly video streams—from vehicle-mounted imaging sensors (dashcams), we can create complementary information layers to develop a vegetation risk model that reveals the risks to powerlines from roadside trees at different scales—from the span between utility poles, to device exposure zones (that is, outage locations corresponding to isolating devices, each of which protects a section of power line), and on down to the circuit level. The model provides electric utilities with a powerful tool for guiding spatially optimized vegetation management and supporting decision making about grid hardening.

In the ongoing Remote Sensing of Forest–Infrastructure System project, researchers at the Eversource Energy Center have been making significant progress on two fronts: we are automating the extraction of information on the physical structure and health of roadside trees from multi-modal remote sensing data sets, and we are developing a machine learning–based model of vegetation risk to powerlines.

Aerial LiDAR (Light Detection and Ranging) plays a major role in modeling the three-dimensional structure of roadside vegetation. LiDAR-derived proximity pixel maps point to trees that are within striking distance of powerlines. Advancing from the LiDAR-based map we completed in 2016 for the entire state of Connecticut, we are in the process of producing a far more detailed map using the publicly available LiDAR data acquisition from 2023. The higher point density of the more recent data set allows us to probe the physical structure of trees in greater detail—we can, for instance, model individual tree stems and measure tree canopies, deriving useful information on their locations and metrics at the tree and stand levels. Meanwhile, in contrast to overhead remote sensing, vehicle-mounted imaging cameras can provide a street view perspective and penetrate into roadside forest at ground level to localize and identify both trees and infrastructure.

Having obtained the data, we trained artificial intelligence (AI) models to extract defoliated and dead tree canopies from high-resolution aerial images taken along utility infrastructure corridors. We also harnessed the dashcam data with AI algorithms, to detect, identify, track, and localize roadside tree information and utility infrastructure attributes automatically. Once we combine the two information streams with data on other environmental factors, we can produce an accurate and detailed vegetation risk profile along powerline corridors.



A graphic representation of how remote sensing data sets from a variety of sources provide different information for modeling the forest–infrastructure system.

LiDar *(Light Detection and Ranging) is a remote-sensing technology that determines distances by targeting an object or a surface with a laser and measuring the time for the reflected light to return to the receiver*

Collaboration for Forest Management

Roadside forest and vegetation management practices are ongoing throughout Connecticut to minimize power outages by addressing potential tree-related issues and challenges within the utility protection zone. Since these programs affect what roadside forests look like, they rely on regulatory approval to balance maintaining reliable power with acquiring vegetation management program resources and managing the roadside forests.

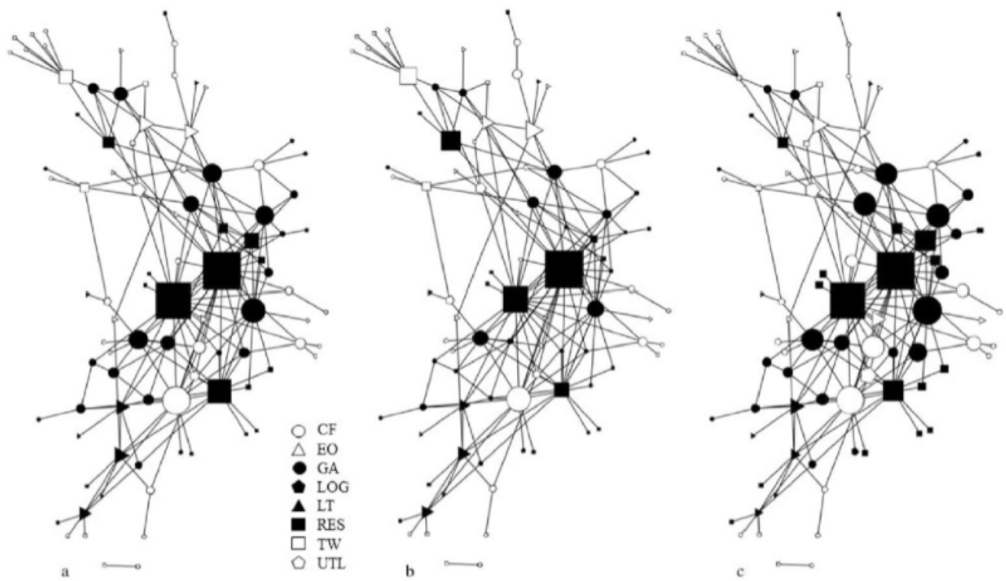
As part of the interdisciplinary Stormwise project at the Eversource Energy Center, the study of human dimensions has, since 2015, been helping Center researchers understand public concerns about and opportunities for innovations in roadside forest management across Connecticut. Human dimensions is the social science that seeks to understand how people make decisions about natural resources, like trees, and the characteristics of people that affect those decisions.

Recent "pulse event" stressors—like spongy moth, drought, and severe weather—that take place within and beyond the utility protection zone have brought attention to related tree failures and the stability of roadside trees and their landscape-level impacts across land ownership boundaries. In response to such concerns, our latest project phase focused on nonresidential public, quasi-public, and private sectors of the statewide forest management community. Our objectives were, first, to evaluate vegetation and forest managers' interests in the implementation of novel treatments and collaboration "beyond their property" for a broader vision of roadside vegetation management reaching outside the utility protection zone; and, second, to assess the interrelationships of forest managers in decision making about forest stressors, particularly with regard to roadside vegetation.

To accomplish these objectives, we conducted semi-structured interviews with thirty-nine members of the Connecticut forest management community. Participants reported that they were balancing between one and nine forest management objectives concurrently. The two objectives related to roadside vegetation management most frequently identified were public safety and the mitigation of hazardous conditions, while support from and satisfaction among the public and other stakeholders was the most frequently noted challenge. We also learned that professional biases related to public perspectives about forest management decisions may contribute to ongoing challenges. Many participants avoided active management along roadsides for reasons of worker safety and the need for extra resources, such as specialized certifications and traffic control. More broadly, immediate roadside vegetation issues, such as public safety, were prioritized over long-term planning beyond property boundaries.

*The **utility protection zone** is the space within which utility companies are allowed to perform vegetation management to protect their infrastructure and services. In Connecticut, this means "any rectangular area extending horizontally for a distance of eight feet from any outermost electrical conductor or wire installed from pole to pole and vertically from the ground to the sky" (CGS § 16-234).*

Participants said they engage in collaboration about forest management at some level, which typically occurs with individuals representing occupations other than their own (for example, agency personnel and consulting foresters). These interactions are motivated by professional networks and relationships, management relevance, and the sharing of information or experiences. Collaborative roles were dominated by a few individuals who are considered trusted sources by many participants; the departure of those individuals may lead to less information exchange among managers. Participants identified greater availability of and access to information and opportunities for in-person relationship and network building as ways to enhance ongoing communication. These findings suggested that the roadside forest is largely avoided beyond routine utility vegetation management, and structured organization of associated landowners may facilitate collaboration. The next steps for the project include exploring the role of vegetation management within resiliency planning for town and municipal land use.



Connecticut forest management community information sharing network, based on: (a) degree, (b) betweenness, and (c) eigenvector centrality. Symbols designate occupation groups (CF = consulting forester; EO = environmental organization; GA = government agency; LOG = logger; LT = land trust; RES = researcher; TW = tree warden; UTL = utility). Nodes represent individual community members. Larger nodes denoted a greater number of relationships. Edges (lines) represented interrelationships. Adapted from Cabral et al. (2024).

Grid Vulnerability and Resilience

Extreme weather and the rising occurrence of cyber-physical threats increasingly challenge the ability of electric companies to keep the grid safe. Eversource Energy Center researchers are working to determine the frequency with which extreme weather events happen, assess the risk when they do, and detect and defend against cyberattacks on control systems.

Predicting Outage Intervals

In the United States, severe storms inflict tens of billions of dollars in damage annually. Through their work on the UConn Outage Prediction Model, Eversource Energy Center researchers know that those weather patterns associated with large amounts of precipitation and high wind speeds are among the most destructive. With the changing climate increasing both the frequency and intensity of such events, estimating their return periods (that is, the average time intervals between their occurrences) and evaluating the effectiveness of resilience enhancement strategies can help utilities and regulatory authorities plan more efficiently for the rising risks of power outages.

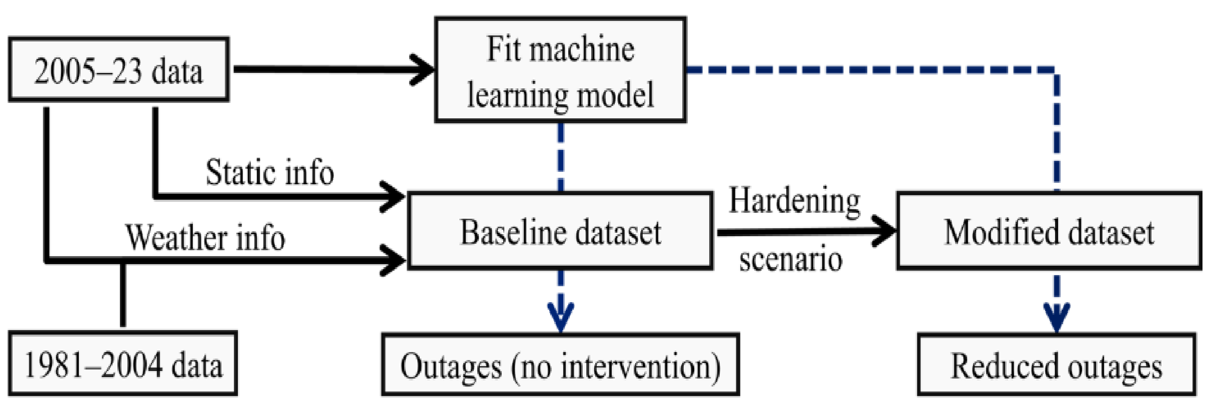
Currently, in work supported by the Electric Power Research Institute (EPRI), our research team is developing a framework to calculate the return periods of power outage events. Based on a machine learning model, the proposed framework estimates the likelihood of outages by combining recent infrastructural information, topographical data, the characteristics of vegetation and the risk of its striking powerlines nearby, and weather data corresponding to storms that occurred over a period spanning several decades. The return periods of power outage events are then calculated through the application of theoretical statistical relationships. The results allow us not only to draw conclusions about historical storms but to approximate the frequency of the more severe events that could occur in the future.

Then, we modify the input of the model by artificially applying grid-hardening intervention scenarios, like tree trimming or the relocation of overhead powerlines underground. The model's output is then used to quantify relative improvements—that is, to estimate how much less frequent outage events of a certain magnitude become after the interventions.

