2022–23 ANNUAL REPORT

EVERSOURCE ENERGY CENTER

A utility-university partnership at UConn

Contents

WELCOME

DEAR FRIENDS,

Fiscal 2022–23 marked one more milestone year for the Eversource Energy Center, during which the Center more than doubled from 2021 the number of newly funded federal projects. 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 confronting the great resilience challenges faced by the energy industry at the intersection of weather extremes, climate change, and clean power infrastructure. Today, it is better positioned than ever to continue and expand that work around clean energy sustainability and adaptation to climate change.

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 on our Sponsors and Partnerships page 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 more research projects than ever before. Among them are the extension of the Center's Outage Prediction Model to transmission systems, utility service territories in other states, and the forecasting of tree failures, snowfall, and wind gusts. 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 cyber security, the 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 increase student diversity at the Center. Toward the latter objective, we continue to set aside funds to support underrepresented and minority students so they can conduct research on Center projects. To date, we have funded a total of eleven URM interns.

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

WHO WE ARE

The Eversource Energy Center
is the leading partnership between an energy utility and a university in the United States. A trusted source of energy expertise, the Center is striving to advance new research and technologies to ensure reliable power during extreme weather and security events. Our Center's consortium approach is to create partnerships, develop next-generation technology and software, and collaborate to meet current and future reliability and energy needs.

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

OUR TEAM

Principal Investigators

Department of Civil and Environmental Engineering

Emmanouil N. Anagnostou, *Board of Trustees Distinguished Professor, Eversource Energy Endowed Chair in Environmental Engineering, Director of the Eversource Energy Center*
Diego Cerrai, *Assistant Professor, Associate Director and Manager of the Eversource Energy Center*
Marina Astitha, *Assistant Professor, Weather Forecasting Team Lead*
Amvrossios Bagtzoglou, *Associate Professor, Grid Resilience Team Lead*
Malaquias Peña, *Associate Professor, Grid Modernization Graduate Certificate and Diversity, Equity and Inclusion Coordinator*
Guiling Wang, *Professor*
Wei Zhang, *Assistant Professor*

Department of Computer Science and Engineering

Amir Herzberg, *Professor*
Fei Miao, *Assistant Professor*

Department of Electrical and Computer Engineering

Ali Bazzi, *Associate Professor*
Yang Cao, *Professor*
Sung-Yeul Park, *Associate Professor*
Zongjie Wang, *Assistant Professor*
Junbo Zhao, *Assistant Professor, Associate Director of the Eversource Energy Center, Grid Modernization Team Lead*

Department of Finance

Fred Carstensen, *Professor, Director of the Connecticut Center for Economic Analysis*

Department of Mechanical Engineering

Georgios "George" Matheou, *Assistant Professor*

Department of Natural Resources and the Environment

Robert Fahey, *Assistant Professor, Associate Director of the Eversource Energy Center, Tree and Forest Management Team Lead*
Thomas H. Meyer, *Professor*
Anita Morzillo, *Assistant Professor*
Chandi Witharana, *Assistant Professor in Residence*
Thomas Worthley, *Assistant Extension Professor, Forestry Specialist*
Zhe Zhu, *Assistant Professor*

Department of Operations and Information Management

David Wanik, *Assistant Professor in Residence*

Graduate Research Assistants

Department of Civil and Environmental Engineering

Zhixia Ding
Farzaneh Esmaeilian
Brian Filipiak
Binit Guatam
Kang He
William Hughes
Israt Jahan
Klinath Katuri
Ummaul Khaira
Mariam Khanam
Yitong Liu
Faezeh Fooladi Mahani
Panagiotis Mitsopoulos
Mahjabeen Fatema Mitu
Sita Nyame
Jason Philhower
Andreas Prevezianos
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Genevieve Rigler
Francesco Rouhana
Buket Sahin
Shah Saki
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Bernard Akaawase

School of Mechanical, Aerospace, and Manufacturing Engineering

Yongjie Lu

Department of Natural Resources and the Environment

Nicholas Cranmer
Mari Cullerton
Durga Joshi
Shashika Himandi Gardeye Lamahewage
Susmitha Lamichhane
Kexin Kathy Song
Harshana Wedagedara
Evan Zocco

Postdocs

Ankur Srivastava
Kingsley Udeh

Center Research Staff

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Fangni Lei, *Assistant Research Professor, jointly with Department of Civil and Environmental Engineering*
Cory Merow, *Assistant Research Professor, jointly with Department of Ecology and Evolutionary Biology*
Thi Ha Nguyen, *Assistant Research Professor, jointly with Department of Electrical and Computer Engineering*
Giulia Sofia, *Assistant Research Professor, jointly with Department of Civil and Environmental Engineering*
Xinxuan Zhang, *Assistant Research Professor, jointly with Department of Civil and Environmental Engineering*

Center Staff

Ronny Heredia, *Financial Assistant for Eversource Energy Center*
Marybeth Brandi, *Pre-Award Specialist*

Collaborators

Zoi Dokou, *Assistant Professor, California State University, Sacramento*
Baptiste Francois, *Research Assistant Professor, University of Massachusetts, Amherst*
Marcello Graziano, *Associate Professor, Southern Connecticut State University*
Peter Gunther, *Senior Research Fellow, Connecticut Center for Economic Analysis*
Jordan Kern, *Assistant Professor, North Carolina State University*
Andreas Langousis, *Assistant Professor, University of Patras*
Efthymios Nikolopoulos, *Assistant Professor, Florida Institute of Technology*
Melkior Ornik, *Assistant Professor, University of Illinois Urbana-Champaign*
Raymond V. Petniunas, *Member, Academy of Distinguished Engineers*

MILESTONES FY2022-23

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.

KEY INITIATIVES

Several projects funded by federal agencies and by industry partners were awarded in FY2022–23 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 2020. Expansion of the diversity initiatives launched in previous years continued to demonstrate the priority the Center places on its commitment to an inclusive environment.

EVERSOURCE PROJECTS

Eversource Energy supported 22 projects in FY2022–23, covering six thematic areas:

- Outage Prediction Modeling and Emergency Response
- Resilience System Modeling and Economic Effects
- Vegetation Management, Outreach, and Forest Science
- Renewable Energy and Grid Integration
- Cyber and Physical Security
- Offshore Wind Energy

UNDERGRADUATE STUDENT RESEARCH

The Undergraduate Research Initiative begun in 2021 was expanded in FY2022–23 to become the Pioneering Diversity Initiative. Focusing exclusively on underrepresented minority students, the expanded initiative engaged 13 undergraduates in research aligned with the six thematic areas. Their efforts met with great success, with all the projects producing papers submitted to and published or accepted for publication by high-profile peer-reviewed journals.

OUR SPONSORS

Eversource (principal sponsor)

Avangrid

Connecticut Department of Energy and Environmental Protection (DEEP)

Dominion Energy

Electric Power Research Institute (EPRI)

Google

Housatonic Valley Association

Independent System Operator of New England (ISO-NE)

National Aeronautics and Space Administration (NASA)

National Oceanic and Atmospheric Administration (NOAA)

National Science Foundation (NSF)

New York State Energy Research and Development Authority (NYSERDA)

Schneider Electric

South Central Connecticut Regional Water Authority

Travelers

United Illuminating Company (UI)

U.S. Department of Defense (DOD)

U.S. Department of Energy (DOE)

U.S. Environmental Protection Agency (EPA)

U.S. Geological Survey (USGS)

Weather and Marine Engineering Technologies

STRATEGIC PARTNERSHIPS

The Center is continuing its collaboration with Bay State Wind Energy, the Electric Power Research Institute, and the University of Albany Atmospheric Research Center in the areas of offshore wind resource characterization, water conservation, and grid vulnerability and the establishment of a new Industry-University Cooperative Research Center (IUCRC), focusing on Weather Innovation and Smart Energy and Resilience (WISER). The Center has initiated new partnerships with Dominion Energy for the development of an outage prediction model for North Carolina and Virginia and with Exelon for developing an outage prediction model and estimating the effectiveness of grid resilience initiatives for southeastern Pennsylvania, southern New Jersey, Maryland, Delaware, and the District of Columbia. We have also 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.

BAY STATE WIND ENERGY

Bay State Wind Energy has brought together Eversource and Ørsted, builder of the first and largest offshore wind farms in the world. The new partnership combines Ørsted's preeminent offshore wind development capability with Eversource's predominant presence in the Northeast, its industry-leading financial strength, and its expertise in regional transmission development. In 2019, the Center signed a sponsor research agreement to expand its activities beyond Eversource CT. This agreement approved support for an integrated research project to enhance environmental monitoring and modeling capabilities for offshore wind energy generation.

DOMINION ENERGY

Dominion Energy is a major publicly traded energy company that supplies electricity to parts of Virginia, North Carolina, and South Carolina and natural gas to nine states, offering clean, safe, reliable, and affordable energy to more than 7 million customers. In 2022, Dominion Energy funded a new project to research and develop OPM modules to predict rain and wind, thunderstorms, snow and ice, and tropical storms in Virginia and North Carolina. A secondary goal was to quantify the strengths and generalizability of the models previously developed for the northeastern United States. In a separate project, researchers sought to develop and implement robust estimation of distribution system state to enhance Dominion's system visibility in the wake of increased penetration of distributed energy resources.

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, from 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.

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.

TANTALUS SYSTEMS

Tantalus is a technology company dedicated to helping utilities modernize their distribution grids. Tantalus helps its customers harness the power of data across all their devices and systems deployed throughout the entire distribution grid, from substation to EV charger. They offer smart grid solutions across five levels: intelligent connected devices, communications networks, data management, enterprise applications, and analytics. Our Center has been collaborating with Tantalus Systems on the deployment of their next generation of advanced metering infrastructure (AMI) and smart communications, together with data analytics for Avangrid, under the Connecticut Innovative Energy Solution program.

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/home.html). WISER will provide state-of-the art weather and climate information, combined with leading-edge, industry-inspired research and development, to ensure reliable and resilient energy in the 21st century. Following the awarding of the planning grant, planning activities took place between 2021 and 2022. The WISER Center was established in 2023 and will support research in the areas of renewable energy, outage management, grid resilience, and climate change.

CENTER BY THE NUMBERS

Publications and Patents 2016-June 2023

Peer-reviewed	193
Patents	4

Students

Undergraduates	7
Graduates	60

Expenditures

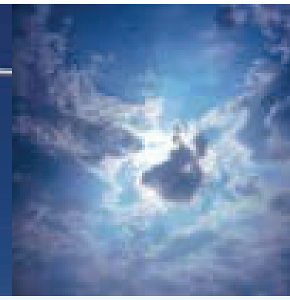
2016	$998,059
2017	$2,158,683
2018	$2,423,839
2019	$2,454,938
2020	$2,156,234
2021	$2,366,012
2022	$3,508,000
2023	$3,418,186

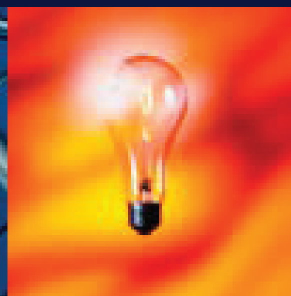
Awarded Amounts

2016–present
$37,792,757

Proposals Pending

$104 million

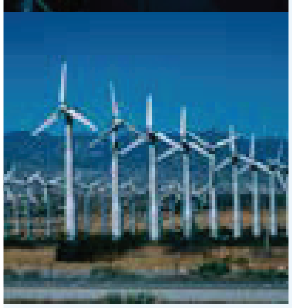
UCONN

Preparing for the Grid of the Future

The Power Grid Modernization Certificate Program at the University of Connecticut

The modernization initiative to create the power grid of the future is one of the largest investments and most consequential infrastructure projects in the United States. It needs an engineering workforce with the interdisciplinary skills to do the job.

At UConn's Eversource Energy Center, utility engineers can gain these skills in a four-course, fully online program that will prepare them for the new technologies and the challenges of managing an increasingly complex electric grid. The graduate-level engineering certificate conferred upon completion is approved by the Board of Trustees of the University of Connecticut and can be applied toward a Master of Engineering degree.

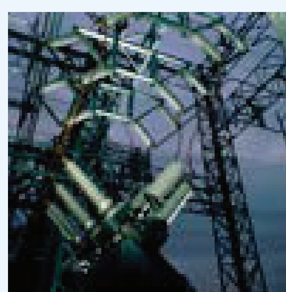
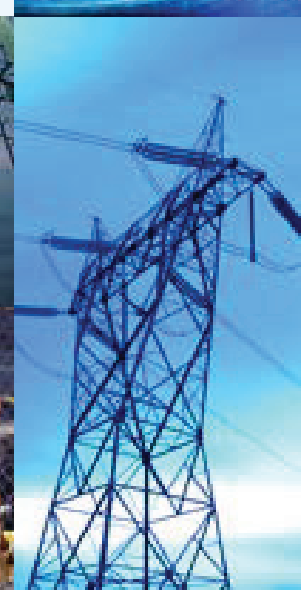
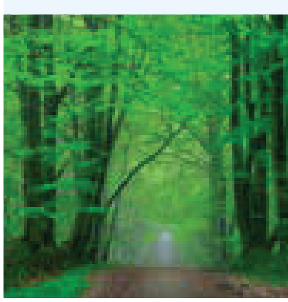
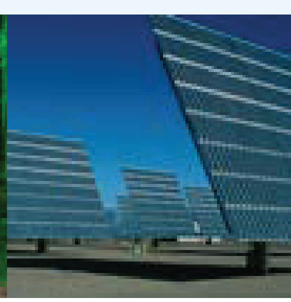
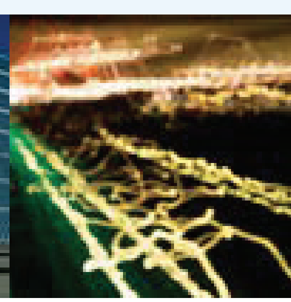



EXPAND YOUR HORIZONS. ADVANCE YOUR CAREER.

Join the modernization effort to bring about a more resilient, secure, sustainable, and reliable power grid by applying for UConn's Power Grid Modernization Certificate Program today.

FOR MORE INFORMATION, VISIT

https://advancededucation.engineering.uconn.edu/credit-programs/certificates/certificate-power-grid-modernization


STORM IMPACT

Eversource Energy Center researchers continue advancing and expanding their efforts to predict and mitigate the effects of storms on the electric grid. Latest developments include the extension of UConn's Outage Prediction Model to transmission systems, utility service territories in other states, and the forecasting of tree failures, snowfall, and wind gusts.

"Astounding Results" in Predicting Probabilities

In its ongoing work on the UConn Outage Prediction Model, the Eversource Energy Center team of researchers responsible for the OPM's development has continued to improve its capability to predict the power outages associated with major storms.

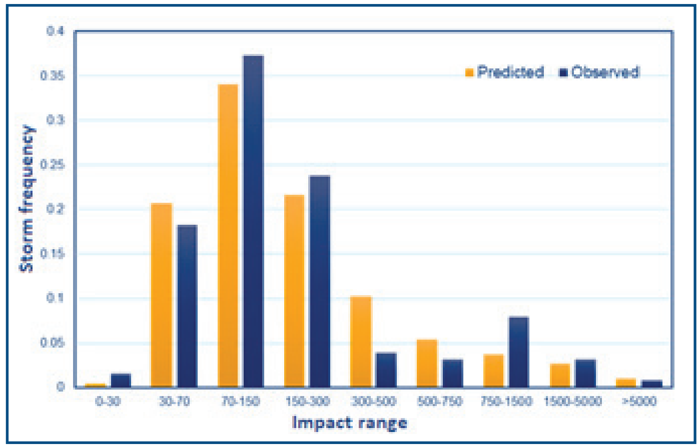
Between 2015 and 2018, the team issued only deterministic outage forecasts in advance of storms—that is, we predicted the number of outages that would happen but not the likelihood of the expected impact. To provide more refined predictions for upcoming storms that would allow utilities to prioritize their preparations with greater precision, we began in 2019 to complement the deterministic forecasts with a probability table. This table divides into nine categories the number of system failures (or trouble spots) that the OPM predicts will happen as the result of an upcoming weather event and provides percentages indicating the probability that the resulting outages will fall within each of these "impact ranges." Each impact range corresponds in turn to an emergency preparedness action level for each of the four Eversource service territories: Connecticut, western Massachusetts, eastern Massachusetts, and New Hampshire.

