Transdisciplinary Approaches for Modelling the Economy in a Changing Climate: The Case of New England and "Sandy 2030"

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Abstract

As power systems transition away from fossil fuels, renewable energy is playing an increasingly central role in electricity generation. However, less is known about how renewable-dominated grids respond to extreme weather events. This study explores the potential impacts of a hurricane, akin to Hurricane Sandy, on New England's future power grid, which is expected to experience a higher penetration of renewable energy, particularly wind power. Our findings reveal that during the hurricane, substantial increases in wind energy generation, especially with widespread offshore wind deployment, can result in significant curtailment and periods of volatile energy prices. Specifically, as a storm passes over a large wind farm, energy production initially rises gradually, then abruptly drops from maximum output to zero, spikes back to maximum, and eventually declines as the storm moves away. This generation volatility can present critical challenges to the reliability and resilience of the power system and market stability. These results underscore the urgent need for policies that strengthen energy storage capacity and transmission connections across regions to ensure grid stability, especially during extreme weather conditions.

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Introduction

The U.S. energy system is undergoing a major transformation, with increasing reliance on renewable energy sources, particularly wind and solar, to decarbonize electricity generation while electrifying substantial areas of the economy (Graziano et al., 2020). By 2030, renewable energy penetration in New England is expected to increase two- to six-fold for variable sources and 3% to 10% for controllable sources compared to 2018 levels. By 2040, renewable energy is expected to contribute 56% of total energy generation, marking a more than 500% increase from 2021 levels (Boughan 2021). While extensive research examines how decarbonization affects electricity generation and the transition to renewable-based power systems (Michaelidis, 2023), less is known about how these evolving energy systems will respond to the intensifying risks posed by extreme weather.

Understanding the interaction between extreme weather and transitioning energy grids is critical, as extreme weather events—including hurricanes, flooding, heatwaves, droughts, and wildfires—are becoming more frequent and severe across the globe (Pechony and Shindell 2010; Rahmstorf and Coumou 2011; Dai 2013; Hirabayashi et al. 2013; Prein et al. 2017). These events cause widespread disruptions, including power outages, infrastructure damage, and economic losses, with significant consequences for energy systems (Clarke et al. 2022). Since 1980, the U.S. has experienced 396 extreme events with damages of at least US$1 billion each, amounting to total economic losses exceeding US$2.78 trillion (NCEI 2023). The frequency and cost of these events have risen sharply, from an annual average of 8.8 events per year between 1980 and 2023 to 20.4 events annually in the past five years (2019-2023), and from US$21.9 billion/year in 1980-1989 to US$99.3 billion in 2010-2019 (NCEI 2023). As renewable integration accelerates, understanding how extreme events impact evolving energy grids is essential for ensuring system stability and resilience.

In this study we evaluated the potential impact of Hurricane Sandy – one of the most severe extreme weather events to occur in New England in the 21st century – on the region's future power system. We examined short-term energy generation, demand, and pricing dynamics under 2030 projections. This research significantly enhances our understanding of the resilience of energy systems undergoing low carbon transition in several ways. First, it addresses a significant knowledge gap in how extreme weather events affect power grids heavily reliant on renewable energy sources (RES). While most of the past research focused on power systems operating under renewable energy benchmarks, the effects of extreme events on transitioning energy grids remain uncertain. Our study fills this gap by considering two reference energy projections and providing a regional level analysis for the New England (NE) energy generation and market under the control of the Independent System Operator of New England (ISO-NE) during an extreme weather event. This analysis provides critical insights into market dynamics as electric grids worldwide are projected to transition from fossil-fuel dependence to renewable energy in the coming decades.

In projecting how such energy systems perform under extreme events, we consider Hurricane Sandy, one of the most devastating hurricanes in the NCEI database, which impacted the Northeastern U.S. in 2012. Using a unit commitment (UC) and economic dispatch (ED) model, we

incorporate weather-driven renewable energy generation time series to balance generation and demand while minimizing costs. Our analysis focuses on Connecticut (CT), one of the hardest hit states, where almost half the residents experienced outages lasting up to 9 days (Wanik et al. 2018). This focus is essential given that RES generation is inherently variable, depending on time of day, location, and weather conditions, including wind speed, precipitation, solar irradiance, and cloud cover, which can significantly fluctuate during extreme events (Engeland et al. 2017). Further, the complementary relationship between photovoltaic (PV) and wind energy sources may be disrupted during such events, as both sources could experience extended periods of reduced solar radiation and wind speeds that exceed turbine cut-off levels (Jacobson 2021; Jacobson et al. 2022; François et al. 2022). Thus, understanding how these factors interact during such large-scale events is essential for evaluating the market dynamics and performance of the energy market as it integrates high levels of RES into a grid that is still evolving (e.g., François et al. 2017; Akdemir et al. 2025).