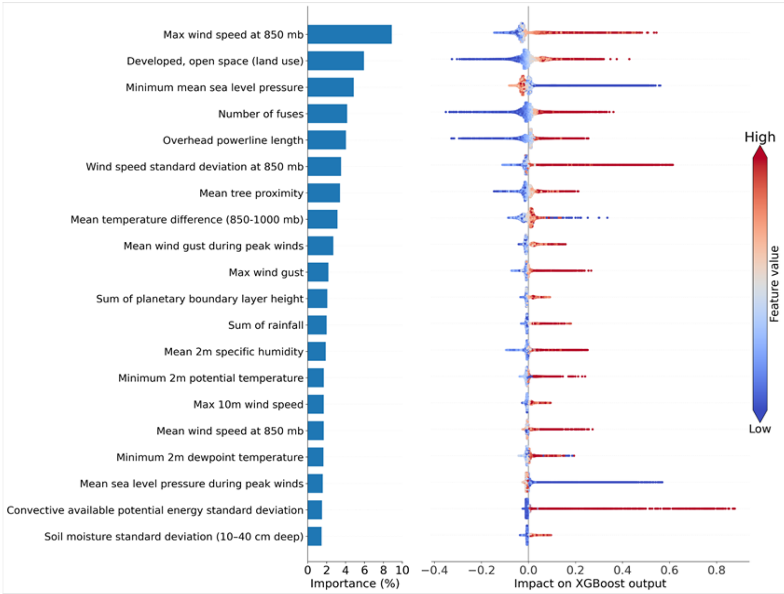
__Return period__ is a statistical measurement that represents the estimated interval between the recurrence of a particular type of event—such as storms or power outages—based on historical data. Although the return period may be expressed as once-in-so-many-years, such as a 100-year flood (or, in the case of power outages, as once-in-so-many-outages), the calculation is only an average; the event may actually occur at any time.

In the next stage of our work, we will employ future climate simulations to assess these scenarios considering various potential climatic trends. This will enable us to evaluate power outage extremes based on the change in frequency of weather extremes.

While the methodology developed for this project is meant primarily for the power distribution grid, we designed it so it can also be applied to other impacts caused by atmospheric phenomena. In upcoming studies, a natural expansion would be the incorporation of a wider variety of grid-hardening interventions, including a guided application that prioritizes more socially vulnerable regions and is complemented by a detailed cost-benefit analysis.

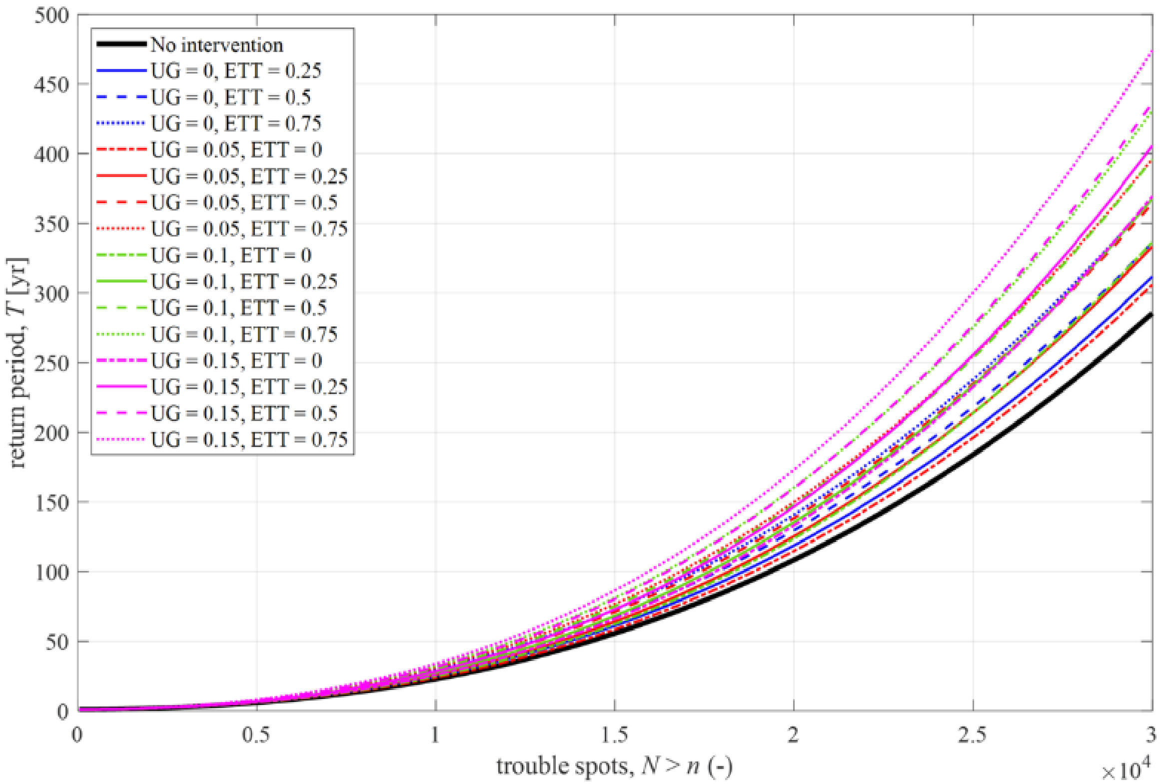


Schematic representation of the application of grid-hardening scenarios.



Feature importances (left) and machine learning model (XGBoost) response (right), computed based on 100,000 datapoints for the 20 most important covariates.

"Trouble spot" *refers to a system outage, caused by physical damage to the electric network—for example, damage to a power line from a fallen tree branch. Each trouble spot can cause multiple customer outages, meaning that, for instance, fifty different customers may be affected by just one branch falling over a line.*



Return period estimates, T, and the minimum number of trouble spots, n, for different scenarios. UG and ETT stand for undergrounding of overhead powerlines and enhanced tree trimming, respectively.

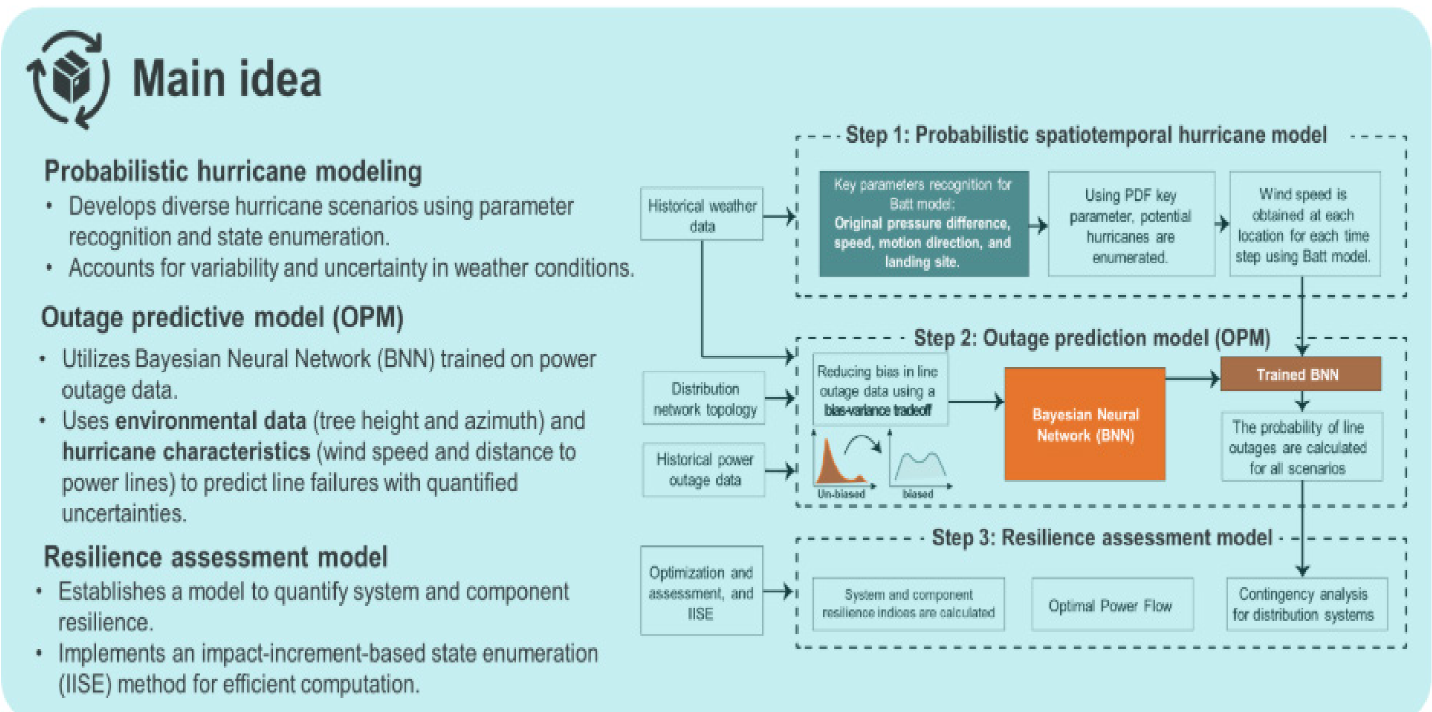
Safeguarding the Distribution Network

Hurricanes and severe storms have consistently demonstrated their destructive impact on electrical distribution systems, causing widespread power outages requiring costly recovery efforts. In line with the Eversource Energy Center's mission to enhance the reliability and resilience of energy systems—particularly during extreme weather events—researchers at the Center sought to create a predictive and adaptive approach to assess and improve the resilience of power distribution networks in the face of these challenges.

Traditional methods to evaluate grid resilience tend to rely on static models that do not fully capture the dynamic and uncertain nature of storm-related disruptions. The Resilience Assessment for Distribution Systems during Hurricanes project addressed this limitation by developing a learning-based framework that uses historical outage data, weather information, and power system characteristics to forecast damage and identify vulnerable components within the distribution network, providing more accurate assessments than previously available and allowing for better planning and resource allocation and more timely recovery efforts.

The innovation introduced by this framework also enables more informed decision making regarding the safeguarding of the distribution network by providing utilities with enhanced visibility into the risks posed by hurricanes. With vulnerable areas pinpointed in advance, utilities can implement targeted preemptive measures, reconfigure the distribution network, and control renewable energy and battery set points to minimize the impact of hurricanes and improve overall grid resilience.

With the completion of this project, the framework serves as a scalable foundation for future work in predictive modeling for grid resilience. Potential applications extend beyond hurricanes to other climate-related events, offering utility companies a robust solution to the growing challenges posed by an increasingly volatile climate.