Number of system failures (trouble spots)	0-30	30-70	70-150	150-300	300-500	500-750	750-1500	1500-5000	5000
Connecticut	0%	5%	15%	50%	25%	5%	0%	0%	0%
Western Massachusetts	30%	60%	10%	0%	0%	0%	0%	0%	0%
Eastern Massachusetts	0%	5%	15%	60%	20%	0%	0%	0%	0%
New Hampshire	0%	10%	40%	40%	10%	0%	0%	0%	0%

Probabilistic forecast for a major storm that took place in New England on November 30, 2022.

By 2022, after three years of gathering forecasts, we had enough data for each impact range and for each probability level to to assess for the first time the OPM's skills in generating probabilistic forecasts. The results were astounding.

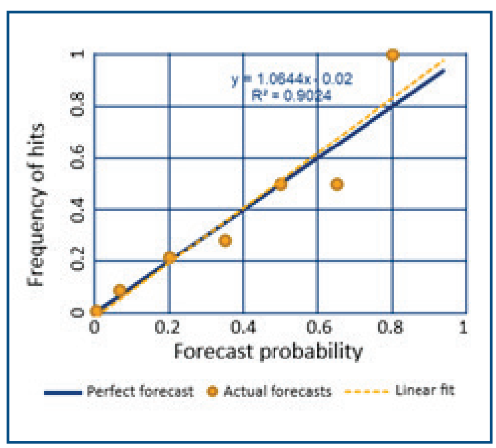
Although underpredictions and overpredictions occurred in a few ranges for the individual territories, the frequency of occurrence of the maximum probability forecast in the table closely reflected the actual frequency of occurrence of events for all territories.



Predicted and observed historical probability distributions for Connecticut.

Beyond assessing forecasting skills by impact range, we also assessed the reliability of the percentages provided. If we were to take all the ranges for which a 40 percent probability was issued, for example, we would expect to find that the actual storm impact falls within that range 40 percent of the time. Based on this principle, we computed the actual frequency of occurrence for each probability level, and we found that our predictions matched the results almost exactly.

The high level of understanding reflected by the calculation we developed of storm impact uncertainty and outage prediction uncertainty is one of the many positive surprises stemming from the research conducted at the Eversource Energy Center and shown in this annual report. This novel understanding will be highly beneficial to Eversource and to any new utility that partners with the OPM team for years to come.



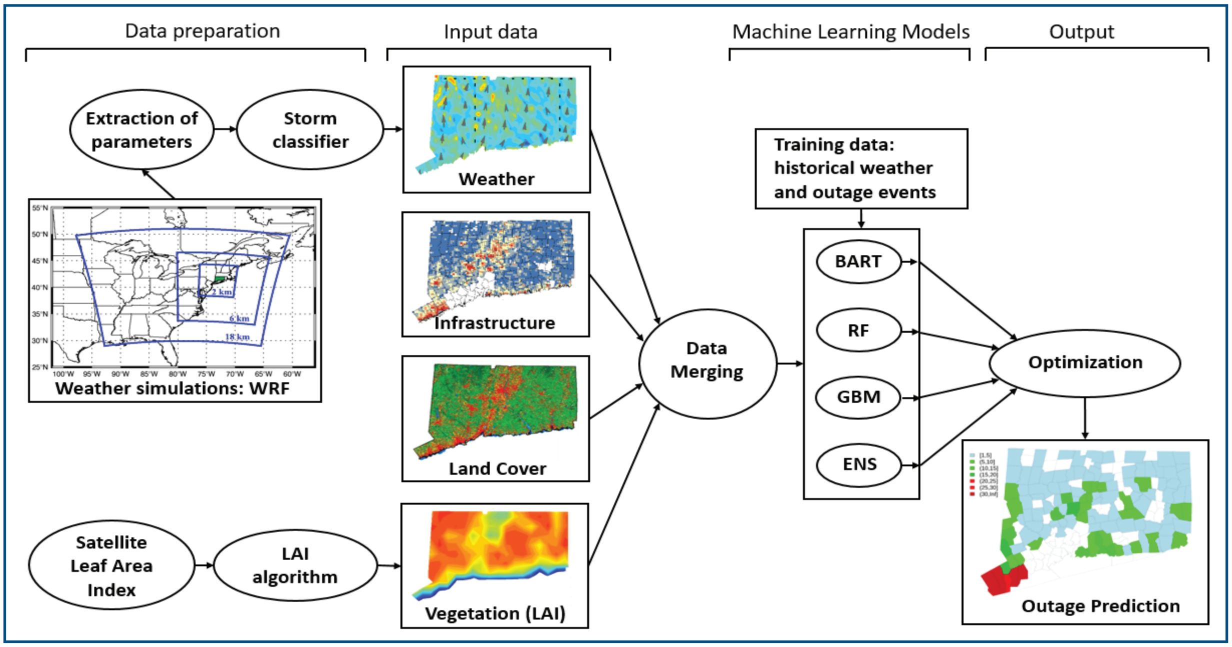
Frequency of occurrences versus forecasted prediction for Connecticut. The probability calculations are extremely reliable, with a coefficient of determination of 0.85 for eastern Massachusetts and New Hampshire, of 0.9 for Connecticut, and above 0.99 for western Massachusetts.

The University of Connecticut Outage Prediction Model

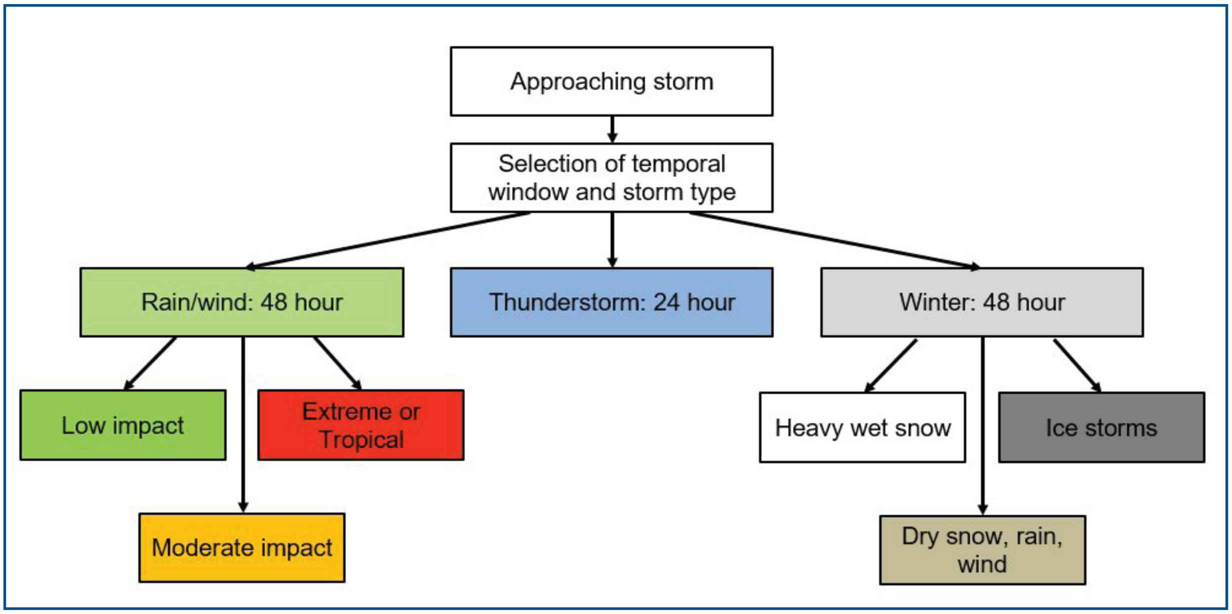
The OPM is a framework developed by researchers at the Eversource Energy Center that integrates weather predictions with infrastructure, land cover and vegetation characteristics, and historical power outage data to predict, through the use of machine learning models, the number and locations of storm 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

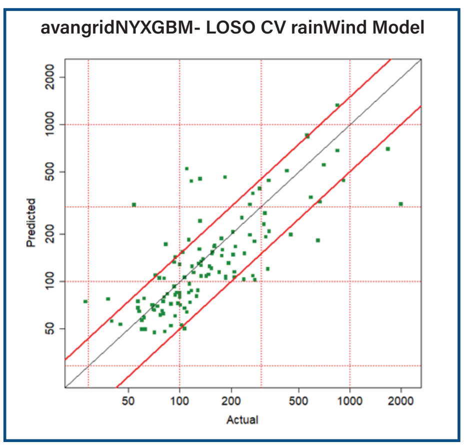


Extending the OPM: Avangrid

As in most other places, the impacts of severe weather events have led to considerable power outages in New York State in the past 20 years. The outages have affected businesses, vital government services, and the lives of millions of electric utility residential customers and others and resulted in billions of dollars in economic losses. The increasing frequency of such extreme events has caused widespread disruptions in the Avangrid NY power grid, leading to a collaborative effort to predict power outages and so mitigate their effects.

In addition to the Eversource Energy Center and Avangrid, the partners engaged in this research are the Atmospheric Sciences Research Center (ASRC) at SUNY Albany, New York State Mesonet, and MESO Inc. The project seeks to map multiple observations from the mesonet—a network of 126 automated weather-monitoring stations throughout the state of New York—to each power circuit in the Avangrid service territory. The resulting approximation of the amount of infrastructure in each circuit will enable us to generate data features that describe a time series of meteorological conditions and to create a database Avangrid can use within the framework developed for the UConn Outage Prediction Model (OPM) to produce accurate outage forecasts for New York. Our collaborators in Albany are doing the in-house weather simulations, while we at the Eversource Energy Center are building the predictive modules of the new OPM for New York.

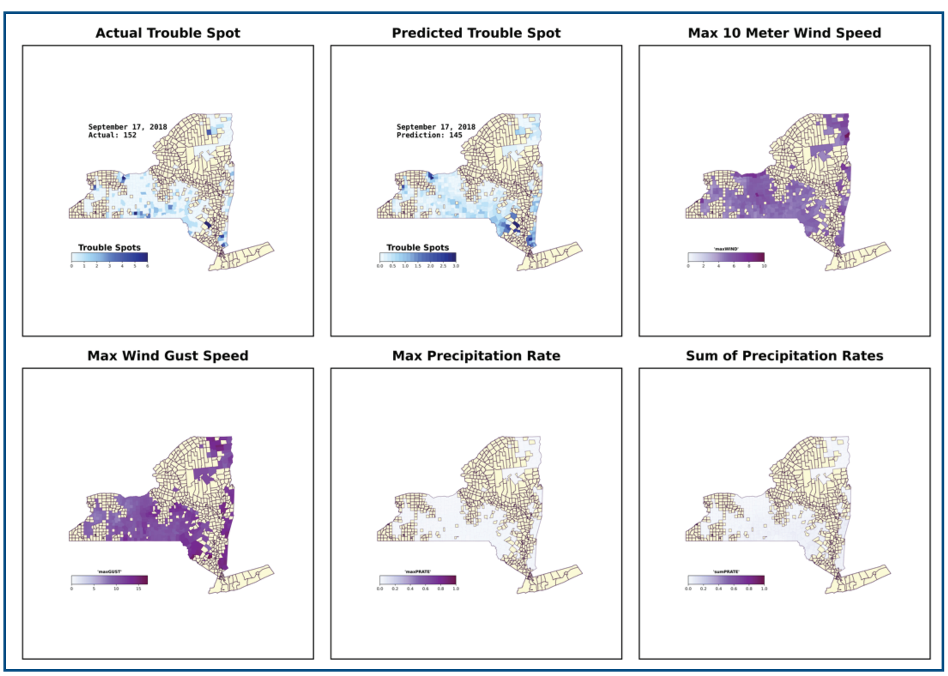
__Machine learning__ is a branch of artificial intelligence (AI). It involves developing algorithms that allow computers to identify and learn from patterns in sample (training) data, based on which they can make predictions whose accuracy increases as they learn. __Deep learning__ is a machine learning methodology for building neural networks with more "layers" that can use data on a larger scale than __shallow learning__.



Scatterplot of the predicted versus actual data. Each point represents values for the relationship between the actual and predicted damage locations from the machine learning model. The black middle line depicts the perfect model, and the red lines represent boundaries of +/- 50 percent error.

Since the outage modules are circuit based, all the data will be aggregated by storm and by circuit in the Avangrid territory. This will allow for some flexibility as to where in the state we obtain our weather data. It will also guarantee realistic predictions of the most extreme and moderate weather-related outage events—that is, it will focus on the prediction of outage totals across power circuits and storm events. The informed description of how multiple weather hazards affect the electric grid will enable Avangrid to increase its efficiency, make improvements that enhance its resiliency to storms, and more easily make repairs to the power circuits.

Our methodology takes into account the significant diversity in the meteorological factors that influence the predictions of moderate to severe storms. Since weather-related power outages represent a complex interaction of weather hazards, infrastructure, and the surrounding environment, this diversification guarantees the development of an outage prediction model for Avangrid that accurately quantifies the outages occurring in its distribution grid and facilitates repairs to the power circuits.

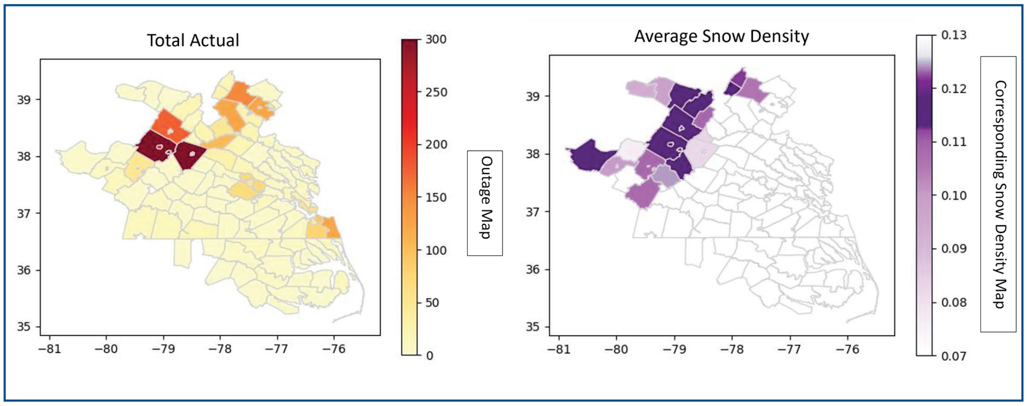


Example parameter maps for a rain and windstorm event in the Avangrid service territory.

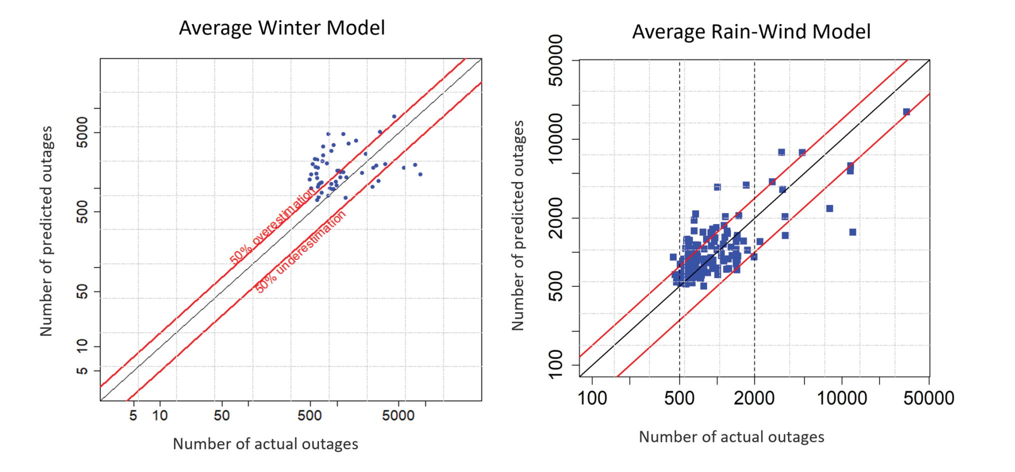
Extending the OPM: Dominion

In February 2022, the Eversource Energy Center at UConn began a collaboration with Dominion Energy, a company headquartered in Richmond, Virginia. The goal is to extend the application of the UConn Outage Prediction Model to Dominion's service territory of Virginia and North Carolina to help utilities there enhance storm preparedness, management, and response. The OPM predicts outages for a given area based on a database of significant storms that took place in that area in the past and the outages they caused. To develop a rain- and windstorm module for Dominion Energy's OPM, a project team comprising Dominion employees and UConn faculty and graduate students created a database of 164 simulations of weather events and associated outages that occurred in Virginia and North Carolina between 2005 and 2022. The OPM applies artificial intelligence to this and other information to obtain an understanding of the complex relationship between outages on the one hand and weather, land surface conditions, electrical infrastructure, and surrounding vegetation on the other. With this understanding, the model can predict the number of outages to be expected in each region of the service territory.