Second, this study sheds new light on the resilience of energy systems with increased penetration of RES. Historically, energy systems have prioritized reliability—ensuring continuous electricity supply—over resilience, which involves hardening infrastructure to withstand extreme weather, modifying operational strategies, and addressing both social and technical vulnerabilities (Montoya-Rincon et al. 2023; Panteli 2017). The concept of resilience has expanded from ecological studies to other fields, including social, economic, infrastructural, and institutional contexts (Kwok et al. 2016). Power system resilience, defined as the ability to anticipate and recover from high-impact, low-probability events, is a relatively new concept (Panteli et al. 2017; Sanstad et al. 2020) and requires comprehensive planning across multiple areas (Siddiqi et al. 2013; Bagheri et al. 2019; Bennett et al. 2021). However, current plans often rely on historical event impacts on past or current system configurations (Montoya-Rincon et al. 2023), which may not fully account for future extreme events. By simulating weather conditions, energy generation, and price during Hurricane Sandy, our study addresses this gap by identifying criticalities and providing valuable insights into how transitioning energy grids can be better prepared for extreme weather amidst increasing renewable energy integration. Understanding these dynamics is crucial as decarbonization accelerates and public utilities and grid operators seek viable pathways to protect the system's vulnerabilities against extreme events while ensuring an uninterrupted electricity supply, despite the inherent variability of RES.

Our results indicate that hurricanes can induce sharp fluctuations in wind energy generation, particularly in scenarios with extensive offshore wind deployment. As a storm progresses, wind farm output exhibits abrupt swings between peak production and curtailment, leading to significant price volatility. These rapid shifts in generation pose challenges for maintaining system stability and highlight the need for strategies to enhance grid resilience in renewable-dominated power systems.

Hurricane Sandy

Hurricane Sandy, also referred to as Sandy, was one of the most devastating storms of the 21st century thus far. Sandy formed on 22 October 2012 in the Caribbean Sea, and after a first landfall in Jamaica on 24 October and a second one in Cuba on 25 October, made a third and final landfall on the New Jersey coast during the evening of 29 October 2012 (Figure 1) (Bryan 2012). Because

of the impressive extent of the storm, approximately three times larger than a typical hurricane, with a diameter of tropical storm force winds exceeding 1,200 km (Zhai 2014), it was dubbed a "Superstorm." Due to its size, Sandy's impact was felt hundreds of miles away from the landfall location and caused power outages affecting 8 million houses and businesses across 21 states as far south as North Carolina, west as Ohio, and north as Maine (Henry and Ramirez-Marquez 2016). The impacts left by Sandy also affected the economy of the entire New England region (Strauss et al. 2021). The widespread impacts of Sandy perturbed the stability of the energy price and provided a unique case for studying the potential impacts of future events of similar intensity. The region is not new to severe damage from extreme weather and power losses (Gallaher et al. 2021) and has made significant effort to increase the resilience of the grid to severe weather events to limit the social and economic damage they produce (Cerrai et al. 2019, Taylor et al. 2023).

