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WIND TURBINE GENERATOR IMPACTS TO MARINE VESSEL RADAR

Committee on Wind Turbine Generator Impacts to Marine Vessel Radar

Ocean Studies Board

Division on Earth and Life Studies

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A Consensus Study Report of
The National Academies of
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Preface

Over the past 15 years or so, the impact of wind turbine generator (WTG) interference on radar performance has caught the attention of the U.S. Departments of Defense and Homeland Security, as well as the Federal Aviation Administration, as they strive to ensure the mission effectiveness of their systems. More recently, in January 2021, the Biden Administration issued Executive Order 14008, resulting in a goal of generating 30 gigawatts of offshore wind energy by 2030. The sheer scale of the requisite deployment of WTG farms on the U.S. Outer Continental Shelf (OCS) to meet the objectives for renewable energy holds unique implications for the Maritime Transportation System (MTS), the connection of waterways and ports supporting commerce and recreation.

As marine vessel radars are common tools used by mariners to navigate the MTS, studying the effects of WTGs on radar performance, as well as identifying corresponding mitigating solutions, is an important undertaking for the maritime stakeholder community. The National Academies of Sciences, Engineering, and Medicine convened the Committee on Wind Turbine Generator Impacts to Marine Vessel Radar in 2021 to conduct this study, and this report is a result of that effort.

Marine vessel radars are not presently optimized to operate in a WTG environment. Marine WTGs are very large structures, with towers on the order of several hundred meters and blade lengths exceeding 100 meters. Being heavily composed of steel, the nominal WTG structure has a large radar cross section. Furthermore, many hundreds to thousands of WTGs will be constructed throughout the U.S. OCS. The combination of high radar reflectivity and vast number of WTGs leads to many strong reflected signals entering the radar receiver, further complicated by other factors, such as multipath and range ambiguous returns. In addition, blade motion generates aspect-dependent, Doppler-spread interference. These various effects, left unresolved, combine to complicate navigation decision-making. Certainly, there is a need to collect more data, develop physics-based models, identify key failure mechanisms, and devise mitigating strategies to effectively manage the situation. Such considerations are highlighted in this report, which provides 28 key findings, as well as two specific conclusions and two actionable recommendations to take marine vessel radar into this new era of expansive, offshore, renewable energy.

This report captures the expertise of some of the nation's leading experts in radar modeling, radar design and applications, marine navigation and safety, and WTG engineering. I want to express my deep appreciation to every member of the committee for their time, talent, and commitment to this important task. I am further grateful for their candor and collegiality, which have served to improve the thought process behind this study while also making for an enjoyable endeavor!

The committee is grateful to the Bureau of Ocean Energy Management for its responsiveness to the many questions and requests for information while developing this report. In particular, we thank Jennifer Draher and Arianna Baker for their guidance throughout the study process. The committee is also grateful to the many individuals who played a role in completing this study. The committee held four major events during the course of the study, and would like to extend its sincere thanks to all those from the federal government, research institutions, private industry, and other stakeholder groups who appeared before the full committee, or provided background information and discussed relevant issues.

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Lastly, the committee extends its deepest appreciation to the National Academies' staff for their invaluable support and many contributions to the project. The successful and timely completion of this effort would not have been possible were it not for the superb efforts of study director Dr. Lexa Skrivanek and program assistant Elizabeth Costa. It has been an honor working with this team, and we are most grateful for their guidance and expertise.

Dr. William Melvin, *Chair*
Committee on Wind Turbine Generator Impacts to Marine Vessel Radar

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The committee would especially like to thank the Bureau of Ocean Energy Management (BOEM) staff and contractors for their invaluable assistance in providing background information and responding to information requested by the committee and for their participation in meetings. In particular, the committee thanks Jennifer Draher, Arianna Baker, and Thomas Kilpatrick.

This report was also greatly enhanced by discussions with participants at the committee's four meetings conducted as part of this study. The committee would like to especially acknowledge the efforts of those who gave presentations at these meetings: Jennifer Draher (BOEM Office of Renewable Energy Programs), Arianna Baker (BOEM Office of Renewable Energy Programs), Eric Kunz (Furuno), David Brigada (Massachusetts Institute of Technology Lincoln Laboratory), Russell Colburn (Booz Allen Hamilton), Jeremiah Sheahen (Maritime Institute of Technology and Graduate Studies [MITAGS]), Robert Becker (MITAGS), Elizabeth Kretovic (Ørsted, North America—Marine Affairs), Ed LeBlanc (Ørsted, North America—Marine Affairs), George Detweiler (U.S. Coast Guard), Bill Haynes (Furuno), Brandon Ennis (Sandia National Laboratories), and Tim Acland (Hensoldt UK [formerly Kelvin Hughes]).

This Consensus Study Report was reviewed as a draft by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Clark Gellings, Clark Gellings and Associates, LLC, and R. Keith Michel, Webb Institute. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Summary

This study assesses the impact of wind turbine generators (WTGs) located on the U.S. Outer Continental Shelf (OCS) on marine vessel radar (MVR) and investigates mitigating solutions. The National Academies of Sciences, Engineering, and Medicine (the National Academies) Committee on Wind Turbine Generator Impacts to Marine Vessel Radar drew two major conclusions from its investigations into the issues identified in the statement of task:

Conclusion 1: Wind turbines in the maritime environment affect marine vessel radar in a situation-dependent manner, with the most common impact being a substantial increase in strong, reflected energy cluttering the operator's display, leading to complications in navigation decision-making.

Conclusion 2: Opportunities exist to ameliorate wind turbine generator–induced interference on marine vessel radars using both active and passive means, such as improved radar signal processing and display logic or signature-enhancing reflectors on small vessels to minimize lost contacts.

These conclusions yield two actionable recommendations centered on (1) filling knowledge gaps through data collection, modeling and analysis, and focused research on an improved understanding of WTG characteristics; and (2) pursuing practicable options to mitigate WTG interference on MVRs through enhanced training, use of radar reflectors on small vessels, use of reference buoys, new radar designs optimized for operation in a WTG environment, and WTGs with reduced radar signatures.