As with UConn's original OPM for the northeastern United States, this first module of the Dominion OPM will enable electric utilities in the service territory to respond swiftly and intelligently to weather-related impacts by informing them of the expected number and locations of outages caused by a typical rain and wind event. It will assist them in upgrading their existing practices and allow for more efficient crew allocation during events. The new module exhibits a mean error below 40 percent, which is in line with the skills of the modules developed for the northeastern United States. The next step for Dominion's Outage Prediction Model project is to create a module that can make outage predictions for winter weather events, followed by one for the territory's thunderstorms.



Total outages in the Dominion service territory (left) and average snow density in the same region (right). The maps demonstrate how average snow density affects outages in the service territory.



	MAPE	CRMSE	R2	NASH
Rain-Wind Events	37%	1807	0.73	.064
Winter Events	116%	1928	0.04	-0.39

Note: MAPE = Mean Absolute Percentage Error; CRMSE = Cumulative Root Mean Square Error; NASH = Nash- Sutcliffe efficiency.

Scatter plots of total storm outages for the cross-validation results for the ML-based average winter model and average rain-wind model. The two parallel red lines represent, respectively, 50 percent OPM overestimation (the top red line) and 50 percent OPM underestimation (the bottom red line). The black 45-degree line between them shows where the predicted and actual results agreed. The error metrics for these results are computed in the table below.

OPM for Transmission Systems

Researchers at the Eversource Energy Center made significant progress in 2022 in the development of a transmission system damage prediction model (Transmission DPM) that determines the probability of transmission component failures in advance of storm events. The Transmission DPM shares some similarities with the UConn Outage Prediction Module (OPM), which has been used to predict the storm-related outages associated with distribution networks. But transmission systems can experience failures, too, as a result of lightning, structural failures under strong gusts, and other weather events. These failures leave more customers without power than those at the distribution level, putting utility companies at an even greater economic disadvantage. Understanding the risks of storm-related transmission system outage can help eliminate unplanned outages and reduce their economic impact.

The Transmission DPM project has conducted two parallel lines of research. First, we developed a machine learning model to predict the probability of weather-related failures in Eversource transmission facilities based on environmental and infrastructural conditions.

*A **fragility curve** is the statistical representation in graphic form of the probability that a given structure will fail under a given type and amount of stress.*

Second, we used a separate model to create, through physics-based simulations, fragility curves to predict the probabilities of structural failures based on different design and meteorological factors.

Finally, we combined the strengths of the two models by creating an integrated model that incorporated fragility curves with machine learning, and we applied it using three different techniques.

The results showed significant improvement of the Transmission DPM over previous versions in its ability to predict outages on transmission lines. By ranking all transmission lines in Connecticut, Massachusetts, and New Hampshire according to their predicted risk, for instance, we found that 80 percent of failures occurred in 37 percent of the lines with the highest risk scores. Exploring the two most destructive storms in our database—tropical storm Isaias in August 2020 and a major nor'easter that brought heavy snow, winds, and flooding to communities from northern Maine to the mid-Atlantic in March 2018—we again found 80 percent of failures occurred among the lines predicted by the model to be most at risk. The model also showed reasonable accuracy with regard to location, as the lines with higher predicted risk tended to correlate with nearby outages—information that indicated which regions or lines were most vulnerable.

The Transmission DPM represents a major advance in outage prediction that will greatly enhance the capacity of ISO New England and other independent system organizations to forecast the probability of transmission line failures ahead of storm events.

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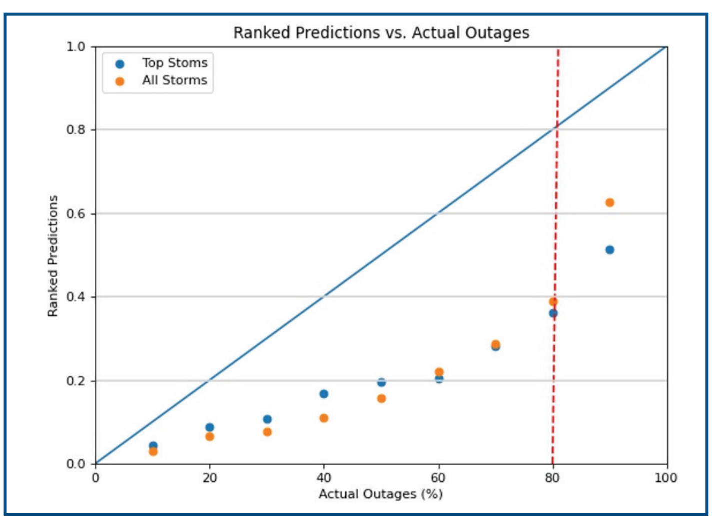
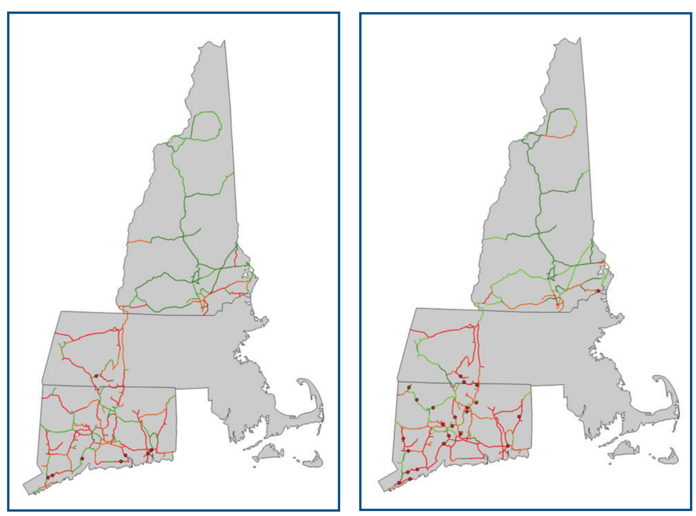


Ranked predictions made by the model versus the outages that actually occurred. The blue dots are based on the outages of the top five storms among those with the most outages in the sample storms used in the model. The orange dots are based on the outages from all the storms used.



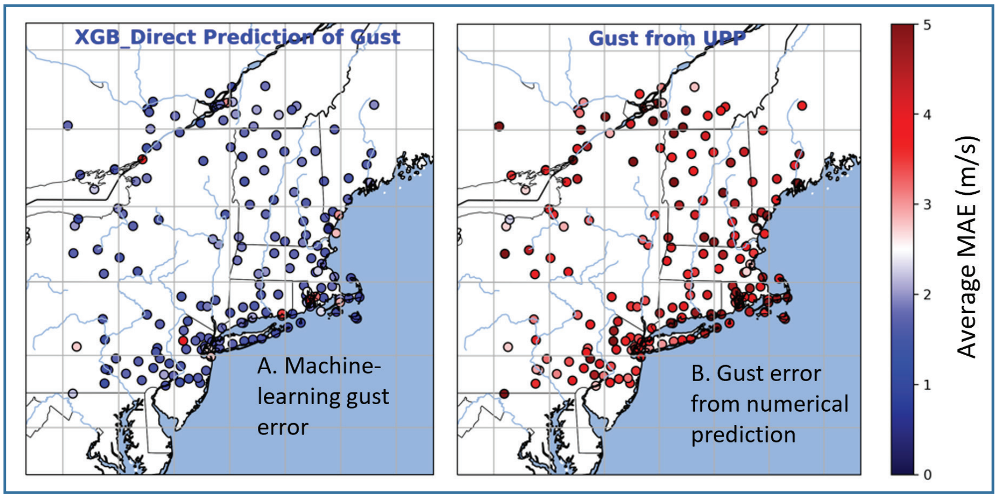
The highest outage-yielding storms in the dataset, on March 7, 2018 (left) and August 4, 2020 (right). The lines on the maps represent the predictions made by the model. The dark green lines correspond to the first prediction quartile, the light green to the second, the orange to the third, and the red to the fourth. The red dots represent the locations of outages

Innovation in Snowfall and Wind Gust Prediction

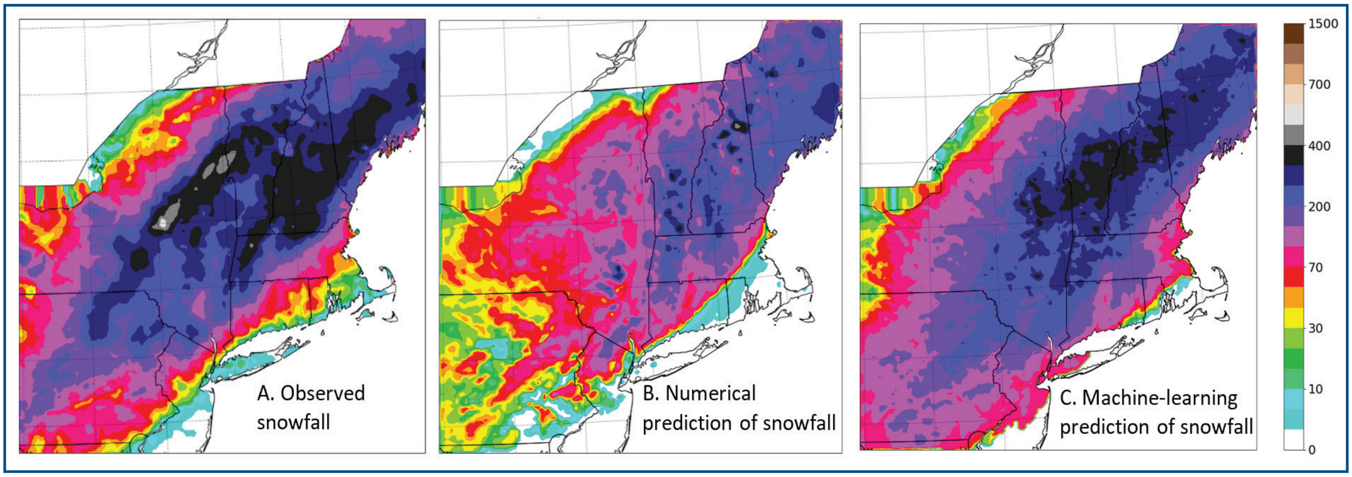
Researchers at the Eversource Energy Center have concluded that when it comes to forecasting snowfall and wind gust accurately during winter storms, the traditional approach to predicting weather—the use of numerical weather prediction (NWP) models—has challenging limitations. As these aspects of weather are crucial to maintaining power reliability in the northeastern United States, we began last year to explore alternative and innovative methods to forecast them by integrating in-house, physics-based NWP with observations and machine learning algorithms.

Since then, we have further developed the methodology and tested its application for wind gust using 61 historical windstorms spanning the period 2005 to 2020 and for snowfall (mainly nor'easters) using 31 historical snowstorms from 2009 to 2022 to train the machine learning algorithms. The application for wind gust was successful, with a 98 percent reduction of the gust bias, a 45 to 60 percent reduction of other gust errors, and a 47 percent increase in the correlation between our predictions and actual observations of gust. Improving our snowfall predictions proved more challenging, with the methodology very successful for some snowstorms and not very helpful for others. The snowfall machine learning method is still under development.

The next steps of the individual projects are to quantify the improvement that can be accomplished for outage prediction when we introduce the improved wind gust and snowfall forecasts to the UConn OPM.



The mean absolute error (MAE) of wind gust for 61 storms at each weather station in the northeastern United States. Map A shows the gust errors in predictions generated by our machine learning methodology (blue indicates low errors). Map B shows the errors with traditional gust prediction (red indicates high errors)



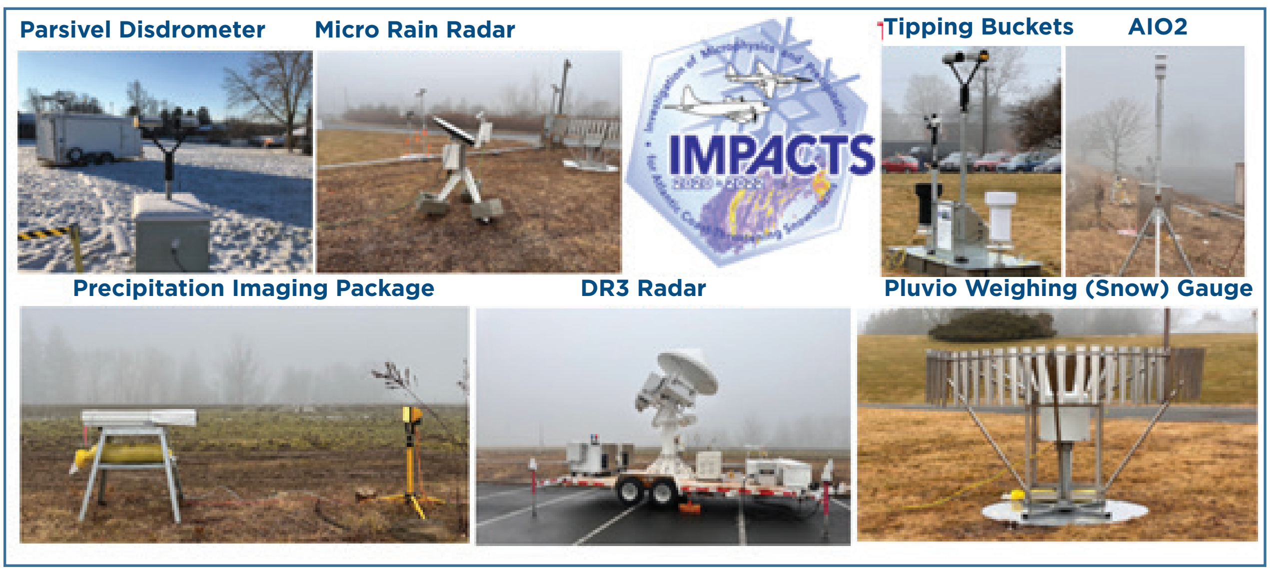
Nor'easter in November 26–28, 2014. Map B shows the underprediction of snowfall by the numerical model, especially with regard to the band of snow that appears in the observations shown in map A. As map C indicates, the machine learning model was better able to capture the snow band.

IMPACTS: Understanding Snow with NASA Data

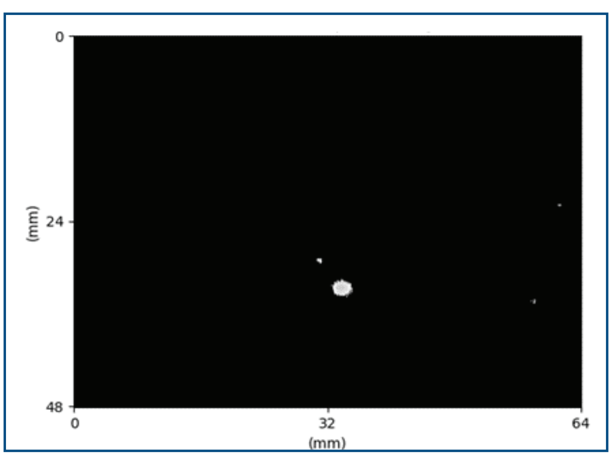
The formation of winter precipitation is not well understood and is strongly affected by changes in temperature and humidity, as well as complex dynamics in the upper atmosphere. With small temperature variations near the surface of the Earth, a snow event may rapidly morph into a rain event, or a rainstorm into a freezing rain event. As a result, winter precipitation predictions are often very uncertain, leading to forecasting errors that can leave utility managers unprepared for heavy snow or ice events that cause widespread outages, when all the managers were expecting was rain.

In 2021, the Eversource Energy Center began a partnership with Colorado State University and the National Aeronautics and Space Administration to participate in NASA's Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) field campaign, which seeks to collect a dense network of observations to enhance our understanding of wintry precipitation in New England. The IMPACTS campaign in Connecticut featured more than twenty-six sensors installed at two locations on the UConn campus that collected data from the surface and upper atmosphere during winter events between 2021 and 2023. Ground sensors, such as tipping buckets, laser disdrometers, anemometers, snow gauges, and precipitation imaging packages, collected data from the surface, while the upper atmosphere was sampled using weather balloons, NASA P3 Orion flyovers, and dropsondes.

