Impact of Tropical and Extratropical Cyclones on Future U.S. Offshore Wind Energy

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Series of symposia on impacts of extreme weather on offshore wind energy

What: Over 60 participants, including government officials, regulators, certification bodies, national laboratory researchers, academia, and industry representatives, gathered in person twice for a comprehensive discussion on the impacts of extreme weather on large-scale deployment of offshore wind energy for the U.S. The dialogue focused on addressing modeling challenges, the need for detailed observational data, refining risk assessment methodologies, and understanding the implications of climate change.

When: 01–02 June 2023 and 01 November 2023

Where: Argonne, Illinois, and Boulder, Colorado.

Keywords: Tropical cyclones; Extratropical cyclones; Offshore wind; multiscale numerical modeling; hurricane observations; Climate change.

Wind turbines off the United States (U.S.) coasts, including the Atlantic, Gulf of Mexico, the Caribbean, as well as the eastern Pacific outer continental shelf region, face significant risks from tropical cyclones (TCs) and extratropical cyclones (ETCs). These extreme weather events can cause severe damage through wind gusts, rapid wind direction changes, extreme waves, and heavy precipitation, impacting turbine blades, foundations, power system, and other infrastructure. Historical data on extreme weather loadings is limited, making vulnerability assessments challenging. For instance, 80% of the North Sea turbines needed repairs due to underestimated metocean conditions (Diamond 2012). Despite these severe weather impacts in European offshore wind energy systems, the conditions are not representative of extreme conditions in the U.S. offshore region where damaging hurricanes occasionally strike. On the contrary, Asia's offshore turbines located in the western North Pacific have suffered typhoon damage (Li et al. 2022) though detailed damage assessments and data sharing are scarcely available. To achieve the Biden-Harris administration's goal of 30 GW of offshore wind power by 2030, it is necessary to expand offshore wind development into hurricane-prone U.S. areas and address technical challenges (Musial et al 2023). This expansion requires an understanding of the risks, improvement in system robustness, and building resilience, especially in the face of increasingly frequent major hurricanes in the North Atlantic (Vacchi et al. 2021).

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Current engineering practices adhere to International Electrotechnical Commission (IEC) standards, which, for Tropical reference turbine class (T-class) turbines, mandate an increase in the reference wind speed from 50 m s-1 to 57 m s-1. Additionally, there practices require the application of a turbulent extreme wind speed model with a 50-year return period for the tower and blades, and a 500-year return period for the substructure (e.g., monopile, jacket; 61400-3 IEC 2019). However, such adjustments to the design standards may not fully encompass the complexity of hurricane events or the variety of damaging load cases. To enhance turbine resilience in hurricane-prone regions, a deeper understanding and improved modeling of atmospheric and oceanic conditions are necessary. The Department of Energy (DOE)'s Office of Energy Efficiency and Renewable Energy (EERE) seeks to meet stakeholder needs and research priorities through symposia and collaboration efforts. To this end, two in-person symposia were hosted. The first meeting, held in June 2023 at Argonne National Laboratory, focused on building the conversations between national labs, regulators, academia, and industry (Figure 1). The second meeting, held in November 2023 at National Science Foundation (NSF) National Center for Atmospheric Research (NCAR), followed up with research progress and identified challenges to strengthen the collaboration between industry and scientific communities. Both meetings aim to address modeling, observational, and engineering challenges for large-scale offshore wind energy deployment, guiding EERE's research direction for the coming years.

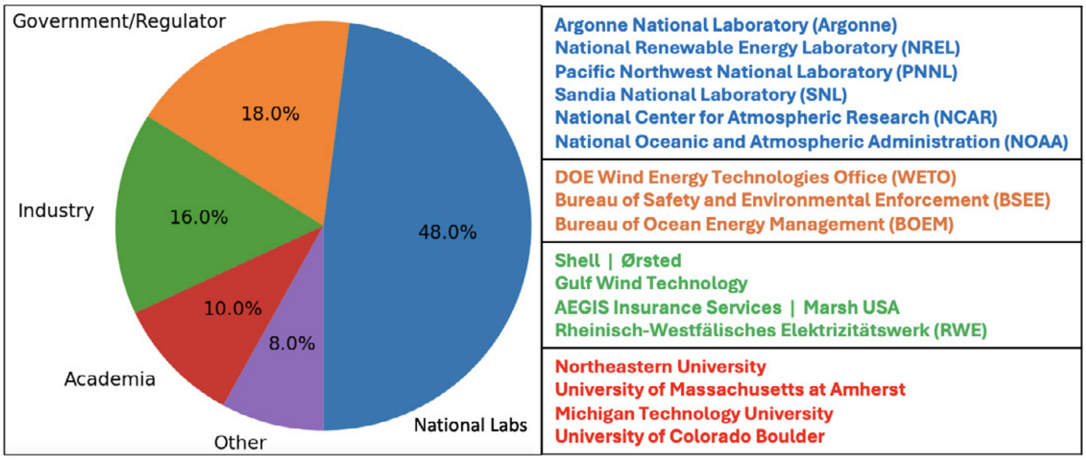

Fig. 1. Distribution of participants by organization type during the two in-person symposia in June and November 2023.