OFFSHORE WIND ENERGY DEVELOPMENTS

Offshore wind energy development is poised to expand across the U.S. OCS, thereby transforming the landscape of this dynamic ocean environment and raising concerns for safe navigation within its boundaries. In an effort to meet growing energy demands in a renewable way, and as part of a government-wide approach to address climate change, the Biden Administration issued Executive Order 14008 in January 2021 prioritizing the expansion of U.S. offshore wind energy. This Executive Order highlighted the need for close coordination and collaboration among federal agencies, states, the private sector, and other key stakeholders to sustainably accelerate offshore wind energy development, and directed the Secretary of the Interior to review siting and permitting processes in offshore waters to determine actions needed to increase renewable energy production. As a result, the U.S. Departments of the Interior (DOI), Energy, and Commerce announced the shared goal to deploy 30 gigawatts (GW) of U.S. offshore wind energy by 2030, while ensuring biodiversity and co-use of the ocean by various stakeholders. To that effect, DOI's Bureau of Ocean Energy Management (BOEM) announced a plan in March 2021 to advance new lease sales and complete a review of at least 16 Construction and Operations Plans (COPs) by 2025, providing more than 19 GW of energy.

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Since that time, the focus of offshore wind energy planning and development has expanded from the U.S. Atlantic OCS to areas in the Gulf of Mexico and Pacific, notably the northern and central coasts of California. By September 2021, lessees of 14 offshore wind energy projects submitted COPs for technical and environmental review by BOEM, thus entering into the final phase of the Bureau's process for authorizing construction of wind energy facilities. Lease areas for these projects cover 1,637,992 acres of the U.S. OCS and are distributed along the Atlantic Coast from Massachusetts to North Carolina.

A myriad of stakeholders operates and intersects across the U.S. OCS, conducting activities vital to the nation's security and marine economy. The placement of WTGs across the U.S. OCS will result in changes to the Marine Transportation System (MTS)—defined as the waterways, ports, and land-side connections integral to moving people and goods to and from water—and, in some cases, alter the traditional paths followed by mariners operating within this system. While the construction of wind turbines is prohibited in certain areas of MTS waterways to facilitate navigation across the U.S. OCS, the presence of wind farms adjacent to shipping safety fairways and navigational routing measures may provide new risks the mariner must consider in order to navigate safely. Of the many tools a mariner leverages for safe navigation, MVR is widely used and relied upon to avoid collision and allision in the marine environment.

Through public outreach and engagement during the offshore renewable energy leasing process, BOEM received input from commercial vessel maritime and commercial fishing industry stakeholders requesting further insight into the impacts of offshore wind energy installations on MVR. Due to the size, structure, and proposed placement of WTGs offshore, the maritime community expressed concern that WTGs could cast radar shadows, obfuscating smaller vessels exiting wind facilities in the vicinity of deep draft vessels in Traffic Separation Schemes. Commercial fisheries representatives highlighted concerns over the limited amount of research conducted on this topic, in addition to other possible forms of radar interference that may preclude safe navigation within an offshore wind facility. Furthermore, previous studies exploring WTG interference to MVR considered European offshore wind farm structures differing in size and spacing relative to those proposed for planned U.S. facilities.

WTGs are large structures predominantly constructed of steel. As a result, they generally have significant electromagnetic reflectivity and the capacity to interfere with radar systems in their vicinity. Additionally, the rotating blades can return large and numerous Doppler-shifted reflections as the blades move relative to a receiving radar system. The installation of WTGs towering hundreds of meters above the sea surface across the U.S. OCS therefore poses potential conflicts with a number of radar missions supporting air traffic control, weather forecasting, homeland security, national defense, maritime commerce, and other activities relying on this technology for surveillance, navigation, and situational awareness. In 2014, the U.S. Departments of Defense and Energy, the Federal Aviation Administration, and the National Oceanic and Atmospheric Administration established the interagency Wind Turbine Radar Interference Mitigation Working Group (WTRIM), observed by the U.S. Department of Homeland Security and BOEM personnel, to identify and develop mitigation solutions and strategies with an emphasis on WTG interference to aircraft and weather surveillance radar systems. BOEM joined the WTRIM as an active member in 2018. In 2020, BOEM called for the National Academies to conduct a study to determine and characterize the impacts of WTGs on MVR used by vessel operators in and adjacent to offshore wind facilities. A second objective of this study is the identification of plausible techniques to mitigate WTG impacts in order to preserve radar

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effectiveness for navigational awareness and safety on vessels both in and adjacent to offshore wind facilities.

In 2021, members of the National Academies committee undertaking this study met virtually to gather information from public sessions with federal employees, industry representatives, researchers, and other stakeholders, and conducted a review of literature in order to develop this report. To clarify the scale, scope, and nature of WTG impacts on MVR, the committee organized its information-gathering efforts around six areas consistent with the study's statement of task (Box S.1): (1) navigation safety, (2) offshore WTG characteristics and deployment, (3) MVR design and operation, (4) electromagnetic characteristics of WTGs, (5) the impact of WTGs on MVR performance, and (6) mitigation strategies. Through this process, the committee also identified tailored mitigation methods to address WTG effects on MVR, including those related to operational procedures, wind turbine design and deployment, radar design, signal and data processing, and other combined approaches, and considered the feasibility of adopting these methods for relevant stakeholders.

BOX S.1
Statement of Task

An ad hoc Committee of the National Academies of Sciences, Engineering, and Medicine will undertake a study to assess impacts of offshore wind turbine generators (WTG) on marine vessel radar and identify techniques that can be used to mitigate those impacts. The study will use a combination of literature review and, if informative and practical, apply or adapt existing models to:

- determine and characterize the impacts of WTG on efficacy of marine vessel radar operated on vessels both within and near existing offshore wind facilities, as well as those facilities anticipated to be installed over the next 15 years on the U.S. outer continental shelf; and
- identify actions that could be taken to reduce the impacts on marine vessel radar to preserve its use as a navigational aid for vessels both in and near WTG facilities.