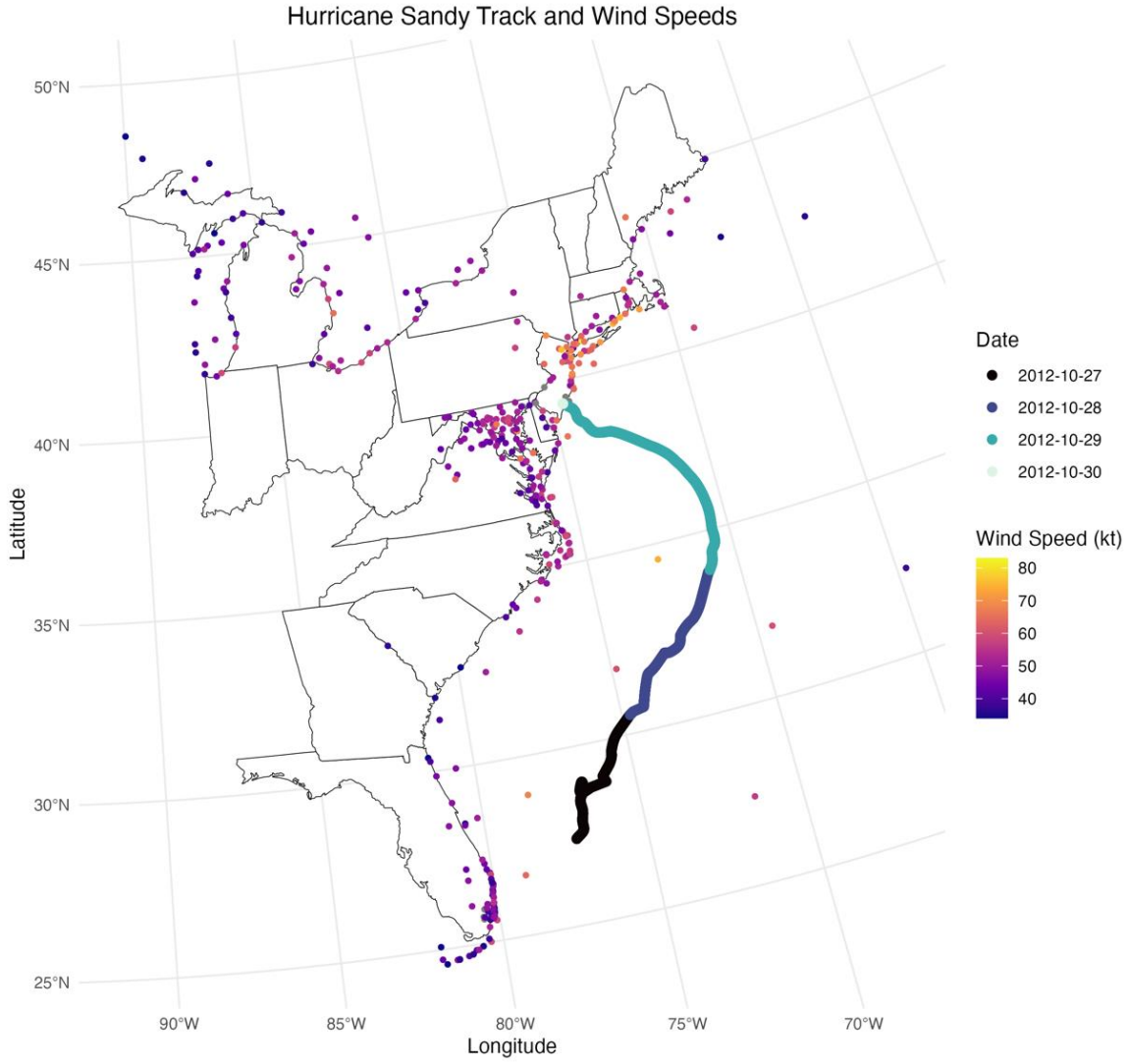


Figure 1: Surface wind gust observations at selected locations during Hurricane Sandy. Figure created by the authors by combining wind observations from Blake et al. (2013) with storm track data from NOAA (2013).

Observed impacts of Hurricane Sandy in 2012

The impacts of hurricane Sandy on the energy generation, demand and price in NE are illustrated in Figure 2. Since at the time almost the entirety of the generation was produced by traditional sources, the generation mix during the storm stayed relatively stable, with nuclear and natural gas power plants contributing the most to energy generation, whereas PV power remained negligible. Wind power saw a slight increase in its share of generation leading up to the peak of the storm around October 29, 2012. Electricity demand, however, was severely affected, dropping to 75% of its normal value due to power outages, during the evening of October 29th (highlighted by the red shaded region) and the following night, with a slow recovery over the following week. It is worth noting the rare instance of a lack of a second electricity demand peak during the afternoon of October 29th, reflecting the widespread outages that occurred during that period. Moreover, the first peak is higher than usual, due to preparedness activities made in advance of the storm, such as charging personal devices, cooking, and increasing home heating.