Researchers have been working with the data collected from the NASA IMPACTS campaign in Connecticut to increase our knowledge of the atmospheric interactions that form different types of precipitation. With this knowledge, we can improve our ability to forecast winter precipitation type and snow density and reduce the uncertainty as to whether there will be rain, ice, or snow. The data can also advance our understanding of what atmospheric conditions produce heavy, wet snow. Our better understanding of snow density—a key component of UConn's winter Outage Prediction Model—will boost the OPM's ability to provide accurate forecasts of power outages caused by winter storms.



Some of the sensors installed in Storrs, Connecticut, for the NASA IMPACTS campaign.



A high-resolution image of a snowflake captured by the Precipitation Imaging Package sensor developed by Dr. Larry Bliven at NASA. The two PIP sensors deployed in Storrs, Connecticut, continuously capture data at 380 frames per second. Images of snowflakes are very rare at this resolution, which is necessary to gain an understanding of how snowflakes move down to the surface and how they differ from each other (heavy or light snow).

Storm Vaia: A Rare View into Tree Failure

In October 2018, storm Vaia brought extreme levels of precipitation and severe winds to the Mediterranean. The forests of Northern Italy in particular suffered unprecedented mass occurrences of tree failure. In wooded regions like New England or central Europe, severe events like Vaia pose dangers to residents, communities, and economies. New techniques to predict tree failure can allow for greater preparedness and guide future forestry practices to protect both the trees and the utilities to which they may pose a threat. At the Eversource Energy Center, researchers are applying valuable insights from storm Vaia to develop these techniques.

The first step in anticipating tree failure is to predict the weather that will make trees fail. To do so, we use computer models and analyze their forecast power to determine how accurate their predictions are. We then develop machine learning models that can learn to predict the future by being "trained" with accurate weather data from the past, provided sufficient data are available. The issue is that machine learning models consider weather data from neighboring locations as independent, but they actually are not. In fact, since the weather in a specific town during a storm is very similar to the weather in a nearby town, the impacts on the two towns will share some similarities. By not considering this, machine learning models will perform differently when tested on a past storm, whose impact is known everywhere, versus a new storm, whose impact is not known anywhere.

> ***Overfitting*** *in machine learning is when a model can make accurate predictions based on its training data but cannot generalize those predictions to new data. Researchers cannot train a model with data (or correlated data) on, for example, a location they would like to test because this information would provide an advantage to the model—that is, the model would "cheat" by looking at the solution.*

In this project, we worked to solve the dual problem of making storm impact predictions for individual regions without knowledge of the impact in adjacent areas and how to know if the predictions are correct without having knowledge of local patterns. An extreme and unique event like Vaia, for which no similar data existed to learn from, presented an opportunity to develop a model trained on new patterns and tested with an innovative and more rigorous method. Specifically, to avoid overfitting, the method excludes from the training dataset not only the data we want to test, but all neighboring data that exhibit correlations with the test data.

When we compared the new method against traditional methods, we found the traditional methods prone to overestimating future forecasting ability, while our method provided a more accurate representation of the forecast error. The model based on this method will provide better predictions of the impact of storms on individual areas that utility decision makers can use in their outage restoration planning.

Storm Vaia caused extreme levels of mass tree failure, as shown in these aerial images

TREE AND FOREST MANAGEMENT

Successful strategies to reduce risks to powerlines from roadside forests are multifaceted, requiring a thorough understanding of vegetation health and management and the creative application of cutting-edge technologies. Researchers in the Eversource Energy Center's Stormwise program are developing these strategies on a variety of fronts.

__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. 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.

NAFRI Project Update

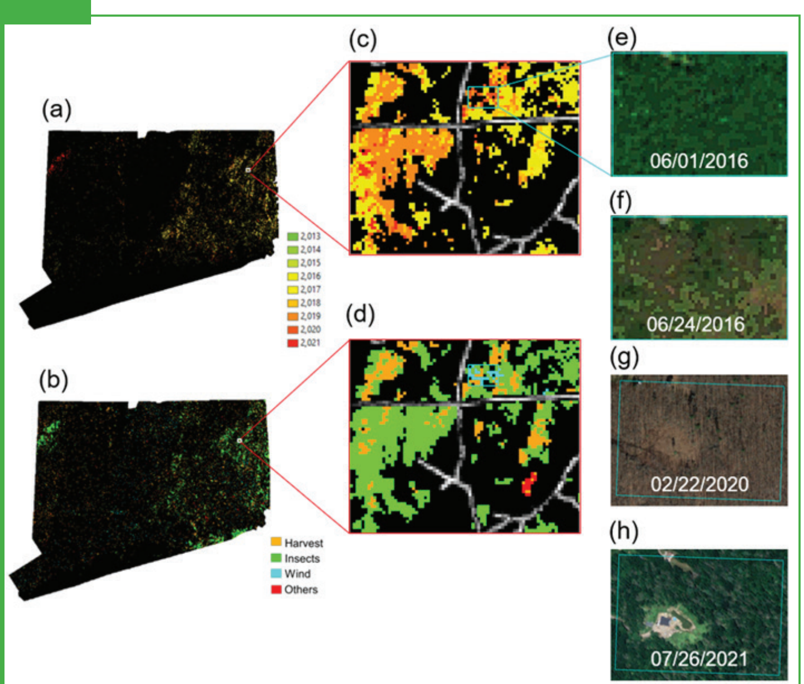
In recent years, forest disturbances, such as droughts and spongy moth outbreaks, have damaged forest health and vitality in New England woodland. Vegetation management to prevent outages as a result of tree failure currently involves manual inspections of dead trees and branch die-offs, which can be time consuming and costly. At the Eversource Energy Center, the research team for the ongoing Near-Real-Time Assessment of Forest Risk to Infrastructure (NAFRI) project has been developing an automated approach to monitoring, characterizing, and evaluating roadside and right-of-way forest risks to powerlines. The project has involved three tasks, two of which are now complete.

In the first task, the NAFRI team monitored forest disturbances using the NASA harmonized Landsat and Sentinel-2 remote-sensing product to create high-resolution maps of forest disturbance in Connecticut. Masking out non-roadside areas on the maps enables the early identification of forest disturbances, including their location, time, and intensity, allowing utility companies to conduct preventive tree trimming at specific sites before the next storm season.

In the second task, the team sought to characterize forest disturbances according to their agents (or causes) because different disturbance agents have different impacts on roadside utility systems. Trees rendered unhealthy by spongy moth infestation, for example, could contribute to elevated risks to powerlines, while tree removal is likely to reduce the risk. Using machine learning techniques, we classified the agents of disturbance into four categories: harvest (including clear-cut and thinning), insects, wind, and others. The resulting disturbance agent maps can be used for further prioritizing vegetation management efforts.

The third NAFRI task is now underway. We are working to build an analytical tool to assess powerline risks that result from changes in forest conditions. This tool will use machine learning and deep learning methods to translate historical forest disturbance into the possibility of tree failure and resulting power outages. We will produce high-resolution "risk score maps" that can be used as the input layers of the University of Connecticut Outage Prediction Model (OPM). We will also provide statistics, such as the percentages of infrastructure at risk, for three subregions.

Overall, the NAFRI project is providing a near-real-time forest health monitoring framework for roadside utility risk assessments. By enabling quick and efficient prioritization of vegetation management efforts to prevent tree-fall events and mitigate the risk of power outages, the project is contributing to improving the resiliency of electric infrastructure in Connecticut and beyond.



High-resolution statewide forest disturbance maps delivered by the NAFRI project. (a) Connecticut forest disturbance maps aggregated by years. Black represents stable surface, and the other colors represent forest disturbances by year. (b) Connecticut forest disturbance maps aggregated by agents. Black represents stable surface, and the other colors represent the causes of forest disturbances. Magnification of the 2016 spongy moth outbreak areas in the white box in (a) and (b) are shown in (c) and (d), respectively. By overlaying the roadside forest density layer, shown as black (low density) and white (high density), we can identify forest disturbances near electric utilities. Closer views of land changes over time in the light blue box in (c) are shown as (e) and (f) from the very-high-resolution RapidEye images and (g) and (h) from Google Earth. Severe spongy moth defoliations in June 2016 are represented by (f). The subsequent windthrow and tree clearing can be found in (g), and the construction event is displayed in (h).

Tree Trimming and Biomechanics

Tree failures pose a high risk to society, with significant environmental, economic, and social costs resulting from the damage they cause to infrastructure. While the annual trimming of trees along roadsides by utilities has been successful in reducing power outages, the procedures are expensive and time consuming, and the effects they may have on the trees' resistance to wind-caused damage are not well understood. A more thorough understanding of the impacts of trimming on the dynamic properties of trees may help balance the competing objectives of reducing power outages, minimizing costs, and maintaining ecosystem services.

The purpose of the Tree Trimming and Biomechanics project underway at the Eversource Energy Center is to learn about the relationships between tree form and movement following the implementation of utility trimming practices along roadsides. The study involves attaching instruments called "accelerometers" to the trunks of thirty trees, half of which have been recently trimmed. In this way we can track the movement and displacement of the trees under varying wind conditions and compare the movement of trimmed and untrimmed trees to each other, as well as that of each trimmed tree before and after trimming. To characterize changes in their crown structure, we have also created a 3D crown model of each untrimmed tree using terrestrial laser scanning (a ground-based counterpart to air- and spaceborne LiDAR), and we will be updating the scans following trimming to analyze how the changes alter the trees' movement and stability.

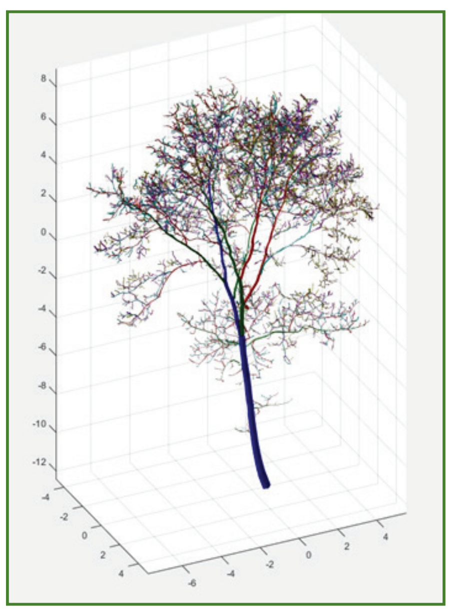
As we continue this analysis over the coming year, we will produce a novel data set from which we can determine the near-term impacts of trimming on the trees in our study. We will also continue to monitor the trees over the course of the next several years—a period corresponding to a standard utility trimming cycle—to document the changes over time in their biomechanical and structural properties following trimming.

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. LiDAR creates* ***point clouds****, which are sets of data points collected from a particular object, space, or geographical area that together provide a picture of that object, space, or area. The denser the point cloud—that is, the more data points within it—the more detailed the picture it provides.*

A large white oak tree in the UConn Forest being trimmed.

Accelerometers are placed below the start of the crown and connected to data loggers at the bases of focal trees to track their movement and displacement.

Point cloud from terrestrial laser scanning of a tree in the study.



Quantitative Structural Model (QSM) built from a terrestrial laser scanning point cloud.

Salvaged Sawlogs: A Stormwise Demonstration

Emerald ash borer (Agrillus planipennis) is an invasive insect pest that has been killing ash trees (Fraxinus americana) and devastating ash stands in Connecticut for several years. The market for ash timber allows for profitable salvage of ash sawlogs where trees are almost or just recently dead and retain their structural integrity. But dead ash trees that are not removed decay rapidly, sometimes creating hazardous conditions along roadsides and threatening power infrastructure. Recently, researchers conducting forest management scenarios under the Stormwise initiative at the Eversource Energy Center demonstrated how an innovative combination of arboricultural and silvicultural techniques can be used, safely and economically, to avert the hazardous conditions associated with road frontage and roadside ash trees adjacent to ash salvage areas.

In the summer of 2022, tree cutters harvested and salvaged sawlogs and fuelwood material from an ash stand infested with emerald ash borer on around 30 acres of the UConn Forest. The parcel on which the ash stand was located fronts on approximately 600 feet of road and power distribution right-of-way along Moulton Road in Storrs, Connecticut. Forest conditions along the right-of-way included sawtimber-sized ash, maple, and hickory trees, comprising an overhead canopy 80 to 100 feet tall, and a dense shrub layer. We identified a total of 21 large dead or dying ash trees along this road segment as potentially hazardous and a threat to power infrastructure.

While timber harvesting in the remainder of the stand was underway, an arboricultural crew simply removed the branches and tops from the ash trees. The trunk of each tree—the portion most suitable for a sawlog—was left standing to be hand-felled later. By removing the risk of powerline interference, this approach allowed for the safe salvage of the sawlogs. Approximately 4,200 board feet of ash sawtimber, plus associated cordwood material, was salvaged from the roadside trees. Sold as logs roadside, this quantity of merchantable timber could be expected to garner $1,890 at current prices.

The combined cost for the arboricultural crew plus the harvesting of the standing tree trunks was an estimated $2,500 to $3,000. Although this exceeded the revenue yielded by the salvaged sawlogs, the difference fell short by far of the anticipated costs of dealing with the hazardous trees one by one as they eventually dropped branches, tipped over, or otherwise failed.

Ultimately, this demonstration illustrated how implementing Stormwise management along adjacent road frontage when conducting other forest management activities represents a worthwhile investment in avoiding greater costs in the future.

Ash logs piled at landing for loading.

Understanding Collaboration in Roadside Forest Management

Throughout Connecticut, utilities are working to minimize power outages through vegetation management programs. These programs can affect what roadside forests look like, and they rely on public acceptance and regulatory approval to balance the maintenance of reliable power with vegetation management resources and the aesthetics of the roadside forest.

As part of the interdisciplinary Stormwise project at the Eversource Energy Center since 2015, the study of human dimensions has been helping UConn researchers understand public concerns about and opportunities for innovation in roadside forest management across the state. "Human dimensions" refers to 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. In earlier phases of this research, we learned that residents have generally favorable attitudes toward the process carried out by utilities to manage roadside vegetation, and they largely understand the tradeoffs between having reliable power and protecting trees. Attitudes vary, though, and are influenced in part by the importance of trees to the individual.

The latest project phase has examined the concerns of the various sectors of the Connecticut forest management community regarding biophysical factors that influence the stability of roadside trees across ownership boundaries. As recent infestations of spongy moths, drought conditions, and severe weather have brought attention to stressors that come from outside the utility protection zone, we have evaluated the opportunities and barriers associated with collaboration among vegetation and forest managers in implementing novel forest management strategies beyond their "property."

To do this, we conducted interviews with thirty-nine members of the Connecticut forest management community. We found that the participants do work together at some level, with communication occurring among individuals representing different occupation groups. Although managers seek information from trusted contacts, they value access to a diversity of other resources, as well. Central collaborative roles are dominated by a few individuals, suggesting that sustainability of communication among the community may depend upon identifying and supporting the efforts of such "go to" individuals over time. Collaboration is motivated by professional networks, personal relationships, management relevance, and the sharing of information or experiences. The process can be hindered, however, by limited resources and time, and a perceived lack of consensus about desired outcomes.

*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).*

Specifically for roadside vegetation management, our participants told us they are constantly balancing numerous forest management objectives with public safety and the mitigation of hazardous conditions. The most frequently noted management challenge was gaining support and satisfaction from the public and other stakeholders. Although the study participants said they recognize the importance of ongoing vegetation management along roadsides, many avoid it for reasons of worker safety and the extra resources needed, such as specialized certifications and traffic control. More broadly, immediate roadside vegetation issues such as public safety are prioritized over long-term planning in coordination with those beyond property boundaries.

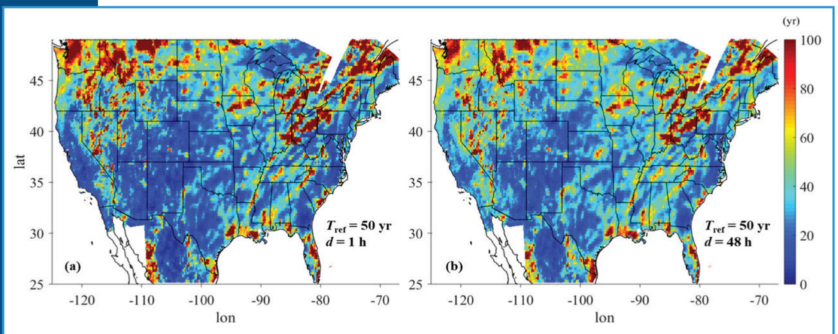
Based on these findings, we believe decision-making processes and management outcomes may be enhanced among the forest management community by increasing the availability of and access to information and opportunities for building in-person relationships, enhancing communication, and encouraging networking. Ongoing research is evaluating forest management professional networks, the information needs of managers and the sources of information they use, and associated transfer of knowledge. Planned work seeks to study opportunities for integrating roadside vegetation management into town-level community resiliency planning efforts.