Participants (Fig. 1) shared their latest scientific, regulatory, and industry knowledge on the state-of-the-art and challenges of U.S. offshore wind energy development. Overall, the

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participants of the two symposia agreed that (1) metocean conditions across potential U.S. offshore wind farm sites are highly heterogeneous, requiring detailed understanding for appropriate risk analysis; (2) reducing uncertainties in weather predictions is essential to secure financing and insurance that incentivize development; (3) a balanced approach that combines stabilizing turbine sizes with collaborative efforts to streamline design and research processes is crucial to expedite regulatory approvals and innovation; (4) quantifying air-sea interaction and their effects on extreme events should be prioritized in the DOE EERE's wind program; (5) obtaining new observations in extreme conditions relevant to turbine and plant designs is essential for improving model accuracy, developing new design criteria, evolving standards, and developing risk-based planning and mitigation strategies; (6) significant modeling advances are needed to provide strategic national wind power generation forecasts and detailed flow characteristics including turbulence, for design, operation and future deployment.

Industry Perspectives on Enhancing Offshore Wind Resilience

Industry representatives highlighted the gap between current design practices, which focus on return periods, and stakeholder perceptions often based on hurricane categories. There is a consensus that sophisticated models capturing complex wind, wave, and current interactions are crucial for assessing the entire wind project infrastructure, from turbines to substations. Additionally, the importance of standardized communication was noted to bridge the gap with non-technical stakeholders. Discussions also delved into offshore wind design challenges, particularly the importance of reducing uncertainty by thoroughly understanding environmental loads. Clear insights into the effects of coupled atmospheric and oceanic models and climate change are deemed essential for revising design standards. Given the lengthy development cycle of offshore wind projects, which includes up to six years of testing, design, survey, and review before commercial installation, foresight and planning are crucial. Notably, data from New England and New Jersey suggest that ETCs may pose a greater threat than TCs at lower return levels (<50-yr), while hurricanes dominate at higher return intervals. This necessitates consideration of larger wind speeds in design for areas affected by both cyclone types and the development of tools for site-specific risk analysis. Moreover, the discussion on insurance underscored the inadequacies of current statistical-loss models covering offshore wind assets, with onshore locations often serving as proxies, except for wave height hazard modeling in the Gulf of Mexico. There is also a significant shortfall in

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the specific claims data necessary to support the development of tailored vulnerability curves. Furthermore, the lack of global standards and consistent modeling assumptions for North America restricts the effective use of international data.

State-of-the-art and future needs

Climate- and weather-scale metocean modeling. Current state-of-the-art modeling systems, like the Coupled Ocean-Atmosphere-Wave-Sediment Transport Modeling System (COAWST, Warner et al. 2010), still overlook crucial components such as non-breaking wave-induced ocean mixing and breaking-wave induced sea spray effects on air-sea fluxes which are important for realistically capturing the major TCs (Zhao et al. 2022). Such missing representation of the wave processes may contribute to larger uncertainty alongside the spatial resolution effects on uncertainties. There's a pressing need to deploy fully integrated models that can realistically represent TC and ETC characteristics by considering all critical interactions at high spatial and temporal resolutions, requiring high-performance computing resources like those available at the national laboratories. Techniques like moving nested domains for atmospheric models and regional refined mesh for atmosphere, ocean and wave models should be prioritized to facilitate high-resolution insights into atmospheric convection, ocean eddies and atmospheric-ocean interactions over U.S. current, planned and potential offshore wind farm sites. Moreover, regional coupled models must be driven at the boundary by reanalysis data or Earth system models (ESMs), which often lack the resolution to accurately capture TC/ETC circulations or do not fully incorporate coupling between the atmosphere, ocean, and waves. There is a need for advancements in ESMs, such as the development of regionally refined models covering both the atmosphere and ocean (Tang et al. 2023), and the inclusion of wave models in the DOE's Exascale Energy and Earth System model. These models would account for wave effects on air-sea momentum and heat fluxes, as well as ocean coupling with the wave Stokes drift using an unstructured grid (Brus et al. 2021). These improvements provide more accurate and effective forcing data for mesoscale models, improve the confidence for future climate projections, and better quantify the uncertainties due to model spread and future emission scenarios (Hawkins and Sutton 2009). The discussion also emphasizes the significance of considering environmental and social impacts, as well as safety issues, for the success of offshore wind projects. These factors are highly location-dependent, influenced by variables such as different marine life, marine growth, and the presence of various fisheries industries. Additionally, collaboration with

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biological scientists and fishermen for monitoring and data collection is beneficial. This partnership aids both parties in gaining a deeper understanding of the environment and assessing the impacts of offshore wind energy on marine life and the fishing industry.