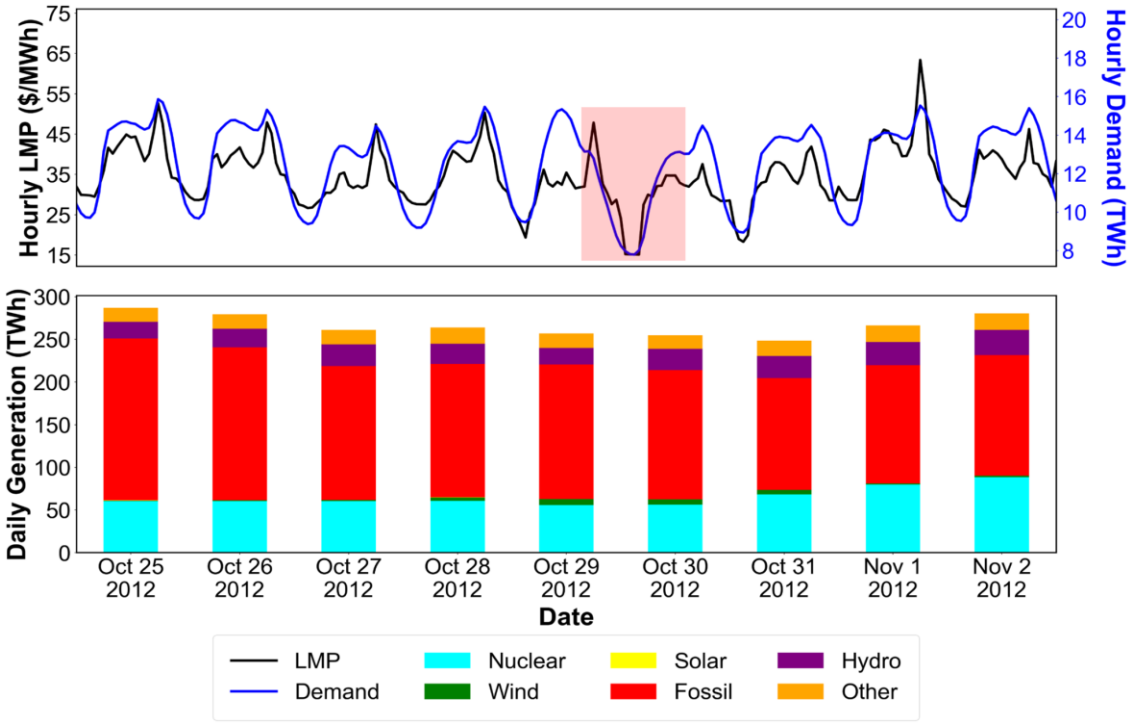


Figure 2: ISO-NE hourly demand, day ahead LMP and daily generation mix during Hurricane Sandy in 2012 (ISO New England, 2021a; ISO New England, 2021b).

Figure 2 also illustrates that locational marginal prices (LMPs) generally follow the same trend as demand, with two exceptions: (i) On the day of the storm (October 29th), LMPs rise dramatically as generation collapses and demand decrease slowly (because of outages), and (ii) when the demand almost recovers on November 1st, there is a peak in LMP caused by a change in the electricity mix; this change in electricity generation results from the storm moving away from the region, leading to a decrease in wind power generation and an increase in electricity demand as outages are resolved.

Simulated Impacts of Hurricane Sandy in 2030

To understand the potential effects of such extreme weather events on the electricity system at both local (CT) and regional (NE) scales, we simulated how Hurricane Sandy's 2012 weather conditions could impact energy generation in 2030. Our analysis employs a unit commitment (UC) and economic dispatch (ED) model, which incorporates weather-driven renewable energy generation time series, to optimize the scheduling of controllable electric power generators to balance generation and demand—netload after accounting for behind-the-meter (BTM) solar PV contributions—while minimizing costs, as detailed in the Method section. To ensure the reliability of the modeling framework, we validated its ability to reproduce historical grid conditions during 2015–2017 (Akdemir et al. 2022). We used two sets of installed capacity projections: the NREL 2018 Standard Scenarios (Gagnon et al. 2020) and the local projections provided by ISO-NE (Chadalavada 2021). The primary difference between the two scenarios lies in assumptions related to the deployment of renewables. ISO-NE foresees a major role for renewables, especially offshore wind, while anticipating a much smaller contribution from traditional energy sources, particularly natural gas (all types), both in CT and within the ISO-NE region as shown in Figure 5 under the Section *Installed Capacity Projections*.