GRID VULNERABILITY AND RESILIENCE

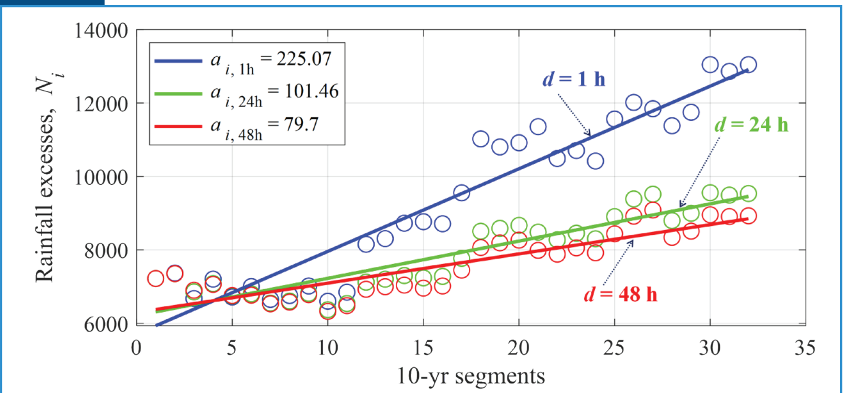
As climate change advances, Eversource Energy Center researchers are working to quantify its effects on the electric grid and find ways to head off the growing risks posed by wind, water, and vegetation.

Grid Resilience in a Warming Climate

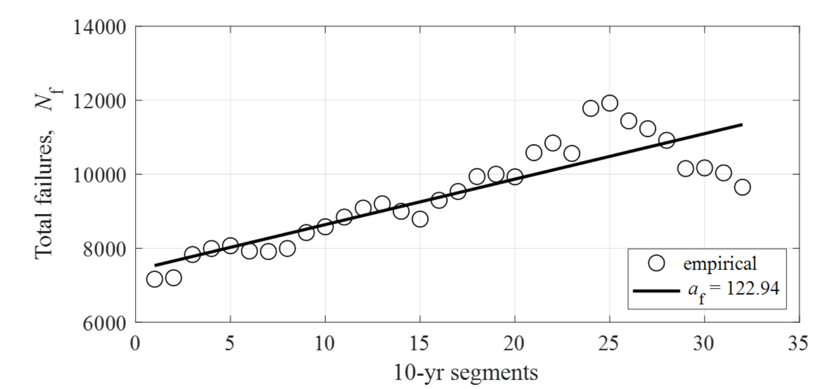
Historically, Connecticut has been susceptible to the remnants or direct landfall of northbound tropical cyclones, as well as nor'easters and extratropical storms. Intense storm events have been occurring more frequently along the Atlantic Coast, and the frequency is expected to continue increasing as climate change accelerates. Such events may lead to significant compound flooding events—that is, events in which flooding occurs from two or more sources, either simultaneously or one after another within a short period of time.



Changes in the frequency of 50-year rainfall intensity levels (that is, occurring on average at least once every 50 years), from the 1980s to the present, over the contiguous United States. The maps show changes for rainfall extremes of both shorter (1-hour; map a) and longer (48-hour; map b) duration.



Evolution of rainfall excesses over the period 1979 to 2019.



Stormwater drainage infrastructure failures over multiple catchments in the Housatonic River basin, 1979–2019.

Recently, researchers at the Eversource Energy Center showed that existing critical infrastructure has been failing at an alarming rate over the past 40 years, a trend that generally agrees with trends observed for extreme rainfall. The intensification of such hydrometeorological extremes, accompanied by sea-level rise, poses an immediate threat to numerous Eversource Energy substations lying close to or within coastal and inland floodplains. As the reliable functioning of electrical substations is paramount for the smooth operation of the distribution grid, damage from severe flooding could affect thousands of Eversource Energy customers and lead to substantial repair and restoration costs.

Grid Resilience in a Warming Climate (GRWC) is a comprehensive effort by Center researchers to address the technical, financial, and societal issues that may arise from the susceptibility of Eversource Energy substations to compound flood events across Connecticut under the influence of climate change. We are creating an integrated framework that combines advanced statistical approaches that account for the continuously changing nature of hydrological and meteorological phenomena, as well as refined hydrological and hydraulic models to simulate the impact of historical flood events.

The methodology we are using for this effort will advance leading-edge research and technology to ensure reliable power during extreme weather events and limit outages for substantial portions of the grid. It will also enable us to identify potential vulnerabilities of the system and highlight areas where design improvements can enhance resiliency. Ultimately, the results of our work will add to our knowledge of the effects of climate change on flood risk and supply valuable information on the future exposure to flooding of critical electric infrastructure across Connecticut.

GRWC is a natural continuation of the existing operational early flood warning system in Connecticut, which evaluates the vulnerability of Eversource Energy substations to flooding in the state. As an ongoing expansion of the system to Massachusetts and New Hampshire continues, it could be accompanied in the future by a similar application of our research.

Intelligent DER Control for Fast Restoration

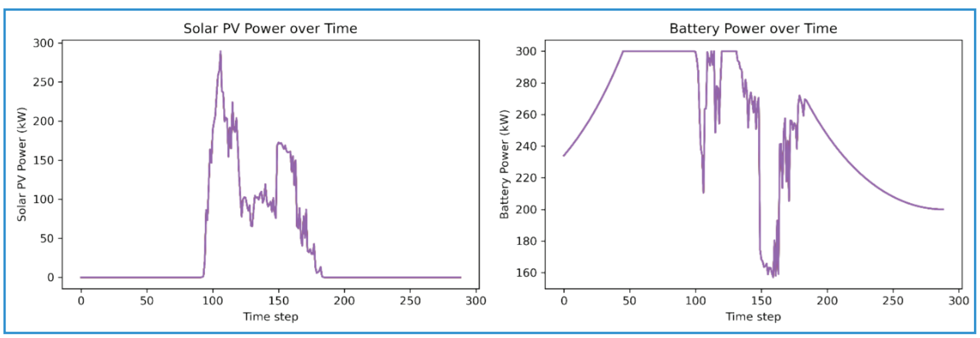
The presence of renewable distributed energy resources (DERs), like solar panels and wind turbines, in electricity generation and distribution complicates the stability and maintenance of the power grid in a number of ways. Researchers at the Eversource Energy Center are using an innovative iterative Model Predictive Control (iMPC) framework to optimize for fast service restoration the energy management of a distribution system that includes photovoltaic (PV) generation and battery energy storage.

__Distributed energy resources__ are small units of electricity generation, like solar panels or generators fueled by natural gas, that are often residential or commercially owned and connected to the utility distribution system (the power grid) at or near the end user.

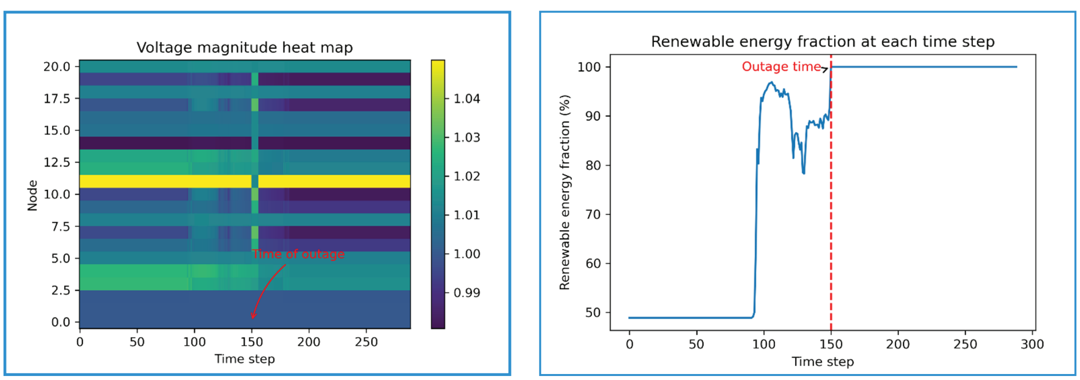
An iterative procedure involves the repetition of steps. The iMPC algorithm operates by predicting the system's behavior over a finite period of time, solving an optimization problem at each time step, and updating the system state accordingly. This ongoing optimization enables the efficient utilization of renewable energy and the maintenance of desired voltage limits within the distribution system.

By allowing continuous refinement of the control inputs based on updated system states, the MPC framework also produces a more robust and efficient approach to power grid restoration. The combination of iMPC with OpenDSS, a widely used power distribution system simulation tool, and the flexibility and scalability of the MPC framework make the innovation ideal for tackling the complex and time-sensitive nature of power outages. iMPC's adaptability to changing grid conditions and real-time information updates contributes to the algorithm's ability to ensure a stable and secure restoration process.

Overall, the outcomes of our work so far demonstrate the potential of iMPC for improved grid reliability and resilience, highlighting the importance of optimization techniques in the integration of renewable energy sources and energy storage systems in modern distribution networks. Future work will focus on refining the iMPC algorithm and incorporating advanced machine learning techniques to enhance its performance further.



DER setpoints for a distribution network controlled by iMPC to allow proper energy management for fast grid service restoration.



Evaluation metrics for restoration using DERs, demonstrating the capability of the proposed iMPC to maintain voltage in a secure range during service restoration.

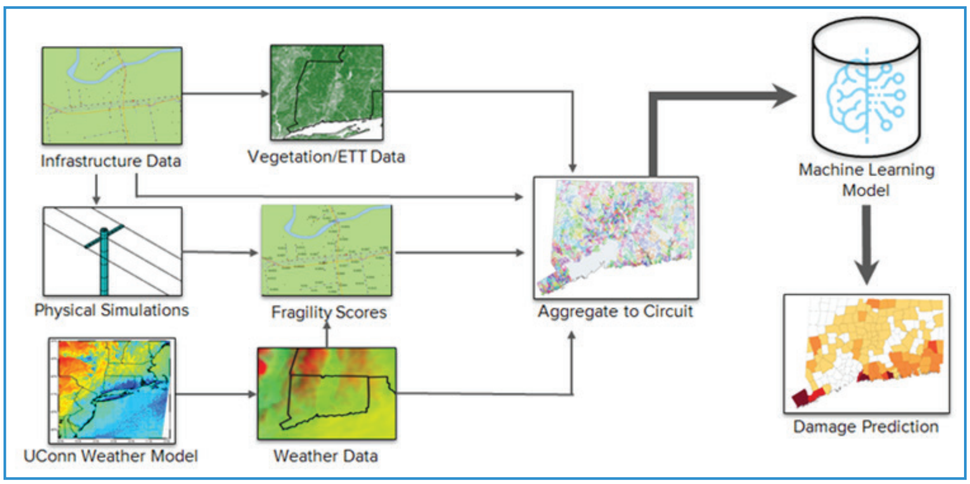
What Works Best? The Resilience OPM

During 2022, researchers at the Eversource Energy Center made significant progress in the development of a distribution-level module of the UConn Outage Prediction Model (OPM) that will measure the benefits of grid hardening actions in reducing power outages.

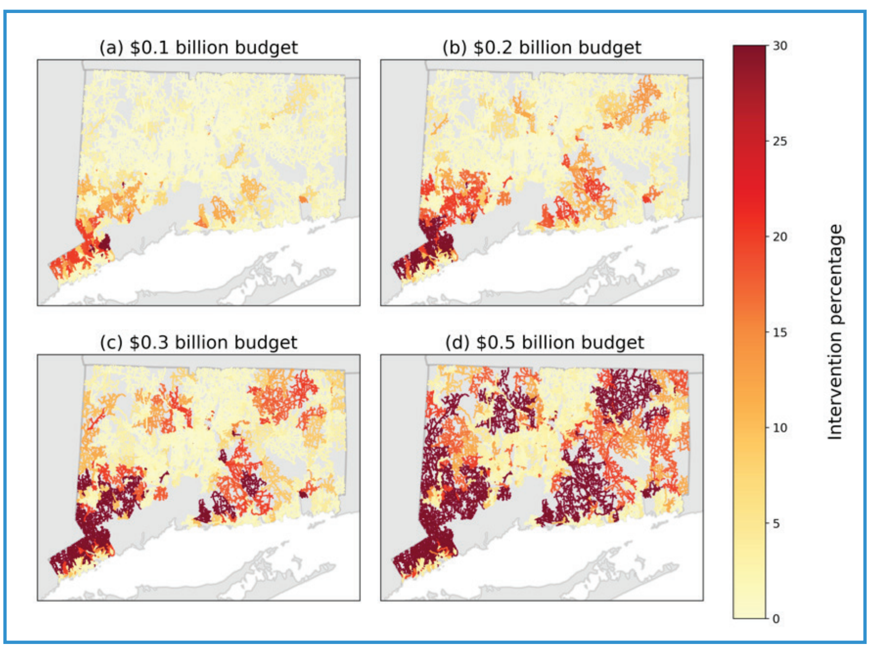
Extreme weather events, such as tropical storm Isaias in 2020, have devastated portions of the power system, leaving residents without power for extended periods and highlighting the need for a more resilient grid. Grid hardening actions, including moving powerlines underground, managing vegetation, and making structural upgrades, can reduce these disastrous consequences. Large-scale applications of such actions can be infeasibly expensive, however, while their benefits can be difficult to quantify. In 2023, for instance, Eversource plans to spend $74 million on vegetation management along more than 4,300 miles of powerlines. Are the benefits it will produce worth that expenditure?

The resilience module of the OPM currently under development will help utilities prioritize investments in resilience measures by assessing their benefits. To create it, researchers combined data related to the topography, vegetation, land cover, and meteorological conditions around the overhead lines and derived the probabilities of structural failure from structural analyses. Using historical outage data, the machine learning model was trained to predict the number of outages occurring along each circuit for each storm event. We then engineered the model to learn how different actions would affect the number of predicted outages—for example, whether the outages would decrease with heightened tree trimming—without substantially losing its predictive accuracy. Next, we presented it with scenarios representative of grid hardening, such as by increasing the amount of trimming done or replacing old poles with newer, stronger ones, and had the model quantify the benefits of the different strategies. Finally, the model determined which actions were best undertaken under limited budgets in particular regions of Connecticut, based on an analysis of such actions carried out in the state over the past sixteen years.

The resilience OPM represents a comprehensive framework for assessing grid resilience and hardening benefits. A provisional patent is pending submission with the UConn patent office for potential commercialization. The work is also advancing academic knowledge through one submitted journal paper, one manuscript in preparation, and several conference presentations. Future efforts could include more rigorous economic analyses considering the social impacts to customers, quantifying benefits in terms of restoration times, and exploring the effects of climate change on resilience.



Resilience OPM architecture.



Example of optimal allocation of hardening strategies (expressed as a percentage of the circuit being hardened) under varying budgetary constraints.