The analysis of impacts to marine vessel radar will include, but not be limited to, parameters such as radar type, radar height, radar range, vessel type and size (vessel carrying radar and vessels to be detected), vessel speeds, turbine height, and turbine spacing. The study will analyze potential impacts from the WTG on the ability to navigate in adverse weather conditions and to detect small fixed objects such as buoys. The study will estimate the magnitude of clutter, mirroring, shadowing, and any other impacts observed or predicted to be caused by WTGs. Finally, the study will consider a variety of mitigation methods including signal filtering, radar antenna relocation, operational training, and replacement of new radar technology, as well as other possible approaches. The study will examine the feasibility of each proposed mitigation method based on vessel type.

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WIND TURBINE GENERATOR IMPACTS TO MARINE VESSEL RADAR

Since the world's first offshore wind farm was installed in Vindeby, Denmark, in 1991, offshore wind farms have become operational in several European and Asian nations. Offshore wind energy generation commenced on the U.S. OCS relatively recently, including the installation of the 30-megawatt (MW), five-turbine Block Island Wind Farm in Rhode Island state waters in 2016 and two 6-MW turbines in federal waters off of Virginia Beach in 2020. Concurrently, WTGs have grown in size and capacity. Globally, from 2010 to 2019, the capacity-weighted average offshore turbine size has grown from 3.5 MW to more than 6 MW, and rotor (blade) diameters have grown from 100 meters (m) to more than 150 m. Taller WTG towers with longer blades and higher capacities are planned for deployment in the coming decade. Upcoming COPs include WTGs with hub heights and rotor diameters approaching 175 m and 250 m, respectively, spaced apart by roughly 1 nautical mile, with most developers submitting WTG capacities of at least 14 MW. Similar to onshore WTGs, WTG towers—the largest part of the structure—are made of steel, as already noted, and are consequently highly conductive, resulting in large, aspect-independent radar reflections. In contrast, returns from the turbine blades are aspect-dependent and can appear even larger than reflections from the tower for certain geometries. It is important to note that blade composition, construction, and orientation all affect the magnitude of the blade contribution to the overall WTG signal visible on a vessel operator's display.

Innovation in WTG engineering has resulted in the design of new configurations to maximize efficiency. The three-bladed horizontal axis wind turbines (HAWTs) will be the standard marine deployment in the near term (10–15 years). Vertical axis wind turbines (VAWTs) may be deployed in the medium to long term (10–20 years) to take advantage of their lower center of gravity for deep water applications and potential for energy-generating efficiency. Both deployments require a stationary tower in their super-structure. Doppler returns from VAWTs will show less dependence on the angle between the WTG and the MVR, such that the Doppler return from VAWTs will generally be more extensive than that of HAWTs. Additionally, monopile (fixed-bottom) WTG foundations will be the standard for the shallow OCS of the U.S. East Coast, whereas floating WTG foundations will be the predominant deployment for the deeper waters of the West Coast.

MVR is a critical instrument for navigation, collision avoidance, and other specialized purposes such as small target detection and tracking, especially in restricted visibility. The Safety of Life at Sea international conventions set forth by the International Maritime Organization require that MVRs (which operate within one of two frequency bands centered on 9.4 gigahertz [GHz] in the X-band and 3 GHz in the S-band, depending on vessel size) be installed on a multitude of commercial vessels for navigation safety. The past decade has seen a shift in MVR design from magnetron-based transmission to solid-state transmission, resulting in the production of radar systems with faster response times, lower transmit power, longer lifespans, and greater frequency stability. Solid-state radars can also accommodate the incorporation of more sophisticated processing techniques, such as Doppler processing used to measure the velocity of moving targets with respect to the radar, and Doppler beam sharpening to improve the resolution of the features of distributed, stationary targets.

WTGs cause radar returns that may appear as interference to MVR, including strong stationary returns from the wind turbine tower, the potential for a strong blade flash return for certain geometries and relative radar-vessel positions, and Doppler-spread clutter generated along the radial extent of the WTG blade, which could obfuscate the radar returns of smaller watercraft or stationary objects, such as buoys. Additionally, multipath reflection from an observer's own

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shipboard MVR (also known as "own vessel") platform is a significant challenge for returns from WTGs, leading to ambiguous detections and generating a potentially confusing picture for the operator. As presently deployed, WTGs reduce the effectiveness of both magnetron-based and Doppler-based MVR; however, similarities and differences exist between both radar classes as to the actual mechanisms leading to WTG-induced degradation. MVR strives to detect both moving and stationary objects to aid safe navigation. While vessel operators can control the radar detection threshold—via changes to the receiver gain—to mitigate strong returns and manage the number of targets shown on the plan position indicator display, this will frequently lead to the unintended consequence of suppressing detections of small targets in and around wind farms, thereby affecting navigation decision-making and situational awareness. *While the study committee carefully distinguishes performance between magnetron and solid-state classes of MVR, the corresponding general impact of WTG-induced degradation will be similar across radar height, radar range, vessel type and size, and other likely parameters.*

It is noteworthy that there are no published studies of WTG interference on Doppler-based solid-state radar used for marine navigation. Previous studies of WTG interference on MVR, such as the 2007 British Wind Energy Association study of the U.K. Kentish Flats Wind Farm, collected wind farm data using magnetron-based radar and did not measure a Doppler signal. Therefore, assertions of the suitability of solid-state radar, or lack thereof, for operation in a WTG environment are inconclusive from these experiments.

WTG interference decreases the effectiveness of MVR mounted on all vessel classes, and the sizes of anticipated marine WTG farms across the U.S. OCS will exacerbate this situation. WTG interaction with MVRs at the scale of the proposed U.S. deployment will lead to unforeseen complications due to heightened effects of propagation, multipath, shadowing, and degraded Automatic Radar Plotting Aid performance. Maritime search and rescue (SAR) assets rely on MVR to search for smaller boats as their primary targets in the conduct of ordinary SAR operations. A loss of contact with smaller vessels due to the various forms of MVR interference could complicate MTS operations, and is therefore particularly consequential when conducting maritime surface SAR operations in and adjacent to an offshore wind farm.