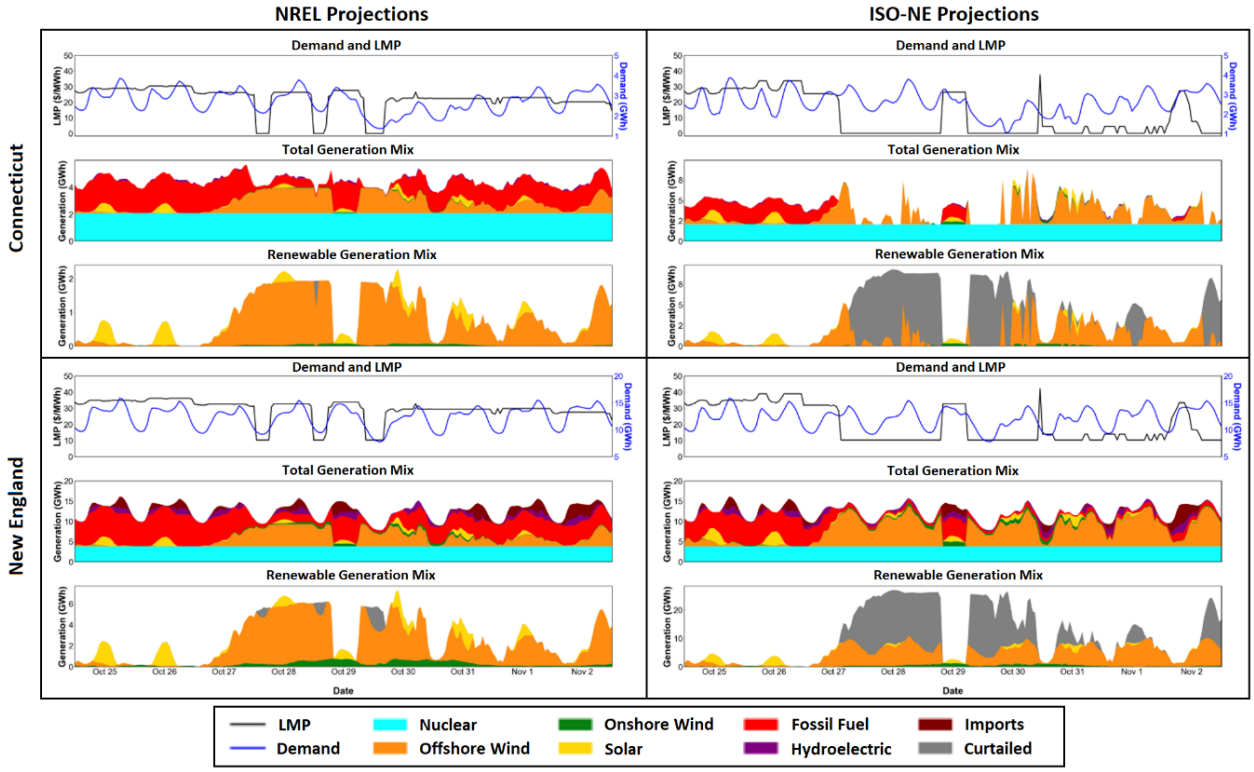


Figure 3: 2030 estimates, based on NREL (left) and ISO-NE (right) projection, for energy demand, LMP, and energy generation for Connecticut (CT) and ISO-NE areas, including curtailment, during the actual conditions of Sandy in 2012.

According to the 2030 NREL simulations (Figure 3 left), both CT and NE could experience substantial energy generation from offshore wind during storm periods (October 27th- October 30th). While PV energy production is reduced during the same period, wind energy significantly increases because of increased wind speeds brought by the approaching storm. Renewable sources do not completely cease operating during the peak of the storm (October 29th) but make

up a very minor portion of the energy generation, particularly when compared to days before or after, due to output reductions linked to safety concerns and curtailment procedures for offshore wind farms. Curtailment is minor under the NREL projection, with only a small amount of renewable energy being cutback, due to low supply-demand imbalance. The NREL demand simulations show fairly uniform amounts throughout the period for both CT and NE with slight decreases in peak demand after the storm peak, particularly in CT; however, during periods of significant wind energy generation before and after the storm, the day ahead hourly LMPs drop over 75% over NE and even more over CT.

The 2030 ISO-NE simulations reveal three major differences compared to the 2030 NREL analysis (Figure 3 right). First, regarding energy generation patterns, in CT, nuclear power constitutes a significant portion of energy generation, with renewable sources, particularly wind, largely fulfilling the remaining energy needs before and after Hurricane Sandy's peak. However, on the peak day of the storm, fossil fuels are required to meet energy demands. Curtailment of renewable energy in CT is notably higher compared to NREL projections due to the much higher availability of offshore wind energy under this more aggressive decarbonization scenario. This higher renewable energy availability has implications on the smaller role played by natural gas plants under the ISO-NE scenario. Across the NE region, energy generation patterns mirror those in CT, although other regions tend to rely more heavily on fossil fuels on average. Second, concerning demand patterns, differences between the 2030 ISO-NE simulations and the 2030 NREL projections are also evident. While overall demand patterns are similar, the ISO-NE simulations show a more pronounced decrease in CT post-storm compared to the NREL projections. Third, in terms of pricing trends, there is an extended period of low LMPs observed for both CT and the NE region before and after the storm's peak. This is primarily due to excess renewable energy generation from wind power, leading to significant curtailment and a decrease in overall prices. Additionally, there are two notable spikes in LMPs for both CT and the NE region, occurring 1.5 and 5 days after the storm peak. These spikes are likely due to the restoration of outages and the subsequent increase in demand.