The core components of the proposed learned-based framework, showing how the hrobabilistic hurricane model, outage prediction model, and resilience assessment model are integrated to assess the resilience of power distribution systems against hurricanes. This approach offers utilities a powerful tool to enhance preparedness by identifying critical weaknesses in the distribution system before storms, reducing the likelihood of extensive damage.

Adversarial and Uncertain
Detection of Cyberattacks in Active Distribution Networks

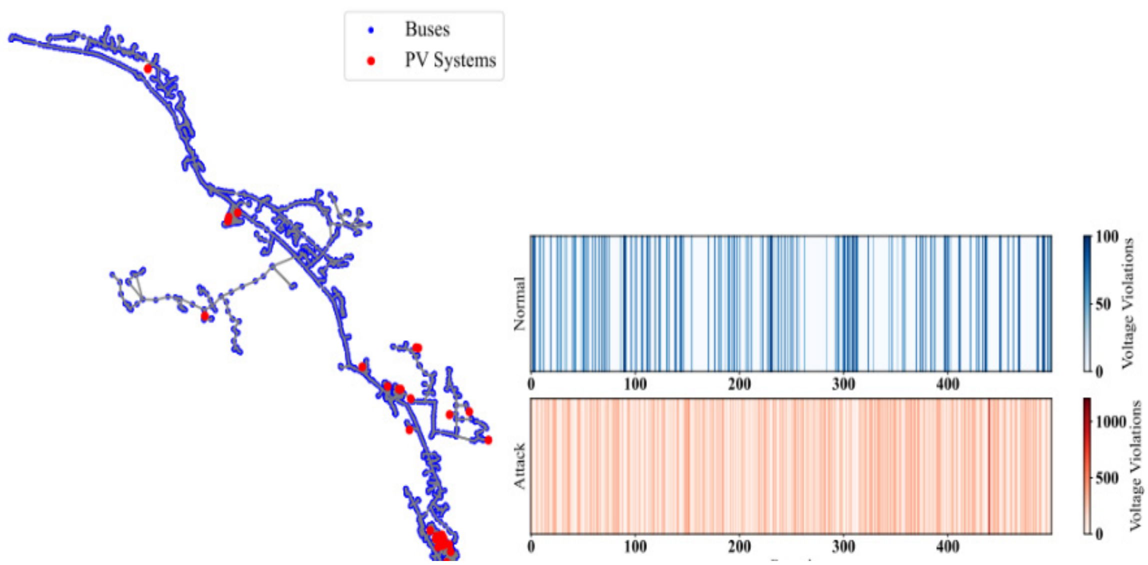
Ensuring stable voltage levels is essential for modern power grids, especially as renewable energy sources like solar panels and wind turbines become more common. Equipment damage, inefficiencies, and outages can result when voltage levels fall outside the safe range as the result of power surges and imbalances, known as voltage violations, in active distribution systems. To prevent them from occurring, utilities use Volt-VAR control, which adjusts reactive power to maintain stability. Volt-VAR systems are, however, subject to threats from sophisticated cyber-physical attacks that target their control settings.

To safeguard grid stability in the face of these threats, researchers at the Eversource Energy Center are working to identify and address vulnerabilities in Volt-VAR control systems. Unlike traditional methods, which examine attacks in isolation, we developed a novel approach to uncover a wider range of weaknesses in the control settings. One of two test scenarios we created incorporates uncertain samples—data points that are difficult to classify as indicative of attack versus normal conditions. The other simulates advanced attacks that are designed to exploit weaknesses by making minimal changes with significant impact to specific control settings.

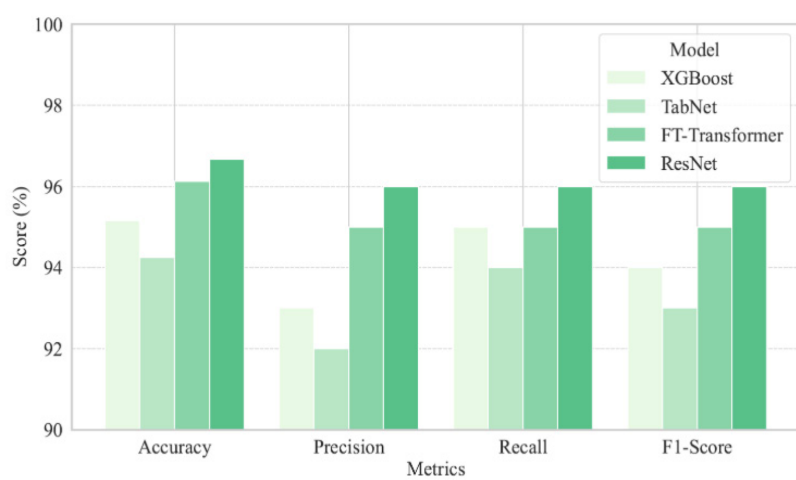
To show the real-world impact of these attacks, we conducted simulations on a large electrical distribution network with over 5,600 nodes. Under attack conditions, voltage violations rose dramatically from 100 to more than 1,000, highlighting the severity of the threat. Our detection framework effectively identified these issues, demonstrating its robustness and scalability for large-scale systems.

Using these datasets, we then tested several machine learning models to detect and mitigate the threats. Among them, ResNet—a deep learning architecture—stood out for its ability to handle even the most challenging attack scenarios, achieving an impressive 96.67 percent accuracy in detecting threats, notably better than the precision of other state of the art methods. This model not only excels in identifying attacks; it provides valuable insights into which parts of the Volt-VAR control settings are most affected.

By exploring these vulnerabilities and offering a robust detection solution, our research represents a significant advancement toward securing the power grid against evolving cyber-physical threats. Ultimately, the insights we've gained will enhance the safety of energy distribution systems and contribute to building a more resilient and reliable energy future.



Counts of voltage violations in normal and attack scenarios over 5,625-node feeder in Colorado.



Comparison of cyberattack detection using ResNet and other state of the art methods.

Grid Modernization

For electric utilities, it is a whole new world of renewable energy sources that pose significant challenges to the continued smooth and safe functioning of the grid. Researchers at the Eversource Energy Center are developing innovative ways to prevent, detect, and solve the issues that come with the integration of these resources into both transmission and distribution systems.

State Estimation: Enhancing Grid Visibility

Grid visibility involves the comprehensive monitoring, assessment, and management of various components and operations within the power grid. This capability enables operators to track electricity flows, oversee infrastructure conditions, and effectively anticipate or respond to system changes or faults. In real-world power systems, achieving complete visibility of the entire grid using only sensors is usually not feasible because of budget constraints, measurement uncertainties, and missing or delayed data.

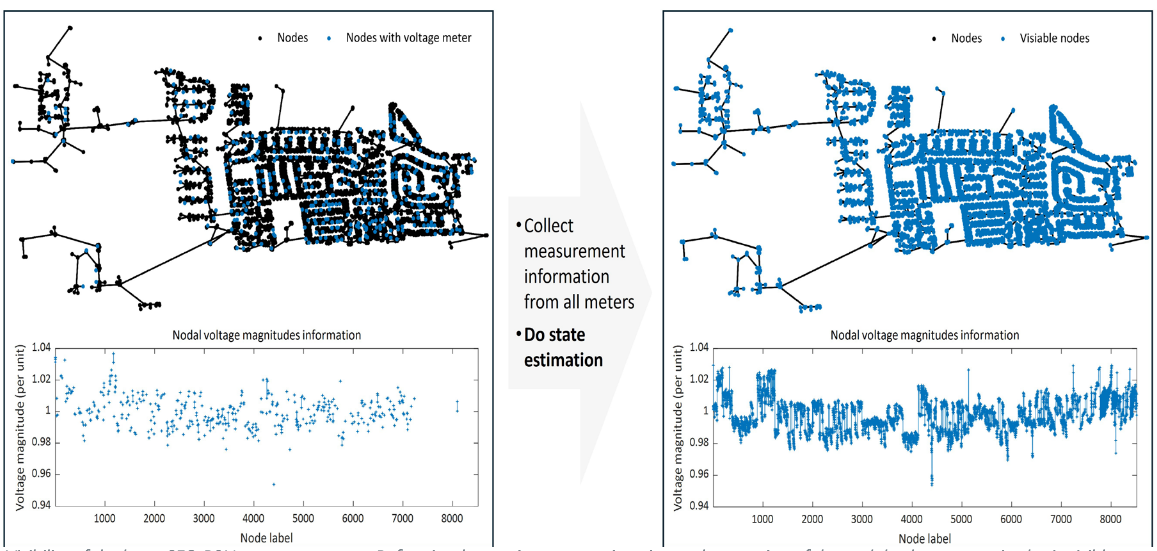
At the Eversource Energy Center, researchers are working to develop a new method for state estimation (SE), a computational technique used in electric power systems to estimate the state (voltage magnitude and angle) of the network based on available measurements that may come from various devices, such as smart meters, sensors, and monitoring systems, installed throughout the network. SE is like having a detailed map that shows not just where the power lines are, but how much electricity is flowing through them and whether everything is working as it should. Enhanced grid visibility through SE allows for better monitoring and control of the electric grid. Utilities can see in real time if there are any disruptions, such as power outages or voltage irregularities, and respond quickly. They can manage loads more effectively, integrate renewable energy sources efficiently, and plan maintenance or upgrades with a clearer understanding of the grid's needs.

The robust state estimator method we have proposed makes use of the Huber loss function. The Huber SE treats data points differently based on the magnitude of differences between the observed value and the estimator predicted value, which makes the estimator more resistant to larger differences. Specifically, for smaller differences, the Huber SE minimizes the square of the difference, while for larger differences, it switches to minimizing the absolute difference.

We have tested the proposed Huber state estimator on a large SFO-P9U area test system, which is a real-world distribution system with 8,515 nodes—that is, points where devices, circuits, or other grid elements connect. In this test system, only 1,703 nodes are directly visible through the use of meters. With implementation of our SE, all nodal voltage magnitudes are accurately estimated; in other words, grid visibility is enhanced from partial to full.

In the future, we will explore several promising directions for continuing to increase the visibility of the entire grid, including optimal sensor placement, detection, and correction of network parameter errors and integration of multiple data sources in SE.

*In predictive models, a **loss function** represents the difference between actual observation and the model estimates. The higher the loss function, the worse the performance of the model.*



Visibility of the large SFO-P9U area test system. Before implementing state estimation, only a portion of the nodal voltage magnitudes is visible (as shown on the left). After implementing state estimation, all nodal voltage magnitudes become visible (as shown on the right), significantly enhancing the grid visibility of the distribution system.