Recommendation 1: The Bureau of Ocean Energy Management and other relevant federal agencies (e.g., members of the federal Wind Turbine Radar Interference Mitigation Working Group) should pursue any practicable opportunities to fill gaps in understanding of wind turbine generator impacts on marine vessel radars operated in and adjacent to wind farms, giving attention to

- **comprehensive test planning, data collection, and evaluation over a range of expected, operational conditions;**
- **innovative and collaborative approaches to facilitate data collection, such as the establishment of a marine vessel radar "sensor integration lab" for all classes or types of marine vessel radars and the development of a validated modeling and simulation capability;**
- **research, development, and characterization of a reduced radar-cross-section wind turbine generator for marine vessel radar;**
- **improvements to operator training models based on verification with physics-based models anchored by field collected data;**

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- **data collection and analysis using prototype systems, preceding the full deployment of vertical axis wind turbines, if and when they become economically feasible for offshore applications, as a means of characterizing their impacts to marine vessel radars; and**
- **data collection and analysis on floating wind turbine generators, which may pose additional challenges for marine vessel radars through their wave-induced movement that will likely provide a less-consistent radar return overall and may also increase clutter and complicate Doppler return interpretation.**

MITIGATION ACTIONS

MVRs are not optimized to operate in the complex environments of a fully populated, continental shelf wind farm. There is no simple MVR modification resulting in a robust WTG operating mode. Additionally, in contrast to investments by developers and operators of air traffic control and military radar systems, compelling WTG mitigation techniques for MVR have not been substantially investigated, implemented, matured, or deployed. Approaches external to the MVR radar design successfully employed for radar applications used elsewhere to deal with strong clutter returns from objects with a large radar cross section (RCS), however, could be considered as a low-cost or alternative means of mitigating WTG interference. These methods could include enhancing the RCS (defined as a measure of the strength of the backscattered signal from a target to the radar with units of square meters) of small vessels or other objects that are difficult to detect, reducing topside scattering from the own vessel structure to reduce false (angle and range ambiguous) returns, and improving operator training. These techniques apply to both magnetron-based and solid-state MVRs.

The environmental complexity that an offshore WTG farm presents to the MVR, its plan position indicator display, and other output products necessitates careful evaluation of training methods and tools to properly assess real-world performance of MVR operators, incorporating realistic scenarios and verified, physics-based and effects-based models.

Solid-state radar technology allows for the application of coherent signal processing methods to filter out both static and dynamic WTG clutter returns to improve detection of moving targets and stationary objects, such as buoys. Thus, solid-state radar offers greater potential in overcoming WTG interference than magnetron-based radar. The MTS stakeholder community could incentivize innovation in MVR products by manufacturers to promote radar designs with increased immunity to WTG interference. For example, development of new, Doppler-based, solid-state MVRs with WTG resilience is possible. However, the majority of MVRs in operation today are still magnetron-based systems, and widespread adoption of solid-state radars will, at present, likely be a gradual process due to the cost of replacement, the long life cycles of existing MVRs, and a lack of regulations that require the functionality provided by solid-state radars.

Additionally, modifications to the WTGs themselves could potentially reduce the WTG radar signature. Previous modeling and simulation efforts have shown, for example, that incorporation of radar absorbing materials and tower shaping can reduce the RCS of WTGs. Preliminary research and development of a reduced-RCS WTG shows promise. However, with the exception of the 2018 QinetiQ Stealth Wind Farm Case Study, to which the committee did not have full access, those efforts have not been fully proven and are not available in the near term.

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Recommendation 2: The Bureau of Ocean Energy Management (BOEM) and other relevant federal agencies (e.g., members of the federal Wind Turbine Radar Interference Mitigation Working Group) should pursue any practicable options to mitigate wind turbine generator impacts on marine vessel radar. BOEM and partners should give attention to the following:

- **The International Maritime Organization's Standards of Training, Certification and Watchkeeping (STCW) Knowledge, Understanding and Proficiency standards of competence to include operating in or adjacent to multiple structures at sea. Similar radar observer training should be considered for U.S. credentialed mariners not subject to STCW code who operate vessels equipped with radar in the vicinity of wind turbine generators.**
- **Updated requirements for vessels less than 150 gross tonnage to exhibit a radar reflector of suitable size and design while underway in or adjacent to a wind farm to improve their detectability when practicable.**
- **The deployment of reference buoys adjacent to wind farms to provide mariners a reference target to appropriately adjust marine vessel radar gain and other control settings to assist in the detection of smaller targets operating in the vicinity of wind farms.**
- **The evaluation and standardization of radar mounting procedures on marine vessels to mitigate the impact of near-field platform interference (i.e., multipath) on radar performance.**
- **The promotion of radar designs with increased immunity to wind turbine generator interference, such as new, Doppler-based, solid-state marine vessel radars with wind turbine generator resilience.**
- **Research and development to prove the performance and feasibility of fieldable material and structural wind turbine generator design components to reduce the radar cross section of wind turbine generators and mitigate their effects on marine vessel radar.**

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1
Introduction

OFFSHORE WIND ENERGY DEVELOPMENT ON THE U.S. OUTER CONTINENTAL SHELF

Offshore wind is an abundant energy resource contributing to diversifying energy portfolios around the world. In the United States, which has approximately 95,471 miles of shoreline, more than 128 million people—more than 40 percent of the nation's total 2021 population—reside in coastal counties where energy demand is high (NOAA, 2021a). Offshore wind energy development on the U.S. Outer Continental Shelf (OCS) is poised for further growth (NOAA, 2021b; NOAA and BEA, 2021) in order to meet increasing energy needs in a low-carbon, renewable way. However, the rapid development of offshore wind farms has implications for the safety of marine navigation in and around these facilities.