Turbine-scale metocean modeling. To design hurricane-resilient wind energy systems, the detailed turbulent microscale wind field and ocean wave field within a hurricane at the turbine scale (e.g., of the order of a few meters spatially and a few seconds temporally) must be better understood. To date, turbine-scale models and microscale models have been limited to idealized hurricanes (e.g., Sanchez Gomez et al. 2023) as modeling challenges in simulating historical storms remain. Idealized hurricanes are subject to simplifying assumptions and may not fully represent the extreme wind characteristics of a real hurricane. To this end, a new generation of high-fidelity microscale prediction tools that are coupled to the weather scales to improve fidelity have been developed (Haupt et al. 2023). These new models were created using the best knowledge from the atmospheric and engineering disciplines and can be used to quantify the hurricane wind and wave field at turbine scale. With higher fidelity metocean data, we may conduct extensive turbine load analysis studies for the extreme conditions ranging from most likely events to worst-case scenarios. This would furnish a better understanding of different characteristics of TC impacts on turbine systems/wind plants, such as wave impact by itself or by the combined wave/wind system. The group agreed that to ensure confidence in the findings drawn from these sensitivity experiments, we first need to validate the modeling system by using existing data sources such as dropsonde data in offshore wind lease areas, lidar data over the Gulf of Mexico, and large-eddy simulations of hurricanes (Sanchez Gomez at al. 2023; Oguejiofor et al. 2023). Additionally, machine learning (ML) approaches have been used to downscale coarse resolution (hundreds or dozens of km) to wind farm scale (e.g., Stengel et al. 2020). There is a need to develop ML techniques for extreme weather impacts to offshore wind energy, particularly, by integrating physical principles into the ML methods that will benefit existing modeling tools.

Extreme load analysis and turbine design. Turbine structural design is driven by extreme and fatigue structural loads. Engineering models are routinely used to compute characteristic loads for ultimate strength and fatigue load analysis of the turbine blades, tower, and other

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support structures. While these models provide an industry-standard, aero-hydro-servo-elastic simulation framework for offshore wind turbine load analysis, they remain limited in their ability to capture extreme wind loads, blade aeroelastic instabilities, and combined aerodynamic and hydrodynamic loading. To this end, many engineering modeling frameworks need to be significantly improved through further incorporated physics-based models or data-driven approaches to better capture the turbine response to extreme weather conditions. The group acknowledges the significant value of the open-access International Energy Agency (IEA) 15-Megawatt reference turbine and proposes additional ideas to enhance these designs, making them more useful for studying TC impacts transparently. Specifically, there is a call for tailored IEA 15MW designs that focus on T-class turbines, particularly for use over the Gulf of Mexico. There is also an expressed need for larger turbine designs to investigate their behavior prior to large-scale industry deployment. Moreover, designing the full structure, including the complete substructure in soil, is crucial, considering the significant variation in soil types across different hurricane-prone regions such as the Gulf of Mexico, Northeast, and Southeast. Beyond turbines, both the industry and insurers identify offshore substations as high-risk points. Furthermore, the group highlighted that while high-fidelity engineering modeling tools offer great potential for informing design ideas, their cost remains prohibitive for full design studies. ML approaches are thus being developed to create surrogate models. These models could significantly accelerate simulations and provide valuable insights into the impact of TCs on different turbine designs.

Observation and validation. Atmospheric data collected from aircraft and dropsondes are valuable, but, for Category 3 and above hurricanes it is challenging to obtain any data near the eyewall. Existing National Oceanic and Atmospheric Administration (NOAA) datasets, such as dropsonde and tail Doppler radar data, alongside data from wave tanks and offshore oil and gas platforms, provide crucial insights into wind and wave behaviors during storm events. However, the utilization of these datasets by the wind energy community is still evolving, with significant data-sharing restrictions noted within the industry and large uncertainty of the measurement quality. Shore-based radar systems can also be used for obtaining information on the wind field, however these face issues with attenuation as well as measurements being impacted by large drops. Innovative platforms like sail drones, wavegliders, and instruments on platforms are emerging as valuable tools for capturing wave