Like Water through a Pipe
The Mathematical Modeling of Power Systems

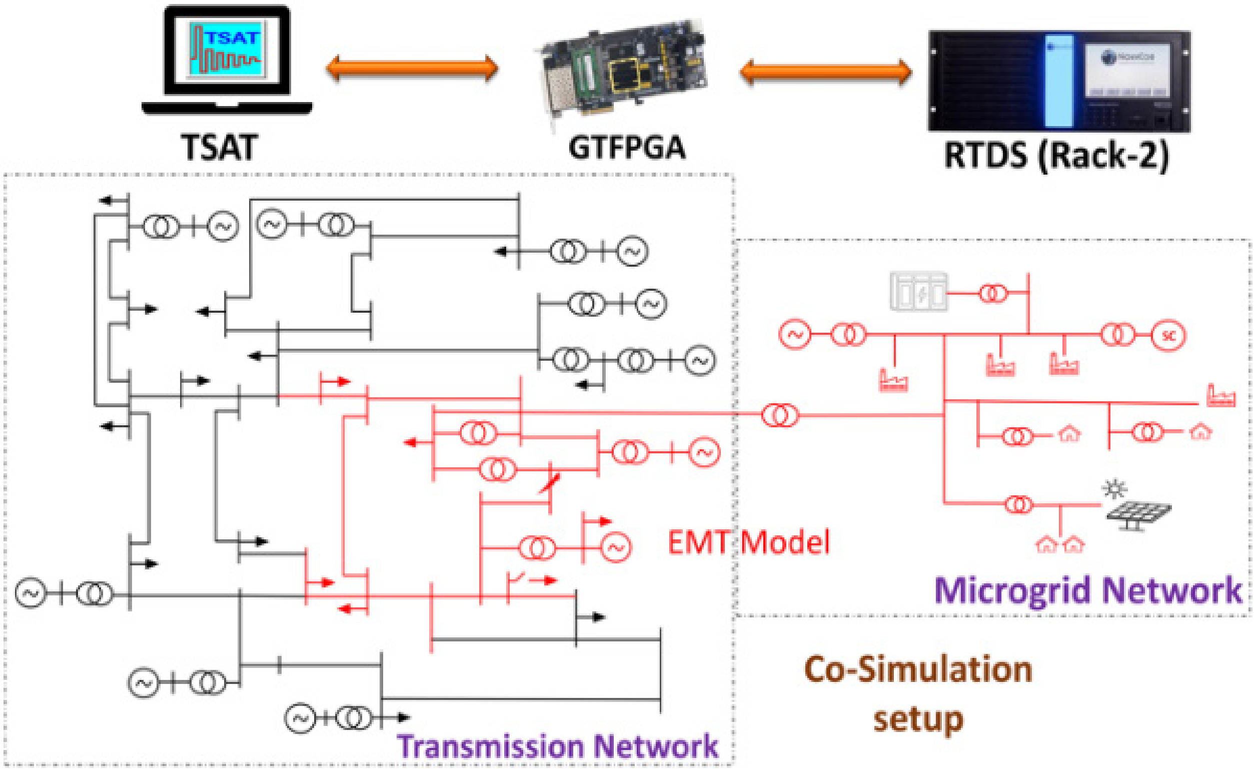
The rapid transformation of energy infrastructure driven by the adoption of clean energy technologies has introduced new challenges for electric utilities and their customers, with power grid operations complicated by the intermittent nature of renewable energy sources and their limited controllability. The lack of inherent support from these resources during grid disturbances further challenges utility operators in developing effective strategies for managing power outages. At the Eversource Energy Center, researchers are using mathematical modeling to develop and validate solutions that could improve both the controllability and resiliency of the grid as the integration of clean energy resources continues.

Compared to traditional fossil fuel–based generation, power grids that rely solely on renewables or on hybrids of renewables and fossil fuels often exhibit reduced system strength. An apt analogy is the movement of water through a pipe, with the flow representing electric current and the water pressure standing in for voltage. The efficient movement of the water depends on the flow and pressure being maintained within allowable ranges, and physical disruptions to the pipe can make controlling both of these difficult. Similarly, in an electric system, the variability of inverter-based resources like renewables makes it harder to control both current and voltage.

The mathematical modeling of power systems enables utility operators, planners, and policymakers to address this difficulty by effectively analyzing system performance under various scenarios. Electromagnetic transient simulation tools are particularly valued for their high accuracy and ability to capture fast-moving disturbances in the power grid. One prominent EMT tool, the Real-Time Digital Simulator (RTDS), not only facilitates detailed EMT modeling but allows the integration of physical devices into simulations. This capability supports the testing and validation of control strategies before their deployment in real-world systems. Despite its accuracy and widespread acceptance, however, particularly for studies involving the integration of inverter-based resources, EMT simulation can be computationally intensive. This makes it less practical for simulating large-scale power systems, such as those serving entire states, like Connecticut.

In our study, funded by the Deep Integration of Distributed Energy Resources into Power System (DIDERPS) project at the Center, we are working with an alternative approach, known as co-simulation, that increasingly is being used to analyze large-scale power systems by combining two different simulation tools. This method enables the separation of power systems into simpler simulations while dedicating major computational resources to studying inverter-based resources in the EMT domain. Since these tools operate on different time scales, we use hardware-based synchronization, such as a Giga Transfer Field Programmable Gate Array (GTFPGA), to ensure proper interfacing and synchronization.

In sum, our approach allows for a detailed analysis of the wide area impacts of renewable energy integration and the evaluation of proposed control strategies. By integrating EMT modeling using RTDS with other modeling tools, co-simulation offers utilities a comprehensive framework to study system behavior. The results will allow them to develop operational strategies that enhance the reliability and performance of their systems.



Schematic of co-simulation with transmission (in black) and microgrid (red) networks.

DER Integration in Energy Communities

Solutions for the Future Energy Landscape

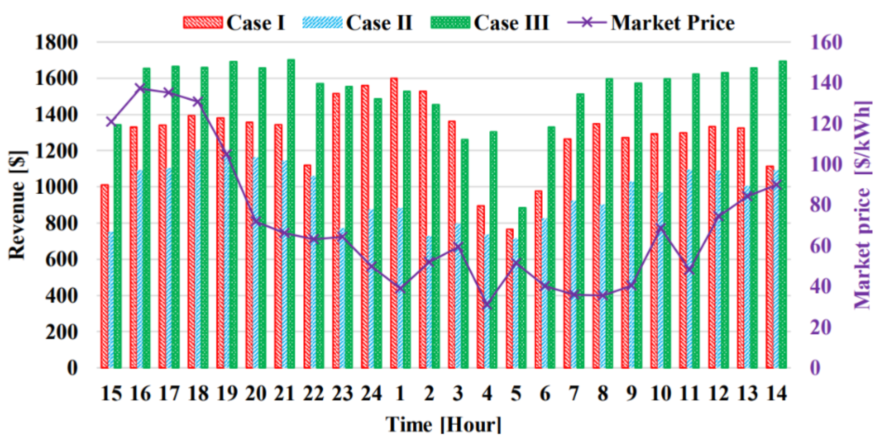
The increasing use of distributed energy resources (DERs), such as such as electric vehicles, energy storage systems, and wind turbines, presents a challenge to power grid reliability and resilience because their variability complicates their integration into the grid. Over the past year, researchers at the Eversource Energy Center have made significant progress in advancing the integration of DERs, specifically within energy communities (ECs). The team's work has led to the development of a scheduling mechanism designed to optimize economic performance and resilience and reduce carbon emissions in ECs. The research focuses in particular on improving grid resilience during different types of extreme events, such as hurricanes, earthquakes, and ice storms, which cause many difficulties even for traditional distribution grid operations.

A key innovation of the project is the introduction of an optimization framework based on network configuration that incorporates a mesh-view grid mapping tool. This framework assesses the correlation between extreme events and the location of grid components to help identify vulnerabilities and more effective mitigation strategies. By considering both geographical and operational factors, the method provides a novel approach to system resilience that prioritizes the protection and strategic reconfiguration of grid assets during disruptive events. The mapping tool is further enhanced by a multi-objective stochastic optimization scheduling mechanism—that is, a mechanism that takes random variables, like the unpredictability of DERs, into account. The scheduling mechanism balances generation costs, resilience, and carbon emissions, thus promoting both economic efficiency and environmental sustainability.

*An **energy community** is a group of consumers and prosumers (that is, those who both produce and consume) who collaboratively generate, manage, and consume energy using distributed energy resources (DERs) such as solar photovoltaic and battery storage. These communities, as defined by the U.S. Department of Energy, enhance local resilience and grid stability through advanced control systems, energy-sharing strategies, and participation in demand response and virtual power plants, contributing to both local and regional grid reliability.*

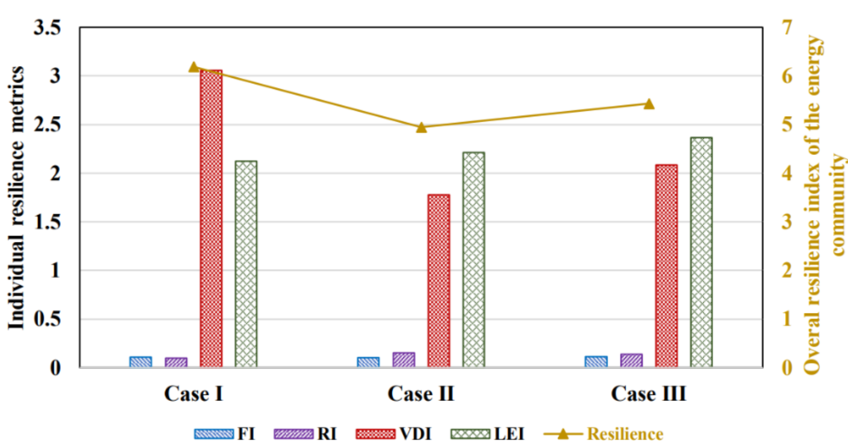
A significant feature of the study is its inclusion of an "Effective Load-Carrying Capability" metric. ELCC quantifies the reliability contributions of renewable energy sources such as wind and solar and plays a vital role in ensuring the power grid can meet demand, even during extreme events. By calculating the ELCC for renewable energy resources, the framework enables the grid to sustain load supply during emergencies. The quantified metrics and methodology are especially relevant in energy communities, where reliance on renewables is increasing and operational flexibility is essential.