In January 2021, the Biden Administration issued Executive Order 14008 calling for the establishment of a new American infrastructure and clean energy economy, and prioritizing the expansion of U.S. offshore wind development as part of a government-wide approach to address climate change (United States, 2021a). This Executive Order recognized the need for close coordination and collaboration among federal agencies, states, the private sector, and other key stakeholders to accelerate offshore wind energy development, create jobs, and enhance the nation’s economy and security. Executive Order 14008 also directed the Secretary of the Interior to review siting and permitting processes in offshore waters to determine actions needed to increase renewable energy production, and resulted in the announcement of new leasing, funding, and development goals. The U.S. Departments of the Interior (DOI), Energy (DOE), and Commerce established the shared goal to deploy 30 gigawatts (GW) of U.S. offshore wind energy by 2030, while protecting biodiversity and encouraging co-use of the ocean by various stakeholders (DOI, 2021a; United States, 2021b).

In an effort to support the domestic offshore wind energy industry in meeting this 2030 target, DOI’s Bureau of Ocean Energy Management (BOEM) aimed to advance new lease sales and complete a review of at least 16 Construction and Operations Plans (COPs) by 2025, representing more than 19 GW of energy (Draher and Baker, 2021; United States, 2021b).

By September 2021, lessees of 14 offshore wind energy projects submitted COPs for technical and environmental review, as well as approval, disapproval, or approval with modifications by BOEM, thus entering into the final phase of the Bureau’s process for authorizing construction of wind energy facilities (BOEM, 2021a). Combined, proposed offshore wind capacity for these projects is 15.538–16.629 GW. Lease areas cover 1,637,992 acres of the U.S. OCS and are distributed along the Atlantic Coast from Massachusetts to North Carolina (Figure 1.1) (BOEM, 2021b; Draher and Baker, 2021). Three other leases, including one for a project led by Vineyard Wind, were currently undergoing site assessment (BOEM, 2021b). BOEM also announced a new priority Wind Energy Area in the New York Bight, located between the Long Island and New Jersey coast, adjacent to the largest metropolitan population center in the nation. While development and planning had thus far focused on the U.S. Atlantic OCS, the Biden Administration also announced a new interagency, state–federal effort to advance areas for

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Wind Turbine Generator Impacts to Marine Vessel Radar

offshore wind off the northern and central coasts of California, opening up the Pacific Coast to commercial-scale offshore clean energy projects (DOI, 2021b; United States, 2021c).

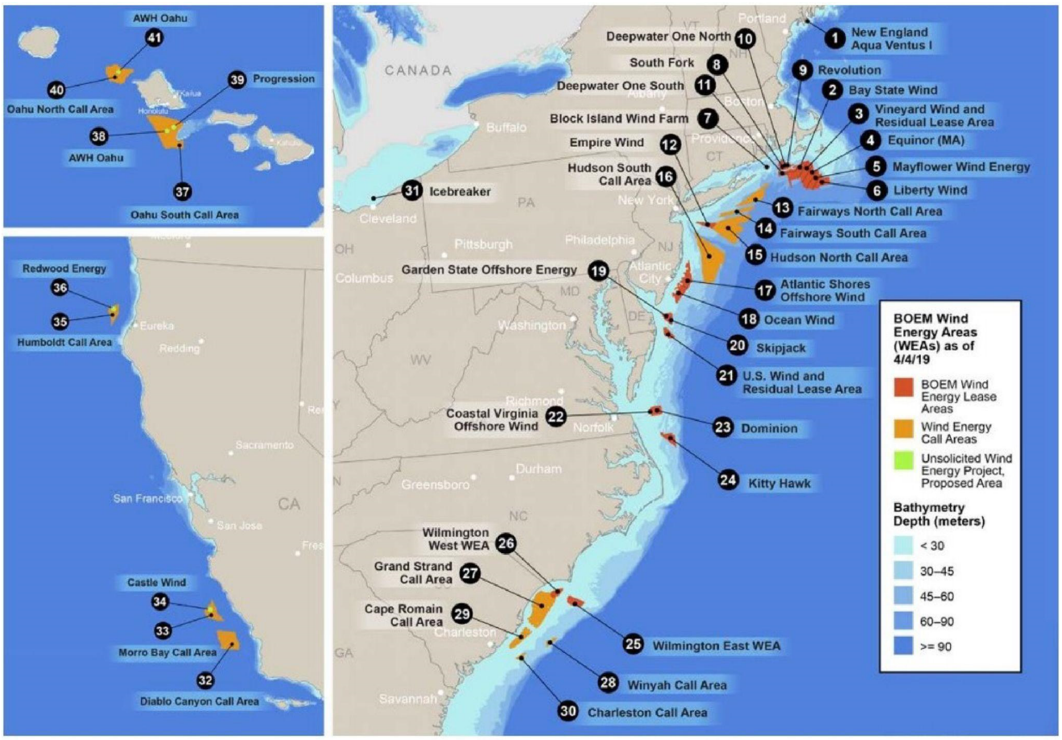

FIGURE 1.1 U.S. offshore wind project activity as of May 31, 2021. Activities include Lease Areas (red), Call Areas (orange), and Wind Energy Areas (green). Prior to awarding leases, the Bureau of Ocean Energy Management (BOEM) identifies and designates Call Areas, which are areas with wind potential. With sufficient interest from developers and public comment, BOEM designates areas with potential for wind development as Wind Energy Areas, where leases can be sold. SOURCE: Musial et al. (2021).

Offshore wind energy is relatively new to the United States. Since the world's first offshore wind farm was installed in Vindeby, Denmark, in 1991 (5-megawatt [MW] capacity), offshore wind installations have become operational in several European nations including the United Kingdom, Germany, Denmark, Belgium, the Netherlands, Sweden, Finland, Portugal, Spain, Ireland, France, and Norway, as well as in Asian nations such as China, South Korea, Japan, Vietnam, and Taiwan (Figure 1.2). In the United States, the 30-MW, five-turbine Block Island Wind Farm in Rhode Island state waters became operational in 2016.[1] The Coastal Virginia Offshore Wind Project resulted in the installation of two turbines in federal waters off of Virginia Beach, which have been operational since 2020 with a combined capacity of 12 MW.[2] In 2020, China installed half of all new global offshore wind capacity (GWEC, 2021). An increase in capacity was recorded in Europe, primarily in the Netherlands and followed by Belgium, the United Kingdom, Germany, and Portugal, in addition to new installations in the United States and

[1] See https://us.orsted.com/wind-projects.
[2] See https://eerscmap.usgs.gov/uswtdb/viewer/#6.02/38.013/-75.401.