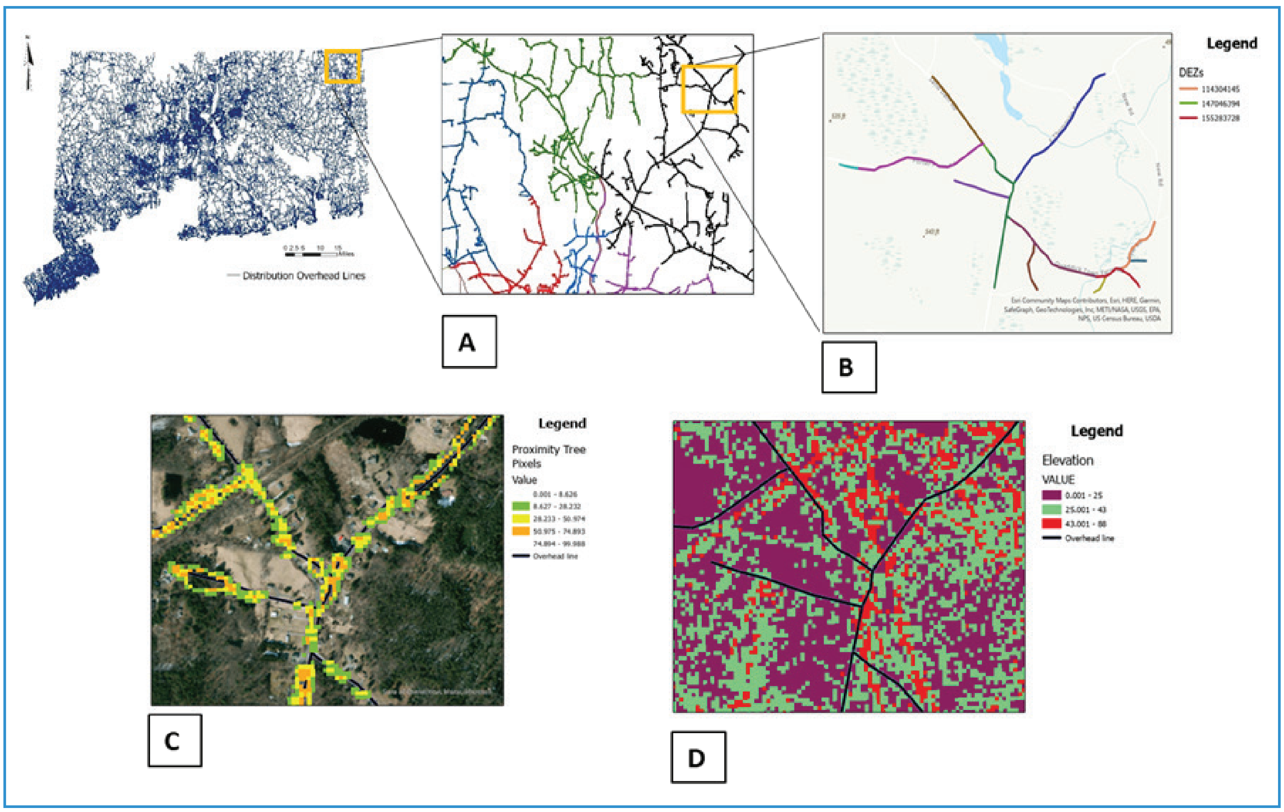
Vegetation Risk Analysis to Optimize Management

Vegetation management is an indispensable way to reduce the risk posed by trees to utility infrastructure. To be most effective, though, vegetation management programs must take into account a variety of environmental and management factors, and, to decide when and where tree trimming or removal is required, they need explicit information on where the risks lie.

The use of remote sensing data enables us to model the physical structure of trees as well as the condition of their health. LiDAR data in particular is useful in creating 3D canopy height models for roadside vegetation and for deriving terrain characteristics. Tree health conditions such as death or defoliation can also be assessed from remote sensing imagery. To develop improved risk models, existing geospatial layers detailing soil characteristics, land cover, utility infrastructure, and tree trimming data can be combined with vegetation information.

Currently, vegetation risk analysis is done at the circuit level, which gives only a coarse picture of vulnerable areas to guide decisions about vegetation management. Researchers at the Eversource Energy Center are making significant efforts to increase our understanding of how local environmental variables, vegetation management practices, infrastructure settings, and tree trimming practices affect tree-related power outages at the powerline level. We have developed and compared multiple machine learning–based vegetation risk models, comprising 19 different combinations of explanatory variables falling into four categories: forest characteristics, soil and terrain, vegetation management, and utility infrastructure. Our findings show that, at the device exposure level, the roadside forest characteristic and infrastructure variables have the strongest impacts on the prediction of vegetation risk to distribution powerlines. In an analysis of the relative importance of the variables, we also found that LiDAR-derived tree variables, powerline length, median tree height, and wire properties were the most significant. Most important, we found that these variables were crucial to the performance of our proposed vegetation risk model.

In sum, our proposed model could guide utilities in prioritizing the areas where they should be conducting tree trimming and removal programs to improve grid resilience and hardening. Such optimal targeting of vegetation management programs would greatly benefit both broad-scale ecological and economic productivity by reducing risk to infrastructure and improving the health of roadside trees.



Map of Eversource Energy overhead distribution network showing circuit power lines (A), device exposure zones (B), proximity tree pixels (C), and elevation (D) along the magnified device exposure zones.

GRID MODERNIZATION

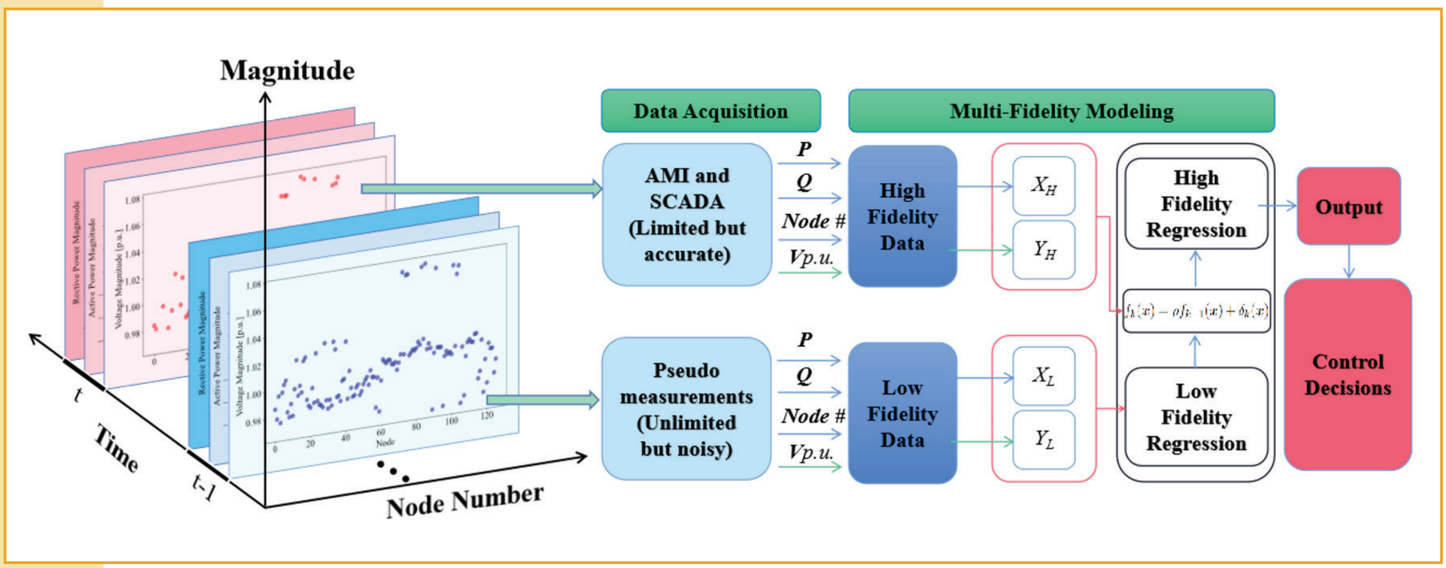
An increasingly complicated electric grid presents new and complicated challenges. Eversource Energy Center researchers are working to address the challenges presented by threats to cyber security, the integration of sustainable forms of energy, and other aspects of the transition to and maintenance of a modernized grid.

NARGP: A New Approach to Grid Visibility

Grid visibility is crucial because it ensures the stability and safety of the power distribution system. If the distribution system is not visible, it cannot be analyzed, which means some power failures cannot be predicted. State estimation—the process of assessing the internal state of an energy system by "fusing" a mathematical model with input and output data measurements—has a wide range of applications in the real-time monitoring and control of power distribution systems. Because we cannot acquire enough real-time measurements, however, the traditional method of distribution system state estimation cannot produce accurate results.

Researchers at the Eversource Energy Center have proposed a probabilistic Nonlinear Autoregressive Gaussian Process (NARGP) approach to achieve greater accuracy by fusing limited real-time data with historical pseudo measurements. We have tested the method on the IEEE 123-node distribution system under three different scenarios, with results that demonstrate its effectiveness and efficiency. The proposed method outperforms other machine learning algorithms while maintaining excellent accuracy with limited high-fidelity data. In subsequent research, we will consider the impact of changes to the configuration of the distribution system. Our continued positive results promise to reduce significantly the cost of installing measurement devices in the distribution system.

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.*



Proposed multi-fidelity modeling framework for probabilistic voltage estimation. An autoregressive scheme is used to fuse multi-fidelity data, with the historical pseudo-measurement data considered low-fidelity and the real-time SCADA (supervisory control and data acquisition) and AMI (advanced metering infrastructure) data considered high-fidelity. Then, the Gaussian process (GP) aims to capture the relationship between the measurement data and node voltage.

Distributed Control: Defeating Hackers with Artificial Intelligence

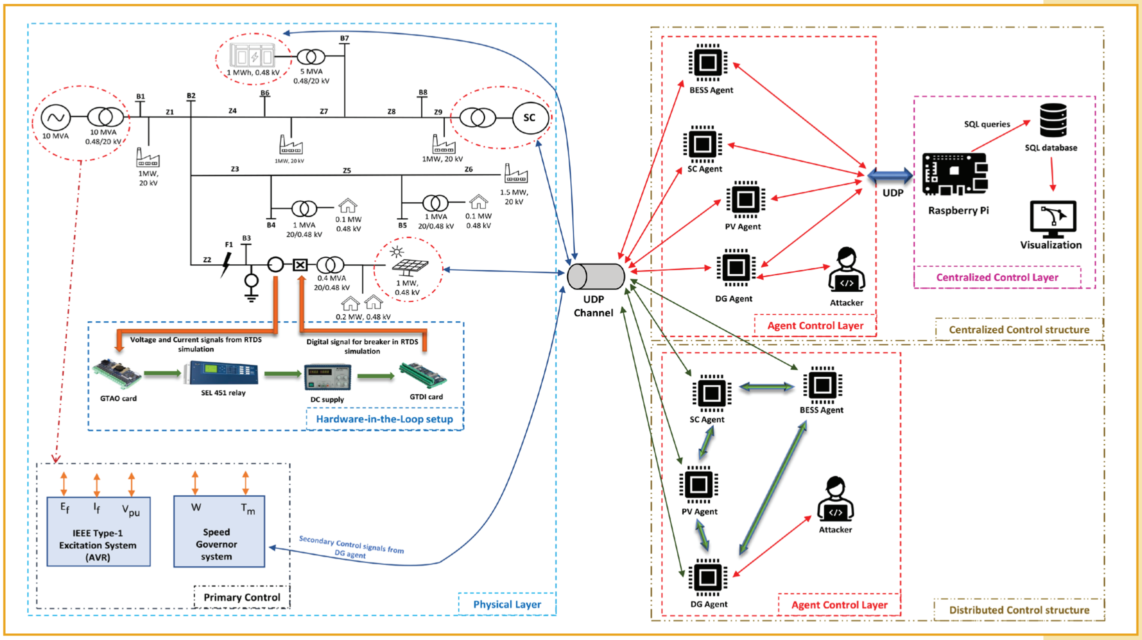
The way we generate and distribute electricity has undergone a significant transformation in recent years. We're now using more renewable distributed energy resources (DERs), like solar panels and wind turbines. We're also using more smart devices that can communicate with each other and make decisions without human intervention. Unfortunately, the increased reliance on digital devices and communication networks that has resulted from these advances has made the power grid more susceptible to cyberattacks. In a denial of service (DoS) attack, for example, a hacker can disrupt the power system and render it unavailable for its intended purpose by flooding it with massive amounts of data that overwhelm its servers, causing power outages and affecting millions of people.

To gain a better understanding of the risks associated with cyberattacks, researchers at the Eversource Energy Center have developed a testbed that simulates a power grid by applying a subfield of artificial intelligence called multi-agent systems. In MAS, multiple agents—that is, computer programs or systems designed to perceive their environment, learn from it, and act without the intervention of a programmer—work together to solve problems. The Center's testbed includes two different MAS-based control architectures: centralized-based and distributed-based. In the traditional centralized architecture, every generation in the grid (such as power from a DER) has a dedicated agent assigned to it that reports to a single control center. This system has the disadvantage that the failure of just one part of the system—the center—can stop the entire system from working, a weakness hackers can exploit to launch cyberattacks. In contrast, the distributed control architecture assigns a dedicated agent to every DER, and these agents only communicate with their neighboring agents.

> ***A testbed,*** *according to the Merriam-Webster dictionary, is "any device, facility, or means for testing something in development." In research related to weather, utilities, and energy generation and distribution, the testbed is often an extremely powerful computer used for machine learning simulations.*

To assess the effectiveness of each control architecture, we simulated a DoS attack by flooding the network with unusable packets of data. The test results showed that the distributed MAS control architecture was more resilient to DoS attacks than the traditional centralized architecture. Since the control was distributed and not located in one central site, the possibility of single-point failure was eliminated.

The developed testbed can help not only the researchers but also utilities to understand the vulnerabilities of traditional control systems and how the resiliency of the distribution system can be improved with distributed control. The findings of this research can help utility operators make informed decisions about their control systems and take steps to protect their systems against cyber threats. The testbed can also be used for training purposes, and will aid the development of further research in this cyber-physical system field.



Schematic diagram of hardware-in-the-loop setup in the Eversource Energy Center's cyber-physical systems testbed with MAS controls.

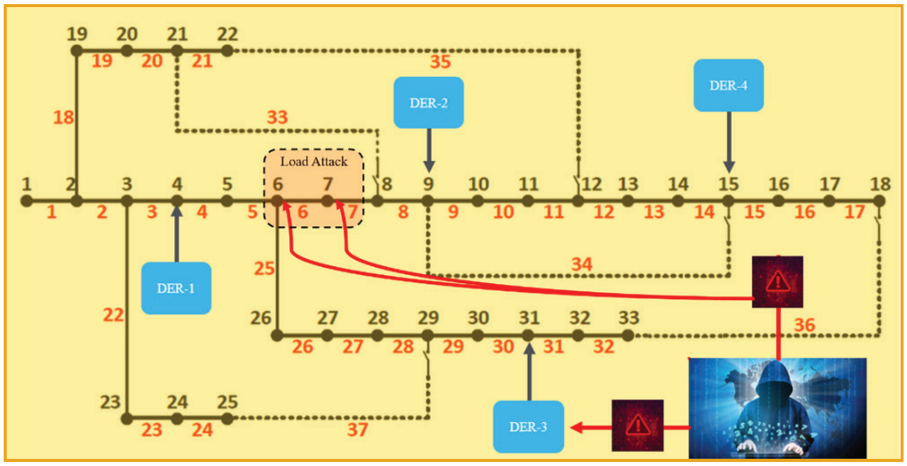
Grid Defense Against Cyberattack

The use of high-performance smart inverters in a power distribution system to change direct current to alternating current is essential to the integration into the electric grid of distributed renewable energy resources (DERs), which generate DC electricity. But while the smart inverter capabilities of DERs makes the grid more reliable, it also exposes its vulnerabilities to activities by hackers by allowing them to enter the grid at the point where the renewable resources are being generated—for example, the homes of people with solar energy systems. To strengthen the grid against these attacks, Eversource Energy Center researchers have developed a defense approach based on deep reinforcement learning (DRL).

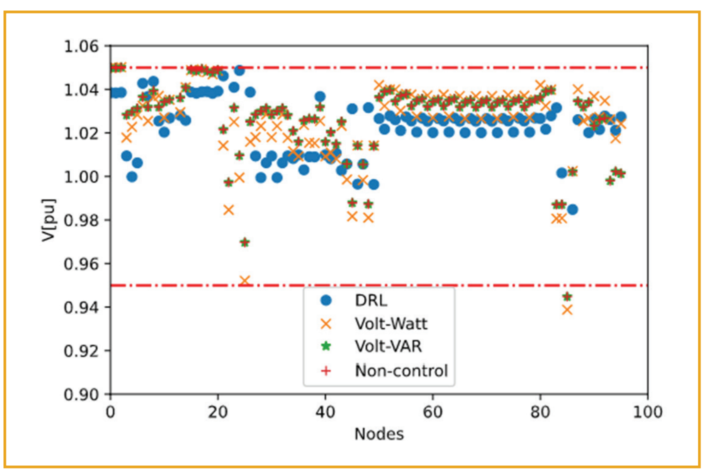
***Deep reinforcement learning** is a subfield of machine learning in which computers learn from their actions by trial and error, much the same way as people learn from experience.*

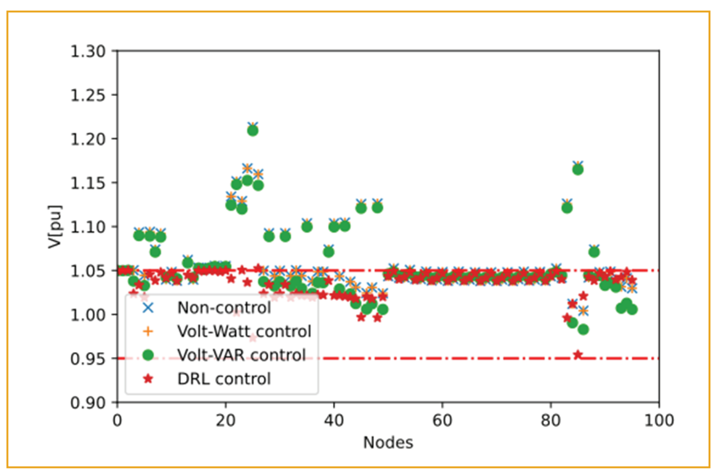
When the distribution system is under attack, the compromised parts of it need to be isolated and shut down until the attack can be stopped and the damage repaired. This means that customers lose power. To minimize the parts of the system that need to be shut down, we reformulated the defense problem by extending the original method for controlling DERs, which could only address continuous actions, to handle single actions as well. Comparisons between our approach and other control approaches showed that our method could achieve better voltage regulation and reduce power losses in the presence of cyberattacks.