Simulations performed on the IEEE 33-bus test system have demonstrated that the proposed framework significantly enhances grid resilience through strategic reconfiguration and optimal use of DERs. The results showed that using electric vehicles and energy storage systems can substantially reduce operating costs while improving the grid's resilience. By optimizing their integration, the framework ensures a more adaptable and robust grid capable of withstanding the impacts of extreme events.



Revenue chart of the energy community in random selected scenarios with multiple types of DERs.

Additionally, the incorporation of carbon emission constraints into the scheduling process enables the framework to align with decarbonization goals. This approach reduces reliance on traditional diesel generators, minimizes imported power from upstream networks, and promotes a cleaner and more sustainable energy infrastructure. Its focus on resilience and cost effectiveness while addressing broader environmental objectives makes it a comprehensive solution for the future energy landscape.



Resilience metrics of the energy community.

*The **IEEE 123-node distribution system** is one of several electrical distribution network models made available to researchers by the Institute of Electrical and Electronic Engineers to provide a common set of data they can use to verify the correctness of their machine learning simulations of problems related to the electric grid.*

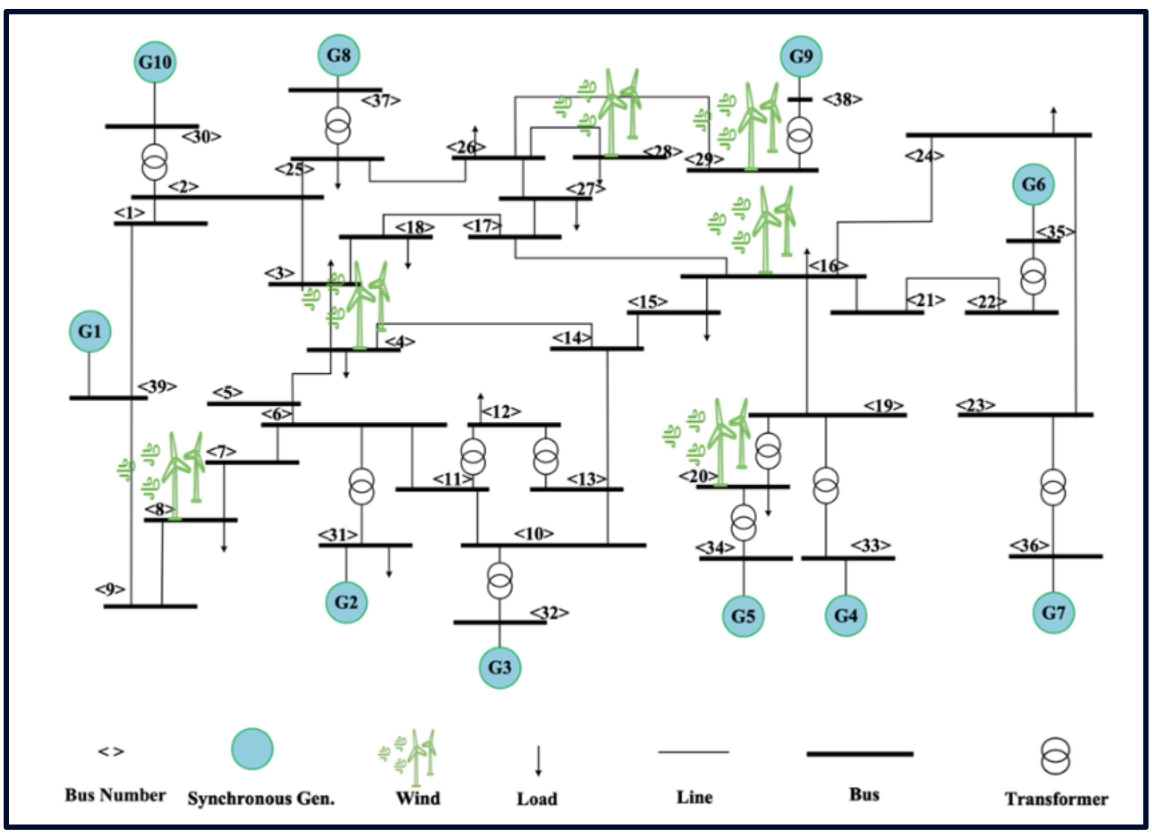
Optimal Power Flow with Renewable Energy Sources

As the penetration of renewable energy sources into today's power grids grows, so, too, does the need for precise and efficient computer models to support power systems management. Traditional optimization algorithms often struggle with the complex, large-scale computations necessary to balance electricity generation with demand, ensure grid stability, and minimize operational costs, especially with intermittent and variable renewable sources like wind. Recent advances in data-driven optimization methods are demonstrating considerable potential in addressing these challenges, though. At the Eversource Energy Center, researchers are working with economic dispatch (ED) and optimal power flow (OPF) models.

The objective of ED models is to determine the most cost-effective way to allocate power generation across available resources to meet current demand. OPF, on the other hand, goes beyond cost by optimizing the flow of power across the network to minimize losses, enhance efficiency, and ensure that system constraints, like voltage limits and line capacities, are not violated. While ED is primarily a cost-focused scheduling tool, OPF addresses the physical realities of power flow; together, they ensure power generation is both economically optimal and technically feasible for secure and efficient grid operation.

In our study, we evaluated the effectiveness of several machine learning models in providing wind forecasting inputs to a standard alternating current optimal power flow (ACOPF) model. The primary goal was to develop and assess an improved deep learning model capable of handling the nonlinear and nonconvex characteristics of ACOPF by establishing connections among loads, generators, and bus outputs. Among the various machine learning architectures we evaluated, a deep learning model that combined convolutional neural networks (CNNs), deep feed-forward neural networks (DFFNNs), hybrid CNN-DFFNNs, and transfer learning (TL) approaches demonstrated the best performance, offering improvement over all the individual models in reducing forecast error.

Looking ahead, this study highlights several areas for further enhancement and suggests implications for stakeholders across the renewable energy sector. For power operators and grid planners, our results underscore the potential of advanced machine learning models to optimize renewable dispatch and minimize operational costs, even as grid complexity grows. Ultimately, by supporting grid stability and cost efficiency, these improved models will help stakeholders integrate renewables more effectively and contribute to the overall resilience and sustainability of the power grid.



An IEEE 39 benchmark system adapted to represent a grid with high wind power penetration—that is, in some buses the conventional generators have been replaced by wind energy sources. Using Monte Carlo simulations, active and reactive power load data are generated for each bus, while synthetic wind power data are produced based on wind turbine physical models and Weibull-distributed wind speed samples.

Wind Energy

Perhaps the most capricious renewable energy source of all, the wind needs to be forecasted if it is to be harnessed. Eversource Energy Center researchers are approaching the problem from a variety of directions—and at different altitudes—to come up with innovative solutions.

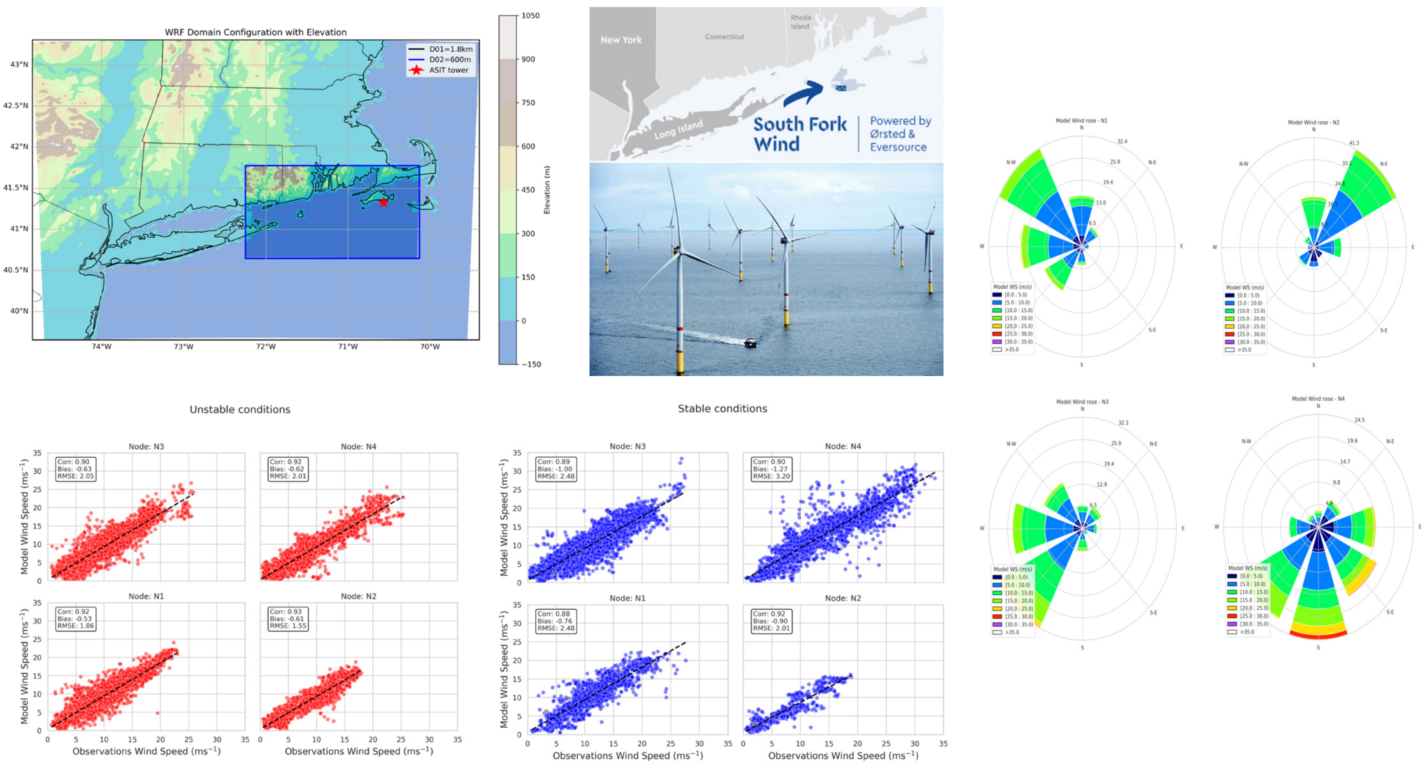
Wind Prediction at High Resolution

The potential to generate wind energy is essential to the mitigation of climate change, and, in the United States, the investment of both money and effort in increasing that potential is growing rapidly through the deployment of offshore wind farm facilities. For planning, siting, and operating these facilities, we need to be able to assess and predict wind speed and direction, wind variability, atmospheric stability, and wind shear up to the height of the wind turbine hub. In addition, since weather extremes affect the reliability of wind turbines and their capacity to produce energy, offshore wind farms must be designed to withstand extreme weather, including tropical storms, extreme wind and wave events, icy conditions, extratropical storms, and extreme heat or cold. Offshore observations are not routinely recorded, so researchers at the Eversource Energy Center run high-resolution weather models to improve our understanding of the weather conditions over wind farms.