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South Korea. As a result, approximately 5.5–6.1 GW of new offshore wind energy capacity was installed worldwide, resulting in a total offshore wind capacity of approximately 35 GW—4.8 percent of the total global cumulative wind power capacity (GWEC, 2021; Musial et al., 2021).

Concurrently, wind turbine generators (WTGs) have grown in size and capacity. Globally, from 2010 to 2019, the capacity-weighted average offshore turbine size has grown from 3.5 MW to more than 6 MW, and rotor (blade) diameters have grown from 100 meters (m) to more than 150 m.[3] Taller WTG towers with larger blade lengths and capacities are planned for deployment in the coming decade (GE, 2018; Siemens Gamesa, 2020; Musial et al., 2021; Vestas, 2021). Upcoming COPs include WTGs with hub heights and rotor diameters approaching 175 m and 250 m, respectively, with most developers submitting WTG capacities of at least 14 MW (BOEM, 2021b; Draher and Baker, 2021).

The placement of WTGs throughout the Marine Transportation System has the possibility to conflict with historical shipping routes. While the U.S. Coast Guard seeks to provide the mariner with safe access to ports that align with historical shipping routes by designating shipping safety fairways and traffic separation schemes adjacent to the wind energy areas, some marine traffic will still transit through the wind farms. Commercial fishing vessels are expected to transit through wind farms to their fishing grounds from their homeport, while passenger vessels and recreational vessels may transit within the wind farms as a destination attraction. The requirement to orient the turbines in “straight rows or columns,” in at least “two lines of orientation,” is expected to provide consistent planned spacing throughout the wind farm in an effort to minimize risks to surface vessels choosing to transit through. Even with a consistent orientation between wind farms, WTGs will impact visual navigation by hiding small contacts. If transiting through the wind farm during periods of restricted visibility, the mariner’s reliance on marine vessel radar (MVR) increases. Therefore, knowing the impacts WTGs have on MVR and possible mitigating solutions is critical to ensuring that navigation can continue by the safest means possible.

With hub heights exceeding 100 m, and structures predominantly made of steel,[4] WTGs are large installations that can have significant electromagnetic reflectivity. As a result, WTGs installed within the line of sight of a radar system can cause clutter and interference, in some cases detrimentally impacting radar performance (Karlson et al., 2014). Furthermore, rotating blades can have large and numerous Doppler returns due to their motion relative to the radar system. The installation of WTGs across the U.S. OCS therefore poses potential conflicts with a number of radar missions supporting air traffic control, weather forecasting, homeland security, national defense, maritime commerce, and other activities relying on this technology for surveillance, navigation, and situational awareness (Gilman et al., 2016). In response to this observation, the U.S. Department of Defense, DOE, Federal Aviation Administration, and National Oceanic and Atmospheric Administration signed a memorandum of understanding to establish the interagency Wind Turbine Radar Interference Mitigation Working Group (WTRIM)[5] to identify and develop mitigation solutions and strategies with an emphasis on WTG interference on aircraft and weather surveillance radar systems. U.S. Department of Homeland Security and BOEM personnel served as observers of the WTRIM, and BOEM joined as an active member in 2018. The WTRIM developed a Federal Interagency Wind Turbine Radar Interference Mitigation Strategy in 2016 to

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[3] See https://www.energy.gov/eere/wind/2019-wind-energy-data-technology-trends; https://www.energy.gov/eere/wind/wind-market-reports-2021-edition#offshore.

[4] See https://www.usgs.gov/faqs/what-materials-are-used-make-wind-turbines?qt-news_science_products=0#qt-news_science_products.

[5] See https://windexchange.energy.gov/projects/radar-interference-working-group.

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coordinate federal research and mitigation activities and encourage development of next-generation radar systems with resistance to turbine interference (Gilman et al., 2016). Of the multiple types of radar that may be affected by WTGs, this report specifically addresses radars used for marine navigation.