We also evaluated the effectiveness of the proposed approach in defending against cyberattacks while the attacks are taking place. Tests of the performance of the different control methods found that, among all of them, our DRL-based approach was able to regulate the voltage most successfully with the least power loss.



Modified IEEE 33-node system for testing attacks. Through trial and error, we found that attacking nodes 6 and 7 at the same time was most likely to cause voltage violations, so we used these two nodes for simulating different types of attack scenarios. We then tested the performance of each method using these targeted nodes.





Voltage regulation performance comparison results under cyberattack. The Volt-Watt and Volt-VAR approaches had low-voltage violation issues, and the power loss was 10 percent higher than the proposed DRL-based approach. While its power loss results were better, a method based on multi-party computation (MPC) had some issues with high-voltage violation. Our proposed method was able to regulate the voltage within security limits and had the least power losses among all approaches.

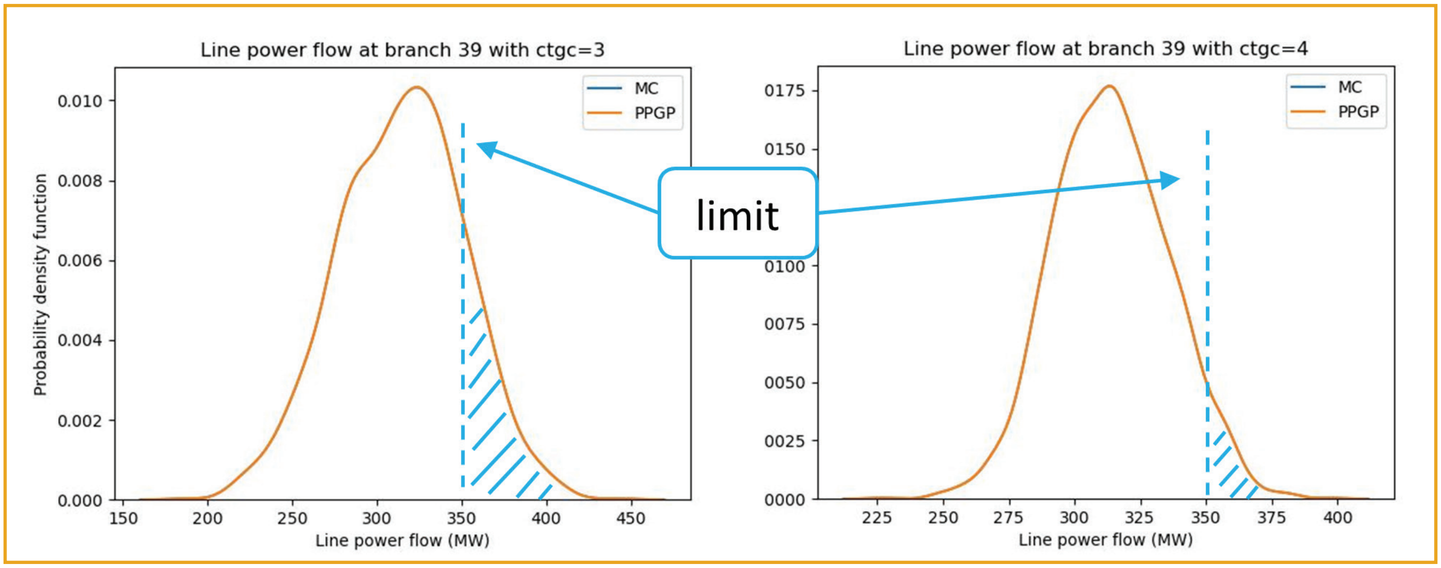
How Much Risk? Predicting Overloads from DERs

The increased integration of renewable energy, such as solar and wind generation, into the power grid is bringing new challenges to utilities. One of these is the overloading risk resulting from the uncertainty of the power flow from these resources under differing conditions. Researchers at the Eversource Energy Center are working to create a method for evaluating this risk by considering both the uncertainty of renewable energy resources and a wide range of power system contingencies that may occur. We will be analyzing more than 4,000 scenarios, including generation and line outages, to identify 100 critical scenarios for predicting the risk of overloads a day before they happen.

Traditional contingency analysis relies solely on deterministic results—that is, it predicts something will happen but not the likelihood it will happen—and does not consider the impacts of uncertain resources. But since renewable generations have correlations with contingencies, their random effects on power systems must be taken into account. The variable power flow from intermittent wind power, for instance, may exceed a line's limit and lead to overloads. This particular problem is complicated by the large number of transmission line branches and scenarios that need to be assessed.

To address this challenge, we have proposed a parallel partial Gaussian process (PPGP) to analyze the probabilities associated with system risks. PPGP is an emulation process, specifically designed to resolve the difficulty of having massive numbers of outputs, that quantifies overload risk. The main idea of PPGP is to share correlated parameters among the Gaussian process predictions under the assumption that line power flows in the same system are correlated.

This method offers detailed and comprehensive information on the risk of overloads due to uncertain renewable energy resources for each line and contingency scenario. By quantifying overload risk, utilities can estimate expected losses and make informed decisions about operations and controls.



Line power flow distribution under different contingencies. The graphs provide an example result of an analysis conducted in the IEEE 39-bus system under the condition that loads are uncertain. As can be observed, the uncertainty of loads and type of contingency together influence the eventual line power flow distribution. Assuming the thermal limit of this line is 350 MW, PPGP can efficiently and accurately assess the probability or risk of overloading due to uncertain loads and DERs for different contingencies.

Forecasting Hourly Energy Demand

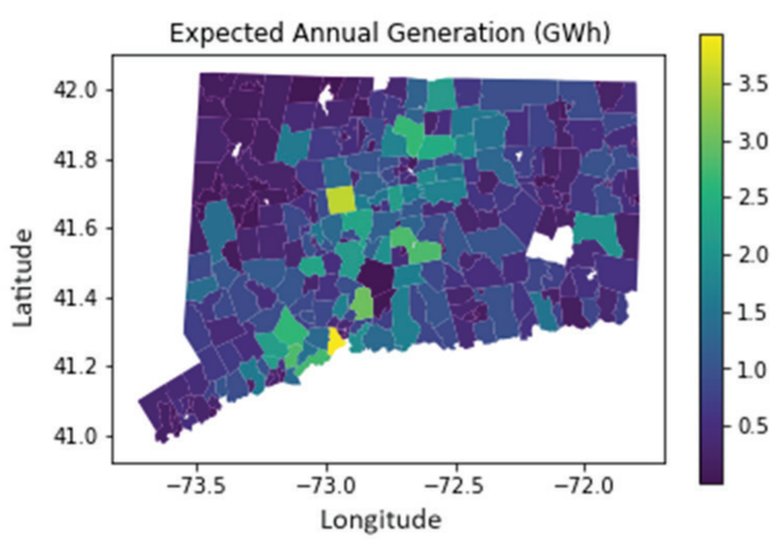
We are in the beginning stages of a clean energy revolution. Many consumers are considering purchasing new electric or hybrid vehicles, installing solar panels on their roofs, and choosing electrified equipment over fossil fuels for lawn mowers, snow blowers, and stoves. In the face of this revolution, along with a changing climate and other factors, how do we know what New England's energy needs are today? What will they be tomorrow and ten years from now?

Researchers at the Eversource Energy Center are working to understand the present relationship between weather and energy and then to model how energy will be used in the future as the climate and technology change.

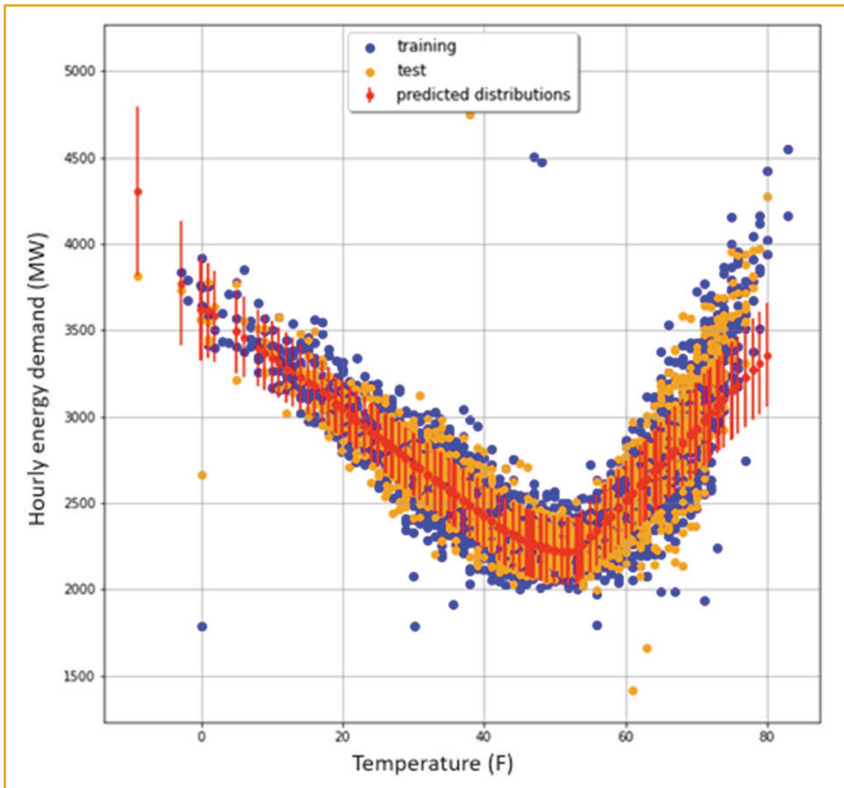
The ongoing shifts in energy use patterns are not being driven by the weather alone. The expansion of commercial and residential rooftop solar installations, for example, has altered the pattern of energy demand during the day. When the sun shines, the photovoltaic (PV) array hums, and net energy usage actually decreases around lunchtime before spiking at dinnertime.

While we have a good understanding of what weather actually occurs at a very local level, forecasting it throughout the day is more uncertain, which makes it difficult to predict energy demand in a way that's relevant to the use of clean energy technologies. The demand prediction model we are developing is trained on "gold standard" historical data to predict the energy demand over time increments that range from very small to quite long. In other words, if we want to predict energy demand for the next hour, day, week, month, or decade, we simply feed our machine learning model a weather forecast. By using different weather forecasts or climate projections, we can create an "ensemble" of possible outcomes and speak about how likely certain energy demand scenarios are to occur.

This innovative model shows the current relationship among weather, technology, and energy demand. Having explored what's happening today, we can now prepare datasets that model possible scenarios of technology adoption—rooftop solar, electric vehicles, and so on—along with climate scenarios to model what New England's energy demands will be in the future. Our hope is that our tool can be used by grid operators to supply enough power to the region efficiently.



Predicted annual power generation from rooftop solar installations in Connecticut (through 2018). The darker colors show where the most installations have occurred.



Results from an early version of the demand prediction model. The blue dots are actual observations, the orange dots are predictions, the red dots are the average energy demand, and the red bars are the standard deviation. Note how the bars get bigger with greater uncertainty.

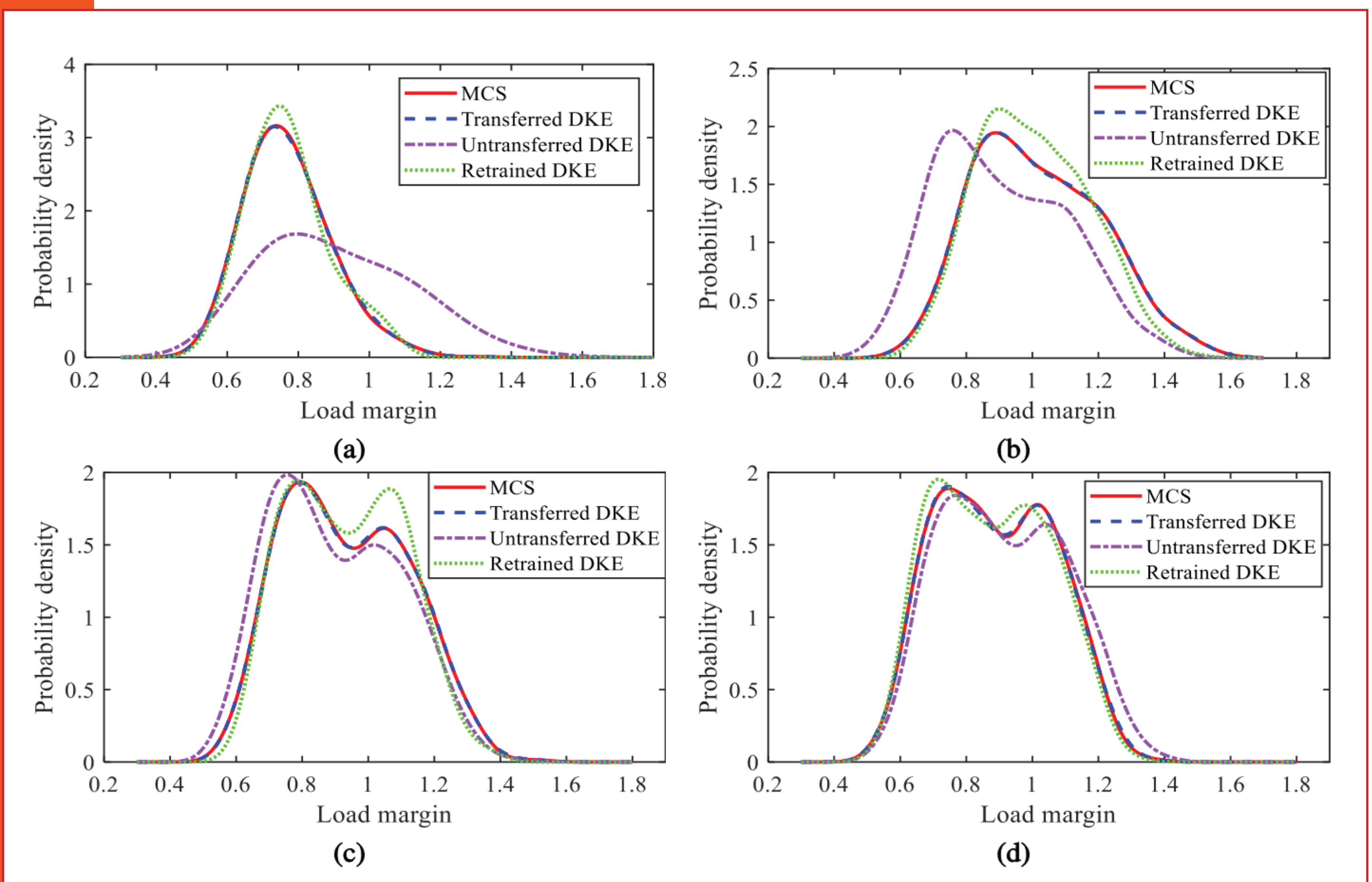
RENEWABLE ENERGY

The Eversource Energy Center continues its development of exciting and innovative technologies to harness the wind, the sun, and any other innovative renewable energy resources.