The scope of the second phase of the Center's five-year (2022–27) offshore wind prediction project is to deploy operationally the high-resolution prediction system we developed during the first phase to simulate localized winds for the South Fork Wind Farm facility in the North Atlantic. Having tested the weather model's configuration and performance for various case studies in the first phase, we used the model to simulate an entire year for the second. The year we used—2020—was an interesting one for such an experiment, in that tropical storms Fay and Isaias reached the northeastern United States in July and August, respectively.

We are currently analyzing the model performance for hub height wind speed (at the wind turbine rotor height of 140 meters), turbulence, and atmospheric stability, using data from an offshore tower from the Woods Hole Oceanographic Institution, with very good results. The next steps involve finalizing the model performance evaluation for wind speed, which will inform our decision about necessary model improvements. The last year of the project will be devoted to automating the wind prediction system to run operationally.

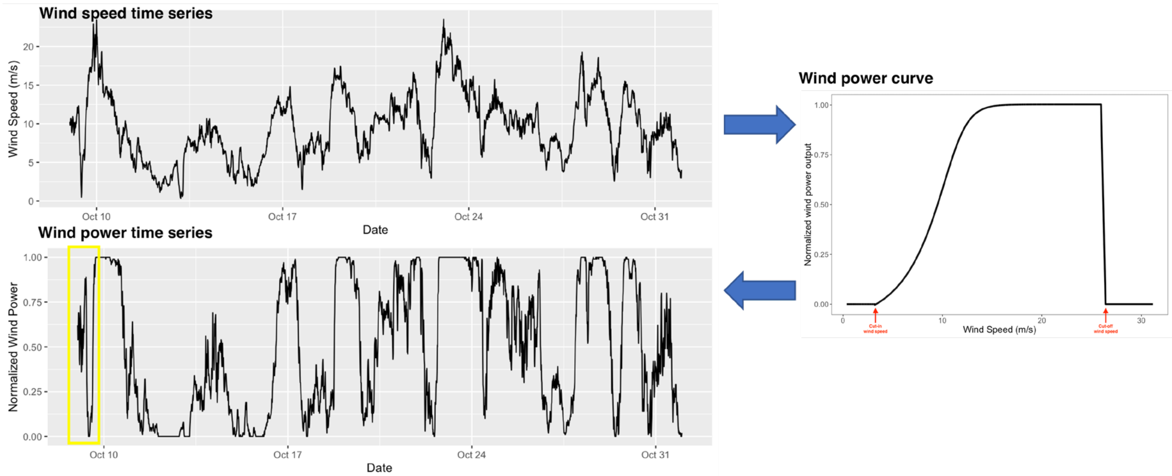
> ***Offshore wind energy*** *is generated by turbines that have fixed foundations in relatively shallow waters or float on platforms where the water is deeper. The South Fork Wind Farm, completed in 2024, provides electricity to Long Island, New York, using systems of cables buried in the seafloor to transmit electricity to the grid.*



Simulations run with a high grid spacing configuration of 600 meters over the South Fork Wind Farm. Reading clockwise from top left, the figures show model domains centered over the South Fork Wind Farm; the location of the wind farm; hub height wind speed and direction; and evaluation of hub height wind speed for stable (blue) and unstable (red) atmospheric conditions. Year 2020 was categorized in four nodes (N1–N4) with different atmospheric forcings, using an unsupervised machine learning technique.

When Change Is in the Wind

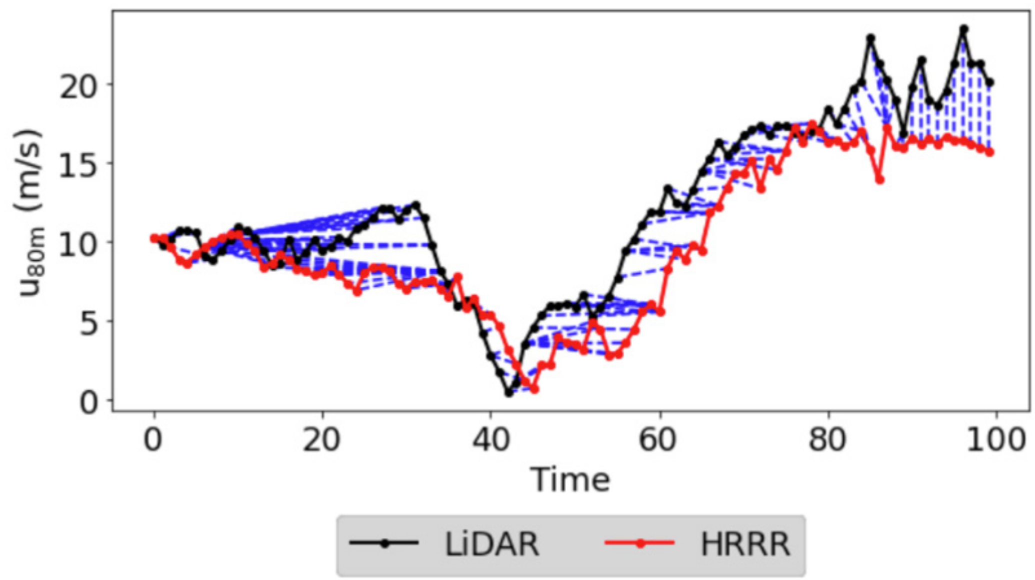
Offshore wind energy projects are a crucial part of renewable energy strategies to reduce fossil fuel power generation. Since wind power can fluctuate unpredictably, the accurate forecasting of offshore wind conditions is essential for utility operators to balance supply and demand effectively. Sudden atypical changes in wind speed, known as wind power ramps, can lead to surges or drops in wind power that are especially problematic for operators, who must rapidly adjust other energy sources or storage solutions to maintain a stable grid.



An example of converting wind speed (upper left) to wind power (lower left) using the wind power curve (right).

Forecasting wind ramps is one of the toughest challenges in wind energy management. Over the past year, researchers at the Eversource Energy Center worked on fine-tuning offshore wind forecasts to improve the prediction of ramp events in New England's offshore areas. We began by identifying systematic timing errors and wind speed underestimates in simulations of future wind patterns from NOAA's High-Resolution Rapid Refresh system by comparing the HRRR forecasts to actual data from LiDAR sensors. We then developed and tested ways to fix these errors by adjusting both the wind speed and timing of the predictions. A method called dynamic time warping showed promise in improving accuracy by aligning timing differences between the HRRR forecasts and the actual data—an adjustment that could be a practical tool for enhancing wind power predictions and making offshore energy systems more reliable. Furthermore, since the bias correction techniques we developed are based on HRRR forecast data, they can be applied across any region in the United States, making this research highly scalable and versatile for various offshore and onshore wind farms.

Refined prediction accuracy for rapid wind power shifts allows power operators to make more informed, timely decisions that stabilize the grid and reduce reliance on costly backup power sources. For stakeholders, improved ramp event forecasts increase confidence in offshore wind as a reliable energy source, supporting long-term investment and integration into the energy mix. Future improvements could produce forecast models that capture more detailed wind behaviors, leading to even more robust and actionable predictions for the offshore wind sector.



Example of phase or timing error. Notice how the HRRR model tends to lag the LiDAR observation during a drop-in-wind-speed event occurring around unit 42 in this 3-hourly time series. This means that while the HRRR captures the events, it does so after they happen, which is of no value for power grid management.

From Globe to Turbine

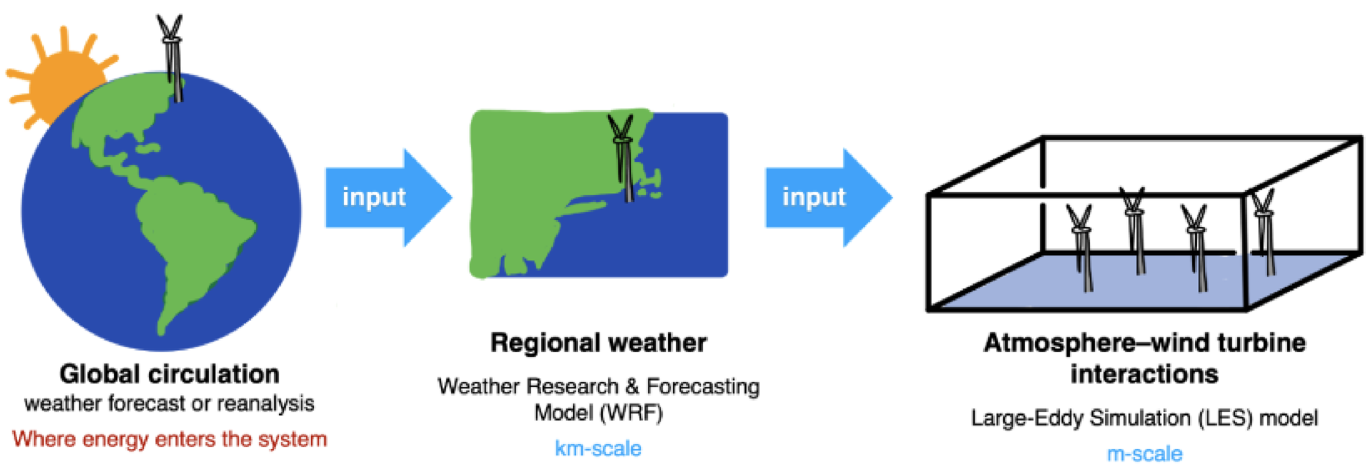
Next-Day Prediction of Wind Power

The South Fork Wind Farm, located 35 miles east of Montauk Point, New York, is the first commercial-scale offshore wind farm in the United States. Wind energy, a clean renewable energy source, has been rapidly growing in the country during the last twenty years. As a natural energy resource, however, wind power is variable, with even subtle weather characteristics, such as the wind direction, affecting generation. The fluctuation is a serious obstacle for the widespread adoption of wind energy that Eversource Energy Center researchers are working to overcome.