Discussions and Conclusion

This paper examines the impact of extreme storms on future energy projections, with a specific focus on renewable energy sources. Using Hurricane Sandy – one of the most severe storms to hit the Northeast United States – as a possible storm impact scenario, the study analyzes short-term energy generation, demand, and pricing dynamics under two distinct 2030 energy resource projections: NREL and ISO-NE. The primary difference between these projections is the significantly larger deployment of offshore wind in the ISO-NE with respect to the NREL one.

Our results reveal notable differences in the hurricane's impact between the two projections. The NREL 2030 simulations exhibited significantly less curtailment and lower overall renewable energy generation compared to the ISO-NE simulations, despite similar demand levels. This discrepancy led to divergent pricing dynamics: in the ISO-NE scenario, energy prices in both CT and the NE region were significantly reduced for several days before and after the peak of Hurricane Sandy, whereas the NREL simulations showed only brief periods of significant price reductions.

These findings highlight key challenges and policy implications for grid performance when relying primarily on offshore wind energy during extreme weather events. First, we identify excess energy production in the hours leading up to and following a hurricane's peak, as offshore wind turbines generate more electricity than needed under both ISO-NE and NREL projections. This surplus leads to substantial curtailment and heightened price volatility. Addressing this issue requires policies that enhance energy distribution during peak events, particularly by expanding interregional transmission capacity. Policies like the BIG WIRES Act (Jenkins et al. 2022) could play a crucial role in mitigating production volatility by enabling excess generation to be transmitted to regions with higher demand or available storage.

Second, our findings reveal that current storage capacity is insufficient to maintain grid stability during severe storms. Expanding storage capacity—both behind-the-meter and within the broader system—can significantly improve resilience. Our analysis suggests that storage technologies must sustain the grid for approximately 6–12 hours, aligning with the period when wind turbines are shut down for safety reasons. Notably, this duration matches storage requirements for addressing day/night renewable energy variability, indicating that batteries already planned to sustain the routine peak demand or low generation times under non-storm conditions could also provide critical support during extreme weather disruptions.

Overall, expanding transmission and storage infrastructure is essential not only for integrating renewable energy more effectively (Sepulveda et al. 2021) but also for mitigating price volatility during extreme events. Enhancing these capabilities will be crucial for ensuring grid reliability and resilience in a decarbonized energy system. Additionally, existing low-carbon, dispatchable sources—such as nuclear power plants in ISO-NE and CT—could play a critical role in maintaining a stable baseload, particularly during periods of low renewable generation.

One limitation of this study is that a hurricane like Sandy, occurring under projected 2030 or 2050 atmospheric conditions, would likely exhibit different wind and precipitation patterns. Wanik et al. (2018) suggest that a future Sandy-like storm could result in 20–40% more outages than the historical event, underscoring the need for further research on evolving storm impacts under climate change.

Methods

Unit Commitment/Economic Dispatch Model

We developed a modified version of the existing unit commitment and economic dispatch (UC/ED) model for ISO-NE (Akdemir et al. 2022). The model simulates ISO-NE electricity grid operations during a hurricane under different renewable energy penetration scenarios and assesses relevant impacts in terms of LMP and system risks. The model covers eight load zones in the ISO-NE market, including New Hampshire (NH), Rhode Island (RI), Connecticut (CT), Maine (ME), Vermont (VT), Northeast Massachusetts (NEMA), Southeast Massachusetts (SEMA), and Western/Central Massachusetts (WCMA). These wholesale load zones can exchange electricity both internally through the ISO-NE transmission system and externally through interconnections with adjacent systems. The UC/ED model is written in Python and utilizes mixed-integer linear programming (MILP). Moreover, we used Gurobi solver throughout the simulations. Figure 4 shows the breakdown of ISO-NE wholesale load zones and energy generation sources by type.