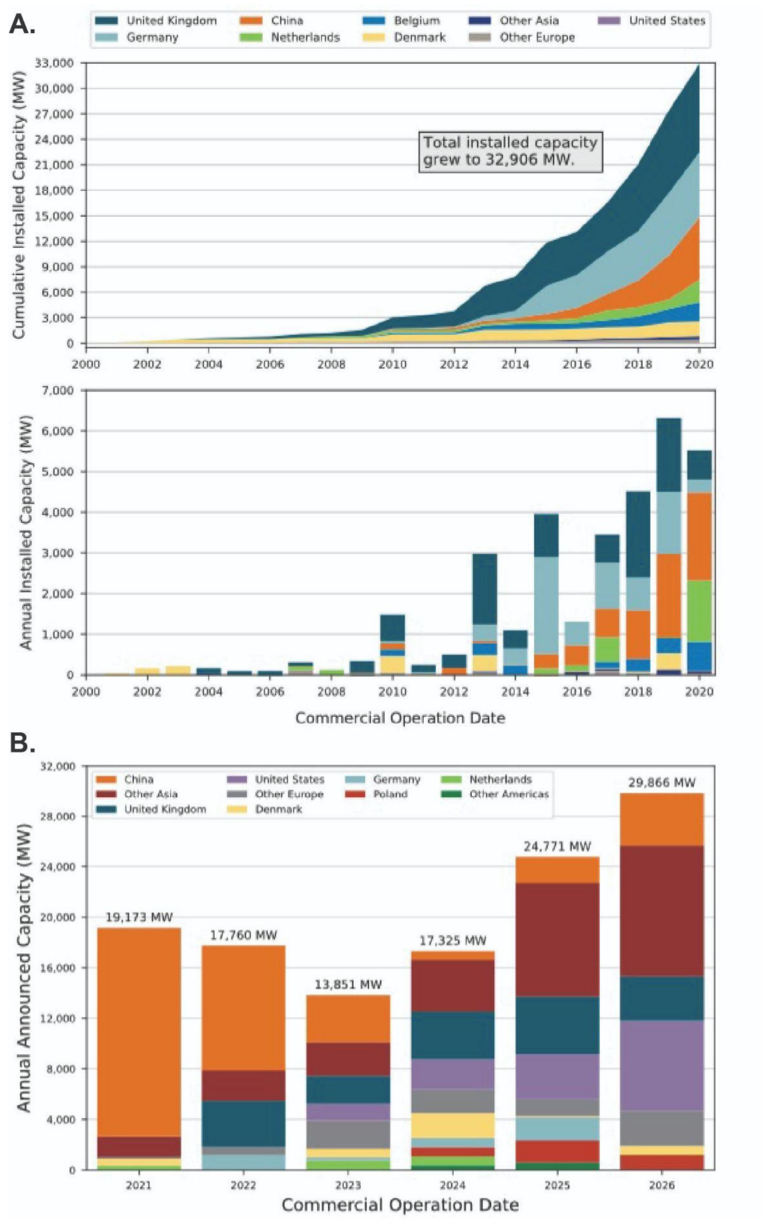

FIGURE 1.2 A global perspective: cumulative offshore wind energy deployment, annual capacity additions, and annual announced capacity. Panel A: Cumulative Installed Offshore Wind Capacity from 2000 to 2020, surpassing 30,000 megawatts (MW) from 2000 to 2020 (top) and Annual Installed Offshore Wind Capacity from 2000 to 2020, surpassing 5,000 MW in 2019 and 2020 (bottom). Panel B: Offshore wind capacity announced by developers for 2021–2026 for projects with financial closure. SOURCE: Panel A and B from Musial et al. (2021).

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MARINE NAVIGATION AND RADAR INTERFERENCE

The U.S. OCS is a dynamic environment where a myriad of stakeholders intersects. The continued development of offshore energy installations in U.S. waters therefore has the potential to impact vessel navigation and safety in their vicinity (Detweiler, 2011). Responsible government agencies seek to reconcile where practicable any conflicts between stakeholder intersections, and, in this regard, consideration for the capabilities of MVR is an important issue. In 2016, the International Maritime Organization (IMO) recognized concerns of vessels operating in the vicinity of wind farms and amended its General Provisions on Ships' Routeing (Resolution A.572(14), As Amended)[6] to include the following paragraph in Section 3 (Responsibilities of Contracting Governments and recommended and mandatory practices):

> 3.14 In planning to establish multiple structures at sea, including but not limited to wind turbines, Governments should take into account, as far as practicable, the impact these could have on the safety of navigation, including any radar interference (IMO Resolution MSC.419 [97]).

This amendment to the General Provisions on Ships' Routeing internationally recognizes the potential impacts wind turbines could have on MVR and underscores the need to understand these impacts in the United States.

Through public outreach and engagement during the offshore renewable energy leasing process, BOEM has received input from commercial vessel maritime and commercial fishing industry stakeholders requesting further insight into the impacts of offshore wind energy installations on MVR[7] (e.g., Salerno et al., 2019; WTRIM, 2020). MVRs have become a critical tool used by operators to navigate and avoid both collision and allision, especially under adverse weather conditions. Due to their size, structure, and proposed placement offshore, the maritime community expressed concern that WTGs may cast radar shadows, obfuscating smaller vessels exiting wind facilities in the vicinity of deep draft vessels in Traffic Separation Schemes. Commercial fisheries representatives raised concerns about the limited amount of research conducted on this topic, in addition to other possible forms of radar interference that may preclude safe navigation within an offshore wind facility, such as radar clutter and mirror effects (false signaling).[8,9] As an example, Figure 1.3 shows a photograph of the radar display taken during the 2019 U.S. delegation visit to the United Kingdom's Race Bank Wind Farm. It should be noted, however, that the photograph was not taken under a formal study framework and it is unclear if the MVR was optimized for operation within the wind farm.

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[6] See Resolution MSC.419(97) (adopted on November 25, 2016) regarding Amendments To The General Provisions On Ships' Routeing (Resolution A.572(14), As Amended), https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MSCResolutions/MSC.419(97).pdf.

[7] Concerns regarding radar interference due to offshore WTGs are also articulated in public comments submitted to the U.S. Coast Guard Port Access Route Study: The Areas Offshore of Massachusetts and Rhode Island (USCG-2019-0131-0026). See https://www.regulations.gov/document/USCG-2019-0131-0026.

[8] See https://www.eenews.net/climatewire/stories/1060387351.

[9] See https://www.marineinsight.com/case-studies/wind-farm-vessel-collides-with-turbine-tower/.

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Few studies have explored WTG interference to MVR. In 2004, the U.K. Maritime and Coastguard Agency (MCA) and QinetiQ conducted a study at the North Hoyle Wind Farm comprised of 2-MW WTGs to assess impacts of WTGs on navigation systems, finding that the WTGs returned strong radar responses producing interfering echoes in both the X- and S-band type radars (Brown and Howard, 2004; MCA, 2008). It was reported that at close range, within 1.5 nautical miles (nmi) of the wind farm, WTGs may produce strong reflected, multiple, and sidelobe echoes that can mask or complicate the identification of real targets (Brown and Howard, 2004; MCA, 2008). Sidelobes are lobes in the antenna radiation pattern that are not in the direction of the main antenna beam. Authors of the 2004 MCA study noted that, while reducing receiver amplification would enable turbines in the main beam to be differentiated from sidelobe echoes on the radar monitor, therefore limiting potential for allision, this approach would also reduce the amplitude of other signals received by the radar from smaller vessels or buoys (Brown and Howard, 2004). Similar effects were explored in a 2007 British Wind Energy Association (BWEA) study evaluating WTG interference in the U.K. Kentish Flats Wind Farm, which features a grid of 30 3-MW WTGs (Marico Marine, 2007). The BWEA study identified wind farm–induced radar clutter, which could be accentuated depending on the positioning of radar infrastructure on the vessel. This study suggested that some of the observed clutter could be suppressed through adjustment of the radar controls, with the caveat that this technique could result in the loss of other targets with a small radar cross section (Marico Marine, 2007).