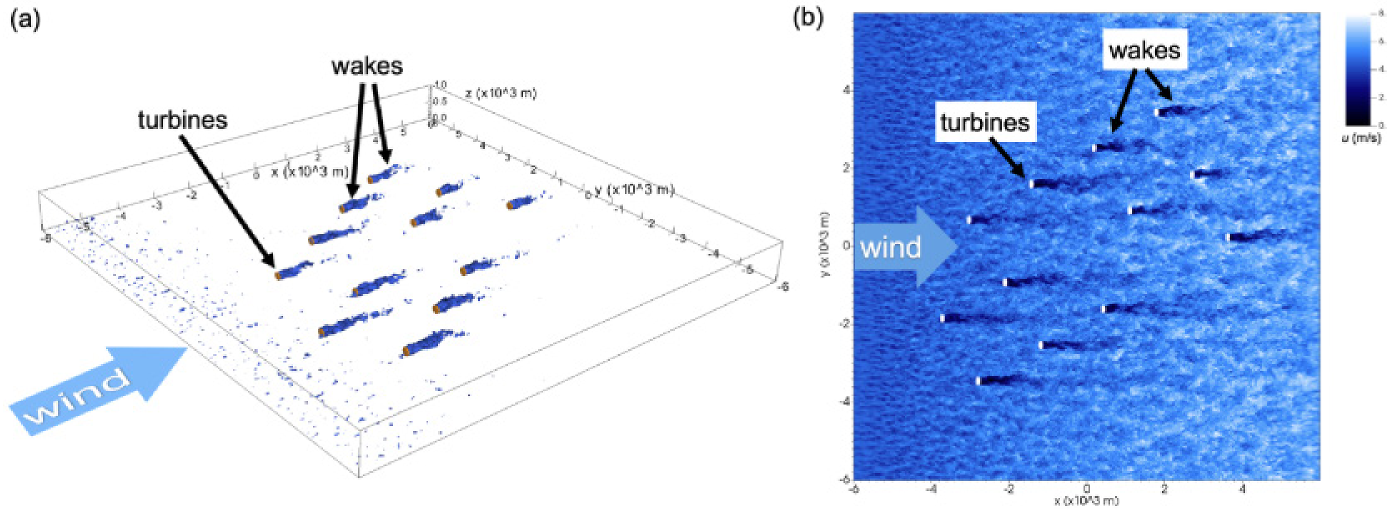
The objective of our project is to develop and validate a new wind-power forecasting system by building on our expertise in fine-scale atmospheric modeling and numerical weather prediction. The new system will generate next-day predictions of wind power that will help utilities plan power resources. When calm weather is anticipated, for instance, alternative energy sources can be used to supplement the reduced power output from the wind farm.

While wind power forecasting is similar in many ways to weather forecasting, the characteristics of the wind farm play an important role because the farm itself interacts with the wind field. In large wind farms like South Fork, the first turbine row is exposed to the undisturbed wind, while downwind turbines can encounter reduced wind speeds. Wind forecasting requires a detailed representation of the wind field around and within the farm that is not feasible to achieve in weather forecasting because it is extremely computationally expensive. We address this challenge by using a series of models to “trickle down” the wind field information provided by regional weather models from the global scale to each wind turbine. Our approach captures the fine-scale atmospheric motions—the small swirls of the wind that weather forecasts miss—consistent with the wind field of the regional model and then uses a high-resolution computer model of the atmosphere, called a large-eddy simulation (LES) model, to calculate the flow in the wind farm. An additional element of the system is the simulation of wind flow with more precision within the farm. In the LES model, we have implemented submodels to predict flow around the wind turbine blades and the energy production of each turbine.

To date, we have assessed the newly developed modeling system for a few mock-forecast days spanning a variety of meteorological conditions. After the initial system assessment is completed, we will work toward automating the process of transferring data between the different models and the setup of the simulations. The goal is a system that will be fully automated and ready for operational wind energy forecasting.



The model hierarchy used to simulate the flow in wind farms. A series of computer models is used to “trickle down” the wind field information from the global scale to each wind turbine.



Visualizations of the wind field in a South Fork wind farm simulation. Wind turbines modify the wind field because they extract energy from the atmosphere, leaving trails of low-speed flow, or wakes, downstream. Turbine wakes extend for relatively large distances downstream and can reduce the incident wind speed on downstream turbines, lowering their power generation potential. The left panel (a) shows a perspective view of the wind farm and the wakes forming downstream of the turbines. The right panel (b) is a contour plot of the wind field on a horizontal plane at the height of the turbine hub. These wakes are visible as the darker lower-speed region in panel (b), as are the fluctuations of the wind speed because of the atmospheric turbulence.

A windmill in New Haven on January. 17, 2024. (Peter Morenus/UConn Photo)

Center Highlights

Faculty at the Eversource Energy Center initiated five major projects in 2024. Here is a rundown of their exciting work now underway.

All the WISER

The Center for Weather Innovation and Smart Energy and Resilience (WISER), established in late 2023 as a National Science Foundation Industry-University Cooperative Research Center (IUCRC), is a collaborative effort between the University of Connecticut and the University at Albany. IUCRCs are designed to help corporate partners and government agencies connect directly and efficiently with university researchers to conduct high-impact research, drive innovative technology development, and develop a high-tech, skilled workforce. The WISER IUCRC capitalizes on the research expertise of both UConn and UAlbany to develop advanced weather and climate-based solutions for the energy industry.

During the center's first year in 2024, WISER received funding to support seven research projects from eight industry members: Avangrid, the Central Hudson Gas & Electric Corporation, Con Edison, the Electric Power Research Institute (EPRI), National Grid, the New York Power Authority, the New York State Energy Research and Development Authority (NYSERDA), and the New York State Foundation for Science, Technology, and Innovation (NYSTAR). The Eversource Energy Center is involved in four of these projects, having to do with offshore wind energy prediction, wildfire modeling, power outage prediction model development, and model uncertainty assessment.

Looking ahead, WISER will expand its impact by integrating more cutting-edge technologies into its work and strengthening partnerships across the energy and environmental sectors. As the center grows, it will advance research in vital areas like renewable energy forecasting, climate risk modeling, and grid resilience, equipping its industry partners with the most innovative, data-driven predictive tools to address both the immediate and long-term challenges posed by extreme weather and climate change. By fostering collaboration between academia and industry, WISER is poised to become a leading resource for solutions that promote a more resilient and sustainable energy infrastructure.

Supporting Grid Resilience through CREST

The northeastern United States is among the top three regions most exposed to billion-dollar natural disasters, including hurricanes, severe Nor'easters, and winter storms. Quantifying the effects of these extreme climate events on the electric grid can help utilities make informed decisions about infrastructure reinforcements, such as vegetation management, pole replacement, power line strengthening, distribution system automation, and undergrounding of parts of their electric circuits. Additionally, utilities can coordinate with communities and regulators to mitigate impacts through improvements to power system resilience.

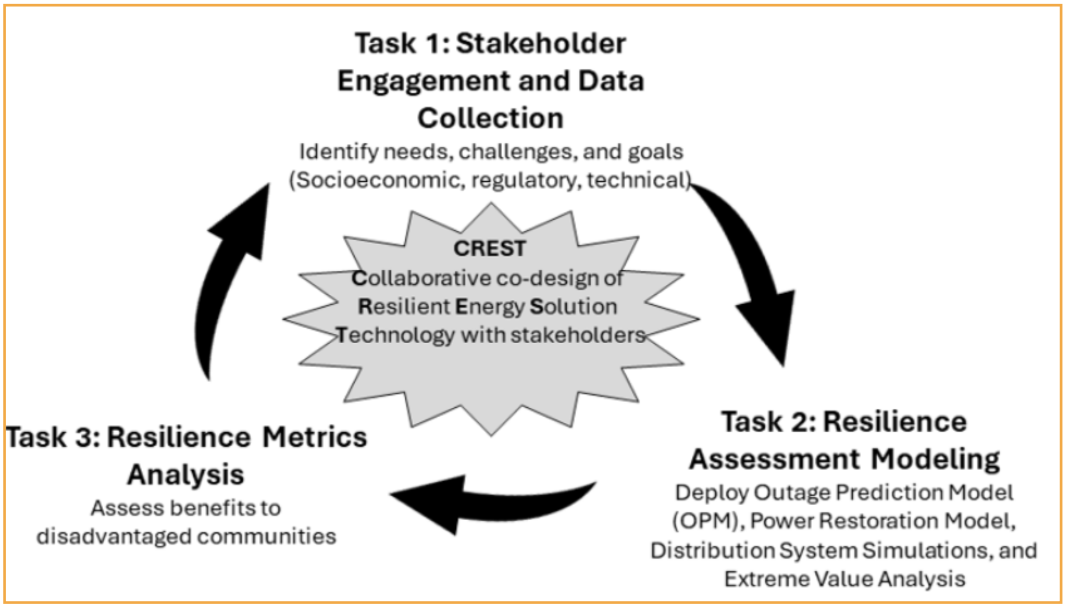
The purpose of the Grid Resilience Assessment and Climate Change Impacts (GRACI) program, according to its funder, the U.S. Department of Energy, is to "support state energy officials, public service commissions, and utilities by providing technical assistance to accelerate the analysis of climate change threats and impacts on electric grid infrastructure, describe best practices for grid operations and investments, and provide additional information and analysis to aid in grid resilience planning and decision-making."

The Eversource Energy Center, in collaboration with researchers from UConn's Departments of Anthropology and Agricultural and Resource Economics, as well as the University at Albany, received funding from GRACI to support the utilities, regulators, and communities who are awarded Grid Resilience State and Tribal Formula Grants by developing and applying the Community co-design of Resilient Energy Solution Technology (CREST) framework. The framework sets out a sociotechnical approach to achieving three objectives:

- Identifying vulnerabilities in distribution systems
- Evaluating the effectiveness of planned resilience improvements co-developed with stakeholders
- Assessing the risk of outage events under current and future climate conditions in terms of their intensity and frequency, considering proposed strategies to improve resilience

In task 1 of the project, a community engagement team will initiate the co-design process by conducting detailed surveys and collecting ethnographic data to assess the specific needs of stakeholders and local communities, as well as their long-term socioeconomic, regulatory, and legal challenges. These co-design plans will inform task 2, the development of a Resilience Assessment Modeling scheme, based on data reflecting the socioeconomic and regulatory challenges specific to the region, and will feed into task 3, a Resilience Metrics Analysis, which will evaluate the impact of different resilience improvement investments and climate change scenarios across the region. The analysis will also determine the optimal balance between return on investment and benefits to disadvantaged communities.

Ultimately, the CREST framework will serve as an objective tool to guide utilities, regulators, and communities in prioritizing equitable investments and co-developing long-term energy solutions. By accounting for various infrastructural reinforcement scenarios, the framework will provide stakeholders with comparative data to evaluate different combinations of grid vulnerability reduction measures proposed to the Formula Grant program. This will enhance decision-making efficiency and support both current and future stakeholder planning.