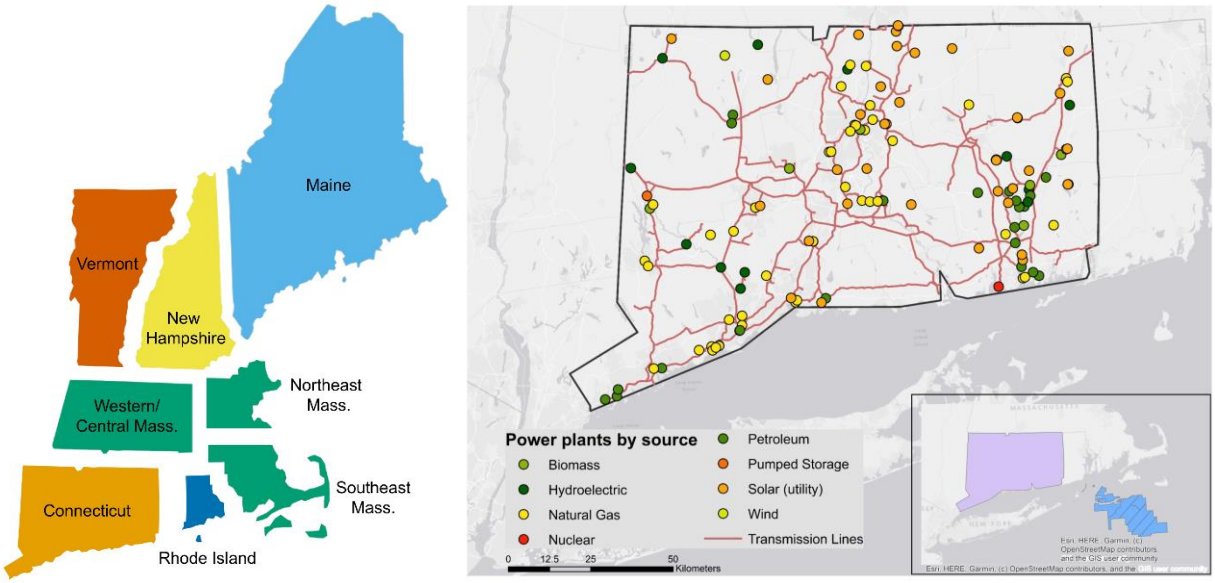


Figure 4: ISO-NE load zones (left) and locations of energy generation sources and transmission connections in Connecticut (right).

The model's target is to minimize the system-wide cost to meet hourly electricity demand and reserves. Numerous constraints on individual generator parameters, zonal energy balance, and transmission line capacities are employed to represent the system more accurately. The main decision variables are binary (on/off) status of the generators and the amount of electricity generated in each generator including renewable energy sources. Although marginal generation cost of renewable energy sources is low, the model can choose to curtail them if needed. Furthermore, model outputs consist of hourly LMPs, hourly generation schedules from each generator, and hourly interchange between zones.

The modeling parameters of thermal generators are gathered from eGRID (EPA 2020). In addition, historical hourly electricity demand and external interchange between October 21, 2012 and November 5, 2012, are fed into the model to represent grid conditions during Hurricane

Sandy (ISO New England, 2021a, 2021c). Detailed information about the UC/ED model can be found in Akdemir et al. 2022.

Installed Capacity Projections

The UC/ED model is fed by historical energy sources installations at the time of Hurricane Sandy (2012) and by future projections (2030) for traditional and renewable energy sources in the New England sub-regions of CT, RI, VT, NH, ME, NEMA, SEMA, and WCMA. The sources included in the model consist of (i) traditional, non-renewable sources (natural gas and oil-gas-steam generators), (ii) nuclear power plants, and (iii) renewable sources (offshore wind, onshore wind, solar photovoltaic, hydroelectric).

We used two sets of projections for the New England area: the NREL 2018 Standard Scenarios (Gagnon et al. 2020), and the local projections provided by the ISO-NE (Chadalavada 2021). Since neither the ISO-NE projections nor the NREL scenarios provided information for all the areas, for all the energy sources, for both 2012 and 2030, data homogenization was performed by relying on the assumptions discussed below.

The NREL database includes target installed capacities for the six New England states, without separation of MA into three load zones (NEMA, SEMA, WCMA), for the period 2010-2050 with a temporal resolution of 2 years. For this research, we collected values for years 2012 and 2030, and we split MA into the three load zones based on future planning. Specifically, since all new offshore wind development is expected to take place in the Atlantic Ocean, south of Martha's Vineyard and Nantucket, we attributed the entire future offshore wind generation to the SEMA region. Similarly, for geographical reasons, we attributed new onshore wind installations to the hilly areas and coastal towns of NEMA (Lamy et al. 2020). For PV and storage, we used ISO-NE's data on hourly Day-Ahead (DA) and Real-Time (RT) energy demand for the eight different load zones to derive proportions for each sub-region of MA. For hydropower, natural gas, coal, and oil-gas-steam, we kept the same proportions for the three Massachusetts subregions as in 2018, and we scaled the generation up based on future statewide projections. The nuclear power plant in SEMA was shut down in 2019; therefore, it is not expected to provide any contribution in 2030 (Holt & Brown 2021).