Adding Certainty to Renewable Generations

An ongoing challenge presented by the integration of renewable energy resources into distribution systems is the random fluctuations in power generation that renewables introduce into the electric grid. This challenge has increased more than ever utilities' need to diagnose accurately the state of the grid. If not addressed appropriately, the fluctuations may lead to such problems as static voltage stability (or load margin), which refers to the capability to maintain stable voltage after a small disturbance. Since the sequence of events that accompanies instability can cause the voltage to collapse throughout the power system, it is vital to assess load margin in the face of the strong uncertainties from renewable generations.

Researchers at the Eversource Energy Center have been working to enhance utilities' ability to determine the likelihood that static voltage stability will occur. Our goal has been to advance the existing machine learning model for probabilistic load margin assessment (PLMA), which can address single fault contingencies, so it can handle changes in the topology (or configuration) of the system, as well. The PLMA we have developed is a probabilistic transferable deep kernel emulator (DKE) machine learning model that can reveal the hidden relationship between load margin and uncertain sources, like solar and wind generations and loads. With this method, we can efficiently predict the likely distribution of load margin, quantify system stability, and quickly update the model accurately when the topology changes by using only hundreds—rather than millions—of samples of data. When implemented, the PLMA will help utilities quantify the stability of their distribution systems, allowing them to address any problems that occur and remaining up to date as the system topology continues to change with the accelerating expansion of renewable energy.



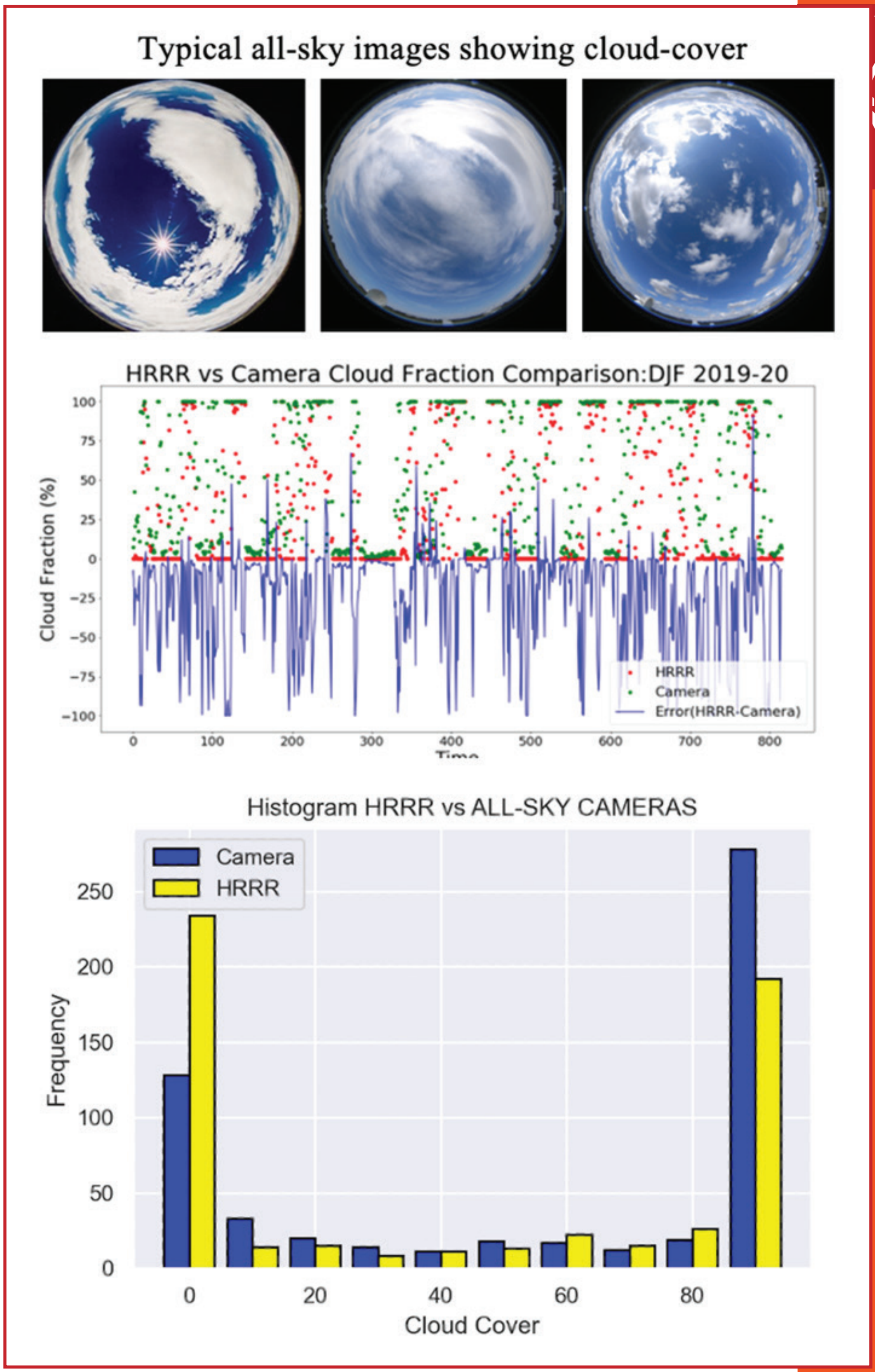
Load margin probability density prediction after transfer learning under various topology scenarios.

Short-Range PV Forecasting with Sky Imagers

An obvious challenge to the wide-scale integration of photovoltaic (PV) technologies into the electric grid is that the sun isn't always shining. To maintain the stability of the grid as solar energy ebbs and flows with the constant transitions among clear sky, partially cloudy sky, and overcast, utilities need to be able to forecast the fluctuations. At the Eversource Energy Center, researchers are using sky imaging to improve our ability to make predictions about solar energy generation so these changes can be anticipated with greater frequency and over closer distances.

Sky imagers—ground-based cameras that take pictures of the sky at regular intervals—provide an unprecedent amount of information about clouds and atmospheric composition. With higher spatial and temporal resolution than satellite images, the photos they take offer grid operators and PV plant operators the promise of forecasts more accurate than those satellite technology or numerical models can provide.

Solar and PV forecast products derived from numerical weather predictions alone have systematic errors, also known as bias, that must be reduced for the forecasts to be useful to power grid operators. Our research activities have included implementing and comparing bias correction techniques. We can, for example, use camera data to remove biases in the percentage of cloud cover inherent to numerical weather predictions, applying a physical formula to convert the fraction of cloud cover into a measurement of solar radiation at the surface and then into PV power production. Our bias-corrected strategy results in significantly more accurate, and more local, forecasts than those produced by earlier methods. The technique will be used to improve forecasts on major PV farms in the Connecticut area.



Top: Examples of the all-sky images that are collected every five minutes. Middle: A comparison of cloud fraction predicted by the operational numerical weather forecast model HRRR (red dots) with that measured by the camera (green dots). The blue line represents the difference between the two—namely, the prediction error. Note that the error values tend to be negative, implying that the forecast model is prone to predict more clear skies than actually occur. Bottom: The histogram of cases for the figure in the middle and for the period December 2019 through February 2020. The histogram shows that for Cloud Cover = 0 (clear skies) the HRRR predicts many more cases than the camera observes. This is not surprising, because the spatial resolution of the model is not high enough to capture clouds that are often tiny. The other end of the histogram shows fewer cases of overcast conditions than observed by the camera.

Listening Beneath the Sea (and Above the Surface): An Annual Update

The prototype Passive Acoustic Listener (PAL) and Sofar's Spotter buoy together comprise a real-time transmitter system that will support offshore wind energy projects by monitoring underwater and surface coastal, marine, and offshore environmental conditions. The underwater acoustic sensor in the PAL and the surface multi-sensor Spotter have new designs this year, developed in an ongoing collaboration between Sofar and the Eversource Energy Center. The new PAL has improved electric circuitry and robust battery housing, while the new Spotter can measure more marine variables than the previous design.

The novelty of this coupled hybrid system is the combination of a low-cost, state-of-the-art passive acoustic sensor that captures signals over a wide range of underwater frequencies with PV-powered surface sensors that measure oceanographic variables while providing near-real-time data processing and transmission. The system is flexible in terms of how and where it can be deployed, and its low power consumption and maintenance needs allow for lengthy field trials in the ocean. The redesign has addressed several challenges, including the potential entanglement of marine animals in the system's mooring line.

__Offshore wind energy__ is generated by turbines that have fixed foundations in relatively shallow waters or float on platforms where the water is deeper. Several wind farms will be installed in the Atlantic Ocean to the South of Cape Cod in the next few years. They will provide electricity to cities in New England, using systems of cables buried in the seafloor to transmit electricity to the grid.

At this writing, technical issues in the transmission of the data from the PAL to the Spotter have put its deployment on hold. Expectations are high, however, that this hurdle will soon be resolved. In total, three systems have been built, and they are expected to be deployed in the fall of 2023.

The new design of the Passive Acoustic Listener (PAL) showing the electronics (left) and the hydrophone sensor (right). The acoustic frequencies collected by the hydrophone are processed for signal classification for whale and ship detection and marine weather systems passing over the PAL.

The Spotter and the Smart Mooring. The data collected by the PAL will be transmitted to the Spotter through the Smart Mooring.

EEC INITIATIVES

With its pioneering certification program in grid modernization and its targeted support for the educational and research efforts of underrepresented and minority (URM) students at the University of Connecticut, the Eversource Energy Center continues to prepare the expert, diverse workforce so essential to building the grid of the future.

Grid Modernization Certificate Program Update

The Grid Modernization Certificate Program, offered to early-career engineers by the Eversource Energy Center at the University of Connecticut's College of Engineering, has continued to grow since the graduation of its first cohort of seven students in Spring 2022, which comprised one graduate from Eversource Energy, five from Avangrid, and one from Enercon. As the Fall 2022 semester began, four more students from Eversource began the program, along with one from United Illuminated (UI) and one from PSEG, and the academic year culminated in Spring 2023 with the graduation of a second cohort of students, including two professionals from Avangrid, seven from Eversource, and one from PSEG Long Island.

Students in the Grid Modernization Certificate Program complete a rigorous 12-credit curriculum. It includes courses in Predictive Analytics, which trains them in end-to-end processing, analytics, and interpretation of modern power grid data; Microgrids, which provides the fundamentals of control techniques, design, and operation of microgrids; Energy Management Systems, which provides operation, control, and management of energy resources in smart distribution grids; and Communication Systems, which introduces the students to smart grid architectures, applications, requirements, technical challenges, and enhancements in communication systems.

In the past year, all four of these courses were revised and updated to provide students with state-of-the-art technology and applications. This ensures the program will continue to meet and exceed the needs of the utility industry for personnel trained to meet the challenges of the grid of the future.

Diversity and Inclusion Initiative Update

As of this writing, the Eversource Energy Center's Diversity and Inclusion Initiative has funded 13 URM students, and it will continue to fund students in the coming semesters. To expand the initiative's reach, the Center has established connections with other groups throughout the university, such as the Institute for Student Success, the Diversity and Inclusion Office, and UConn's regional campuses. Eventually, it will go beyond UConn to include students at other universities throughout Connecticut, as well as at local high schools.

With our first cohort of students graduated and all of our interns having received job offers in their respective fields, we can say that, to date, this program has been a success.

CENTER PRODUCTIVITY

Patents

Anagnostou, E. N., D. Wanik, B. Hartman, and J. He: University of Connecticut, 2021. Systems and Methods for Outage Prediction. U.S. Patent 11,144,835.

Shen, X., E. N. Anagnostou, and Q. Yang: System and Methods to Produce High Resolution Flood Maps in Near Real Time. Provisional U.S. Patent.

Watson, P., D. Cerrai, and E. N. Anagnostou: System and Method for Damage Assessment and Restoration. U.S. Application No. 16/683,701.

Watson, P., W. Hughes, W. Taylor, E. Anagnostou, D. Cerrai, W. Zhang, and A. Bagtzoglou: Systems and Methods for Infrastructure Resilience Estimation and Assessment. Nonprovisional U.S. Patent No. 209670-9060-US01.

Publications

Abdollah, Y., Z. Wang, S. A. Dorado-Rojas, and P. Mandal. 2023. "Quantification of DERs Penetration Level in Microgrids: A Quest for Enhancing Short-Term Power Grid Resilience." 2023 IEEE PES General Meeting.

Abdollah, Y., Z. Wang, P. Siano, and F. Wang. 2023. "A Pathway to Mitigate Climate Change Impacts on Energy Communities: Decarbonization-Based Cost-Effective Grid Resilience Enhancement." 2023 IEEE PES General Meeting.

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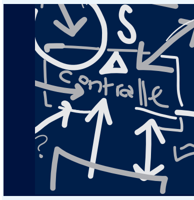

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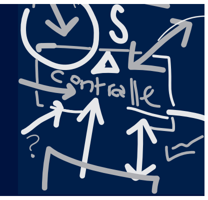

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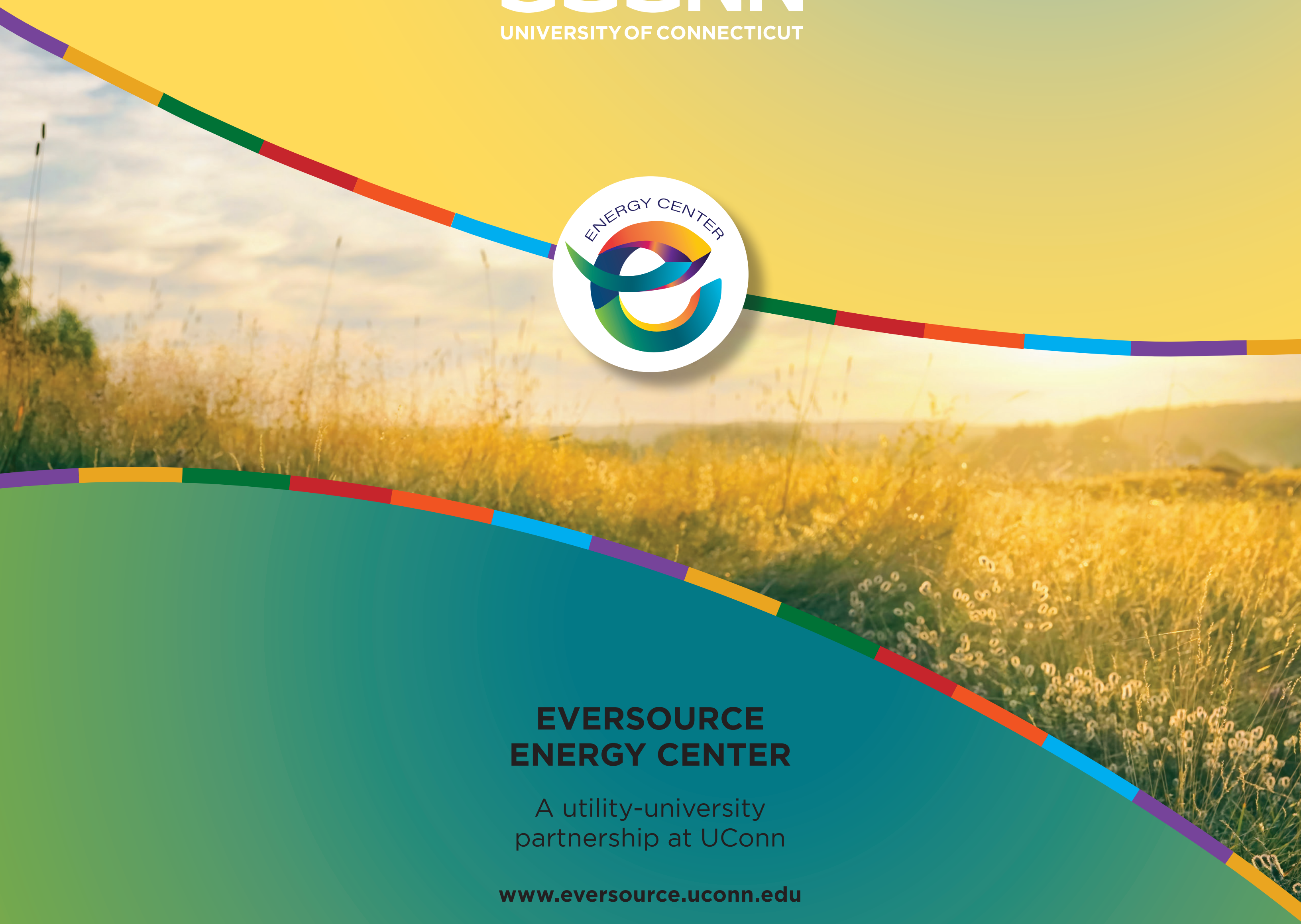

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