Structure of the CREST framework.

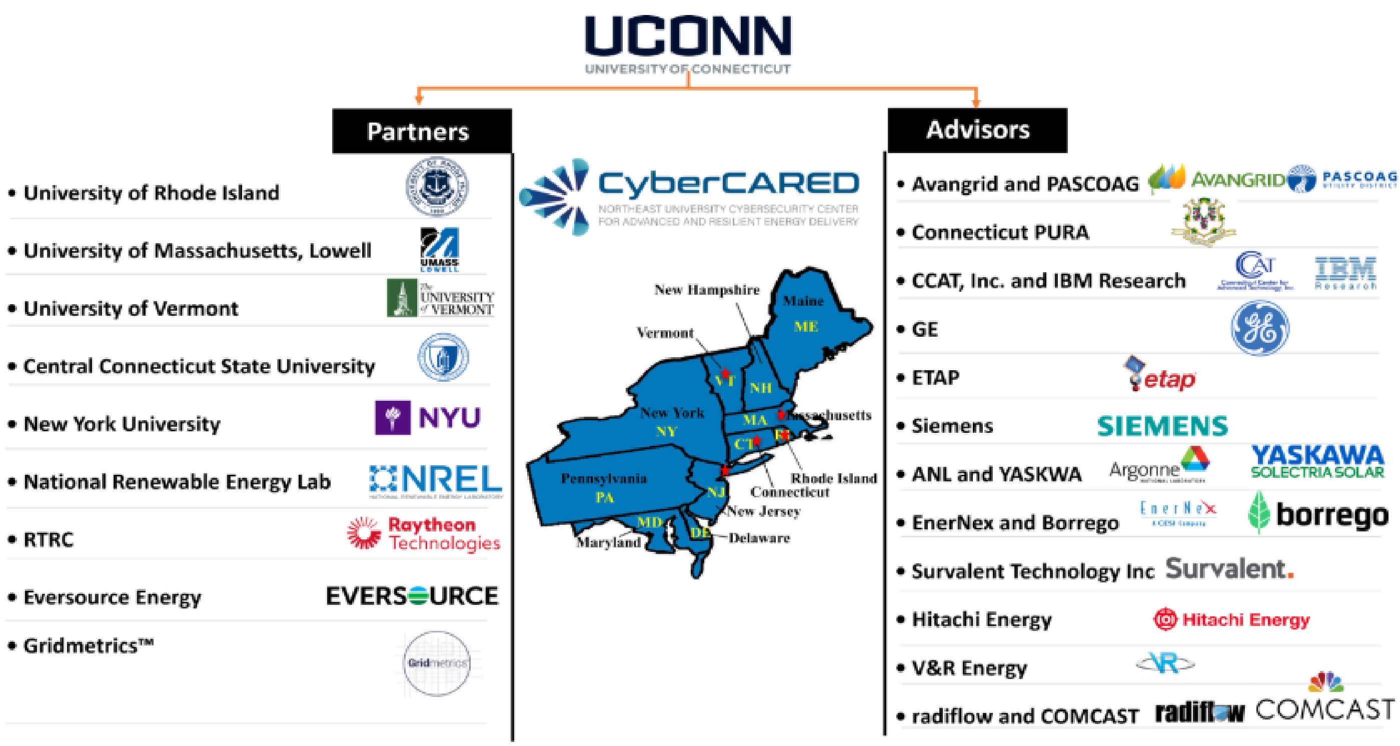
CyberCARED for Cybersecurity

In 2024, the U.S. Department of Energy awarded funding to the University of Connecticut to establish the Northeast University Cybersecurity Center for Advanced and Resilient Energy Delivery (CyberCARED). Its mission is to build and unify regional collaborations among academic institutions and power industry enterprises across the northeastern United States, with the participation of national laboratories and regional government agencies. CyberCARED seeks to prevent and defend against cyberattacks on the region's power grid by developing an intelligent cyber-physical system to identify and simulate attacks on distributed energy resources (DERs) and the distribution system and reveal the risks they pose for grid operation. It will also create and expand innovative programs for education, training, and workforce development in the areas of cyber-physical systems, cybersecurity, edge computing, and intelligence.

The outcome of this collaborative research will be to deliver and demonstrate an integrated cyber-physical emulation, testing, and response platform to mitigate the effect of cyberattacks and quickly restore attacked devices and systems. By demonstrating the application of Eversource Energy's distribution system models with various types of DERs (such as solar, battery, and so on), we will show how the new platform can identify, protect against, detect, recover from, and endure different tiers of adversaries, yielding resilient real-time utility grid operations.

This research is made possible by our unparalleled access to stakeholders and regulatory entities, such as the Connecticut Public Utilities Regulatory Agency (PURA), and strong collaborations with industry experts. It offers new perspectives on how to integrate renewable energy into the electric grid and improve grid resiliency in the face of increased cybersecurity challenges.

> ***Edge computing*** *is a computing framework that brings information storage and computation closer to the sources of the data. Edge computing reduces data latency—the lag time between when data are created or updated and when they become available for use—and speeds up analysis and response.*



CDLR-RENEW

Unlocking the Power

As utilities modernize the electric grid to manage the rising use of renewable energy sources, the changing weather, and other recent challenges to reliability and resilience, an important opportunity is the potential to unlock the capacity of existing transmission lines while avoiding the costly and time-consuming construction of new ones. To this end, researchers at the Eversource Energy Center propose to develop and field demonstrate the real-world benefits of dynamic line rating (DLR) and power flow controller (PFC) technologies. The project will allow the exploration of DLR with PFC to accelerate the United States' ambitious goal of deploying 30 gigawatts of offshore wind by 2030.

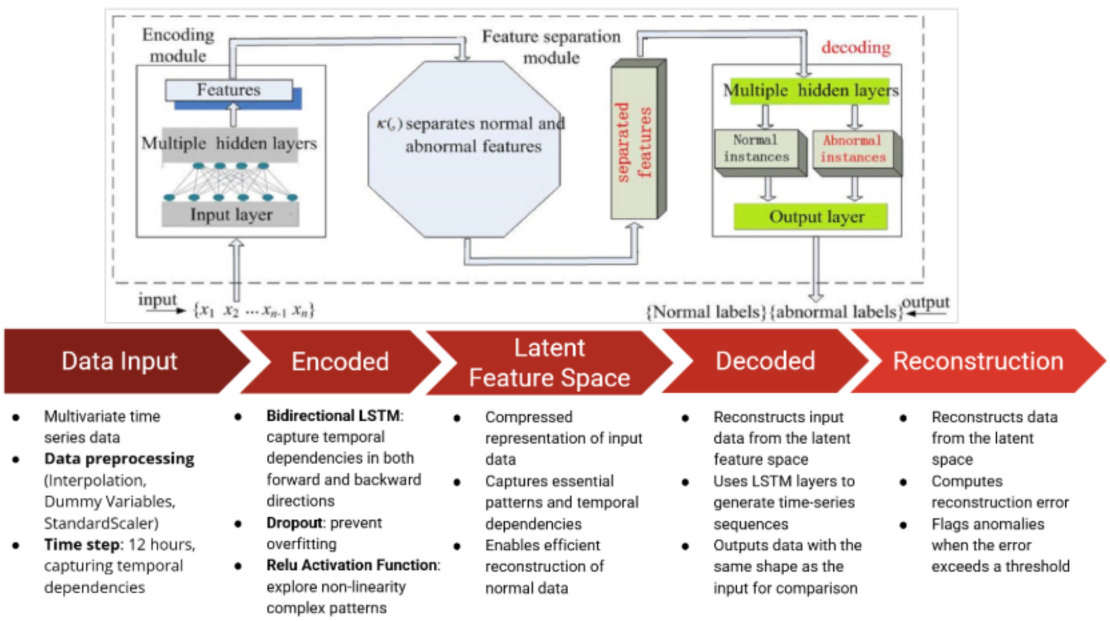
The project, DLR-RENEW—which stands for Dynamic Line Rating Robust Validation, Enhancement and Field Demonstration in New England with Changing Weather and Offshore Wind Integration—will install new solar-powered DLR sensors along existing transmission lines in Massachusetts, where the nation's first utility-scale, 800-megawatt offshore wind farm is slated to come online near Martha's Vineyard in 2025. Placed at strategic points on the 20-mile, 345-kilovolt transmission line between the town of Carver and the Cape Cod Canal, the sensors will enable researchers and utility operators to collect real-time data on factors like ambient and conductor temperature, line angle, and wind speed. The information can then be used to calculate the load-bearing capacity of the lines at any given time and under any given condition.

The next step will be to integrate DLR-aware PFC into commercial software developed by V&R Energy for demonstration under various offshore wind and contingency scenarios. The benefits of DLR will be evaluated in terms of improving line capacity usage and enhancing resilience during stressed system conditions, as well as accelerating renewable energy integration without new transmission line construction. Ultimately, the project will achieve a detailed cost-benefit analysis of grid-enhancing technologies in unlocking transmission line capacity to integrate large offshore wind generations and enhance grid resilience.

The WISPR Project

Wind Impact Study for Power Resilience

The Wind Impact Study for Power Resilience project is part of a collaboration of the Northeast Regional Utility Consortium and academic partners, such as the University of Connecticut, Cornell University, and the University of Albany, to address grid vulnerabilities posed by climate-induced challenges. WISPR's funding of $1.63 million from the U.S. Department of Energy gives UConn a prominent role in this effort.



Modeling for detection of grid abnormalities.

The overall goal of WISPR is to enhance grid resilience, reduce electricity costs, and provide direct benefits to customers while promoting sustainable practices. Project researchers at the Eversource Energy Center are pursuing three main objectives toward this goal. First, by integrating high-resolution LiDAR scans, predictive analytics, and machine learning, we are working to develop advanced dynamic risk assessment models that evaluate strategies for vegetation management and measures to harden utility assets against the threat of damage from storm winds.

Second, we are combining wind projections with climate models and data on vegetation growth patterns to minimize current risks with long-term resilience strategies that ensure utilities are equipped to adapt to evolving environmental conditions.

And, third, by conducting comprehensive cost-benefit analyses and employing multicriteria optimization techniques, we are ensuring the resilience strategies are both cost effective and aligned with community and environmental priorities.

WISPR will significantly enhance the resilience of the power grid across the Northeast. Ultimately, the project will reduce the frequency and severity of outages caused by extreme weather while minimizing costs for utilities and consumers alike, playing a critical role in ensuring the future sustainability and reliability of the electric grid.

Center Productivity

Patent

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