The ISO-NE scenarios project installed capacities of different energy sources until 2027 for all six New England states. We extended these projections to 2030, by applying the 2027 new installations/decommissioning rates for each energy source to the period from 2028 to 2030. These projections included the categories of wind, solar, other renewables, natural gas/oil, natural gas, demand response-passive, and demand response-active. Since the categories differ between NREL and ISO-NE, the ISO-NE projections were split up with respect to the specific renewable fuel source to match NREL. Specifically, the category "*Wind"* in ISO-NE was split into "*Offshore Wind"* and *"Onshore Wind"*. Moreover, ISO-NE's "Solar" and "Battery" projections were split for the sub-regions of Massachusetts by taking the regional proportions for the currently installed PV systems. The breakdown of the energy generation sources in Connecticut and in the entire New England area for both the ISO-NE and the NREL projections for 2018 and 2030 is shown in Figure 5.



Figure 5: Energy generation mix in CT and NE in 2018 and the projections for 2030 by ISO-NE and NREL. The value in the middle of the plot is the total generation in MW.

Energy Generation Estimation

The Total Energy Generation (TEG), expressed in MWh, through the following equation:

$$TEG = hy * CF * TIC$$

where hy = 8760 hours is the number of hours in a year, CF is the capacity factor for each renewable energy source, and TIC is the total installed capacity for that energy source, expressed in MW. The data obtained on energy resources from ISO-NE and utilized the 2012 Hurricane Sandy event as a base case for scenario generation. In addition, data generated for time series datasets by scaling the ISO-NE base case datasets using projections from the NREL for 2018 and 2030. To distribute the time series data across individual states, we analyzed the installed capacity for each region and calculated the contribution of each state to various renewable energy resources. Later, appropriate scaling capacity factors calculated based on the installed capacity weights of each region to simulate potential future scenarios of energy resource integration for each renewable energy source. To calculate the scaling factor for each region, the weights are defined based on the installed capacity of each region using the following equation:

$$W_i = \frac{C_i}{\sum_j C_j}$$

W_i represents the weight, which is used as the scaling factor for a specific region i. The parameter C_i shows the installed capacity of region i , which demonstrates the overall capacity. The term $\sum_j C_j$ illustrates the total installed capacity across all regions, where j is the index shows to each region. The proportional weight for scaling factor of each region calculated relative to the total installed capacity, which enabled the scaling of time series data and projections for individual regions.

Behind-the-meter and Netload Calculations

Integration of behind-the-meter (BTM) PV into the electric grid has recently expanded and will continue to grow significantly in the future. The variable nature of BTM solar PV energy system integration into the electricity grid is expected to increase the complexity in estimating netload, the balance between supply and demand, and market operations. Correspondingly, netload estimation plays an essential role in BTM solar PV application at the transmission system level and is commonly used in ED and UC problems. BTM solar PV systems describe and use the electricity produced and consumed on-site without passing through the customer electricity meter, so it can deliver and reduce the system loads but cannot participate in the wholesale electricity market. Thus, the system operator does not have complete information on the generator's characteristics or the customer electricity meter data. To avoid multiple counting in the total system load estimation, the system operators consider forward capacity market (FCM), energy only resources (EOR) and generators, and BTM PV. Here, the FCM market refers to PV resources eligible for the FCM and can obtain capacity and supply obligations.

BTM and Netload have been computed and estimated for UC and ED problems in this study. The first step was to calculate daily installed capacity for eight New England wholesale electricity market regions for 2018 and 2030 from published time-series datasets. Then, we subtracted installed capacity belonging to FCM distributed resources, PV, and EOR. BTM resources estimated the total hourly PV contribution for each region associated with the gross daily installed capacity while considering the normalized regional PV profile. To calculate the net load for each wholesale market region, we further subtracted BTM resources because they are not participating in the wholesale market. We later used netload production as input for the UC/ED optimization model.

Software and data availability

All the UC/ED model components are open-source and publicly available. All codes of the model and data used are available under MIT free software license (Akdemir & Kern 2022).

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