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characteristics such as wave height and direction. However, all these measurement capabilities are either temporally and/or spatially limited. Spatially distributed Uncrewed Aircraft System (UAS) and specific systems like those used in NOAA's drone project (Cione et al. 2020) are valuable tools for measuring mean wind profiles, although expendable drones' capability for formation flying and turbulence measurement remains uncertain. Given the large area sampled by satellites, satellite data could also be advantageous, but there are issues sampling through heavy rain and extrapolating surface wind speeds to hub-height. The National Aeronautics and Space Administration (NASA) Cyclone Global Navigation Satellite System is an example of a targeted hurricane mission that provides continuous measurements of the ocean surface winds and can see through heavy rain. The group also discussed the needs for measurements of lightning frequency and intensity, as a large fraction of insurance claims for land-based wind turbines are associated with lightning, even with protective systems in place. Suggestions include expanding instrument systems on buoys for multi-height wind speed and direction measurements, overcoming space and power limitations, and fully exploiting UAS capabilities for detailed wind and turbulence profiles. Additionally, open data sharing among stakeholders is identified as a crucial step forward. The development of highly instrumented testbeds and increased remote sensing capabilities, especially for offshore observations, are essential to improve the accuracy of wind and wave modeling. Matching observational data with turbine load conditions to ensure data availability during critical loading events and fostering collaboration between public and private sectors for data access and utilization, are highlighted as key areas for development.

Risk assessment. Meeting discussions highlighted the complexity of assessing offshore wind turbine damage due to factors like installation failures, grid loss during a storm and inability to actively control the rotor, precipitation-induced leading-edge erosion, lightning and more. Industry participants stressed the importance of reducing uncertainty to lower design and deployment costs. They acknowledged the value of risk assessment frameworks, such as the Risk Analysis Framework for Tropical Cyclones (RAFT, Balaguru et al., 2023), for offering valuable insights when supplied with quality data. Additionally, discussions underscored the importance of a risk framework that simultaneously accounts for grid resilience, environmental impact, and post-storm recovery. The discussion also addressed the limitations of historical data for accurate return period estimations of Atlantic TCs and

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highlighted the use of synthetic downscaling methods to generate extensive databases by considering climate change for better risk assessment. The accuracy of return period estimates under climate change and the importance of ETCs for the Northeast Coast were discussed, alongside the unique challenges and social concerns related to Great Lakes offshore wind energy. Insurance industry perspectives questioned the extent of damage expected from severe storms, noting the predominance of wind-related claims and the unknowns of offshore turbine resilience. There is also a pressing need for enhanced modeling approaches that incorporate more detailed microscale physics and fully consider atmosphere-wave-ocean interactions to capture TC and ETC characteristics accurately. Leveraging ML techniques for faster and more efficient simulations, along with high-resolution data from advanced technologies, is crucial. Additionally, reconciling discrepancies in failure rate estimates and further exploring the impacts of climate change on hurricane risks are essential steps toward informing more resilient offshore wind turbine design and operation strategies. Given the needs of high volume of data for extreme weather risk assessment, ML can be used to blend results from multiple physical models for the development of critical probabilistic forecasts.

Leverage the resource. DOE hosts extensive computing resources and expertise, crucial for advancing wind energy penetration via innovation in both physics-based numerical and data-driven models, including complex atmosphere-ocean-wave interactions and high-fidelity turbine-scale models. These models facilitate probabilistic predictions essential for risk assessment, demanding high-resolution modeling and significant computational power for creating training datasets and evaluating model performance. Further research funding is essential to deepen our understanding of extreme weather impacts on offshore wind energy. This includes efforts to improve system coupling between various Earth system components and spatiotemporal scales, and to conduct climate change risk assessments. It also involves expanding observational data to improve model integration. Government and industry roles must adapt to foster a fully integrated renewable electricity grid, emphasizing the importance of open benchmarking and shared datasets. Effective collaboration and clear role delineation between the private and public sectors are crucial for achieving national renewable energy goals and ensuring efficient progress without duplicative efforts.

Main takeaways

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(1) Models ranging from the Earth system to the wind turbine scale must incorporate atmosphere-ocean-wave interactions to ensure accuracy and relevance.

(2) It is crucial to bridge the gaps in spatial and temporal scales between weather predictions and wind turbine operations.

(3) Enhanced observational capabilities are required to capture vertical profiles under extreme conditions, providing crucial data for model validation and improvement.

(4) Effective risk assessment frameworks, coupled with high-quality data, are essential for identifying and mitigating vulnerabilities in offshore wind turbines.

(5) Collaborations between industry, academia, and government are vital for driving forward the resilience and efficiency of offshore wind energy.

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