FIGURE 1.3 Photograph of the display of a shipboard radar operated in a U.K. wind farm.
SOURCE: Seafreeze, Ltd., included in public comments submitted to the 2019 U.S. Coast Guard Port Access Route Study: The Areas Offshore of Massachusetts and Rhode Island (USCG-2019-0131-0026).

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In 2008, radar modeling studies were commissioned by the developer of the Cape Wind farm and subsequently by the U.S. Coast Guard to assess the impact of proposed Cape Wind WTGs on marine radars operating in Nantucket Sound, resulting in the issuance of a Coast Guard assessment of moderate risk for the presence of WTGs on marine navigation in the area (U.S. Coast Guard Memorandum, 2009). More recently, a report prepared for DOE characterized the effects of offshore WTGs on multiple types of radar systems, such as shipborne, airborne, and coastal ocean-monitoring systems (Ling et al., 2013). Using modeled radar equipment simulating X- and S-band radar (which operate within one of two frequency bands centered on 9.4 gigahertz [GHz] in the X-band and 3 GHz in the S-band, depending on vessel size) used in the vicinity of the proposed Cape Wind farm, as well as a generic 10 × 10 WTG grid layout, authors of the 2013 DOE report observed that radar clutter caused by the presence of the wind farm can make it difficult to identify other vessels operating within the wind farm, but did not significantly affect tracking of vessels outside of the wind farm (Ling et al., 2013). They concluded that model results demonstrate a moderate impact on navigational X- and S-band radar (Ling et al., 2013). These and other studies will be discussed in Chapter 2 of this report.

While previous studies indicate that WTGs can affect MVR, they do not assess potential impacts based on the proposed WTG sizes and spacing for wind energy leases on the U.S. OCS seen in current COPs. For comparison, in 2007, the Kentish Flats Wind Farm featured 30 3-MW WTGs in a grid of east-west orientation and turbine spacing of 700 m (0.37 nmi) (Marico Marine, 2007); however, as one example, Ørsted's proposed development of 1,100-MW Ocean Wind I and 1,148-MW Ocean Wind II offshore of New Jersey plans to use more than 170 12-MW GE Haliade-X turbines spaced with a 1 nmi × 0.8 nmi separation (Ørsted, 2021). Adjacent Rhode Island and Massachusetts lease areas could hold hundreds of WTGs on the order of 12 MW each, with spacing up to 1 nmi or greater (BOEM, 2021b).

As momentum builds to deploy offshore wind energy across the U.S. OCS, and innovation in WTG engineering continues, the salient characteristics of offshore wind farms proposed for U.S. development have diverged from those of the Kentish Flats Wind Farm and others evaluated previously for interference on MVR. In light of the size and scope of proposed development in U.S. waters, maritime, commercial fishing industry, and other OCS stakeholders remain concerned and uncertain regarding the impacts of offshore WTGs to MVR, and the extent to which these impacts can hinder navigational awareness and safety within or adjacent to an offshore wind facility (e.g., Salerno et al., 2019; WTRIM, 2020).

STATEMENT OF TASK

In late 2020, BOEM called for a National Academies study to explore the impacts of WTGs on MVR used by vessel operators in and around offshore wind facilities. This report is a result of that study, which aims to determine and characterize the impacts of offshore WTGs on MVR, including radar commonly operated on large maritime commercial vessels and by commercial fishing vessels. Additionally, this study considers plausible techniques to mitigate WTG impacts in order to preserve MVR efficacy for navigational awareness and safety on vessels both in and near offshore wind facilities.

The statement of task for the study is presented in Box 1.1.

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BOX 1.1
Statement of Task

An ad hoc Committee of the National Academies of Sciences, Engineering, and Medicine will undertake a study to assess impacts of offshore wind turbine generators (WTG) on marine vessel radar and identify techniques that can be used to mitigate those impacts. The study will use a combination of literature review and, if informative and practical, apply or adapt existing models to:

- determine and characterize the impacts of WTG on efficacy of marine vessel radar operated on vessels both within and near existing offshore wind facilities, as well as those facilities anticipated to be installed over the next 15 years on the U.S. outer continental shelf; and
- identify actions that could be taken to reduce the impacts on marine vessel radar to preserve its use as a navigational aid for vessels both in and near WTG facilities.

The analysis of impacts to marine vessel radar will include, but not be limited to, parameters such as radar type, radar height, radar range, vessel type and size (vessel carrying radar and vessels to be detected), vessel speeds, turbine height, and turbine spacing. The study will analyze potential impacts from the WTG on the ability to navigate in adverse weather conditions and to detect small fixed objects such as buoys. The study will estimate the magnitude of clutter, mirroring, shadowing, and any other impacts observed or predicted to be caused by WTGs. Finally, the study will consider a variety of mitigation methods including signal filtering, radar antenna relocation, operational training, and replacement of new radar technology, as well as other possible approaches. The study will examine the feasibility of each proposed mitigation method based on vessel type.

REPORT ORGANIZATION

In 2021, members of the National Academies committee undertaking this study gathered information from public sessions with federal employees, industry representatives, researchers, and other stakeholders; written input accompanying these sessions; and review of the literature to develop this report and the recommendations and conclusions outlined herein. In order to clarify the scale, scope, and nature of WTG impacts on MVR, the committee organized its information-gathering efforts around six areas consistent with the study's statement of task (Box 1.1): (1) navigation safety, (2) offshore WTG characteristics and deployment, (3) MVR design and operation, (4) electromagnetic characteristics of WTGs, (5) the impact of WTGs on MVR performance, and (6) mitigation strategies.

During the course of its deliberations, the committee identified that radar class (i.e., magnetron-based versus solid-state) is a discriminating factor in assessing both the impact of WTGs on performance and mitigating solutions. Moreover, as seen in the report, radar design choices affecting predominant electromagnetic phenomenology, such as operating frequency, are influential. However, other parameter variations, such as radar height, radar range, vessel type, and speed, do not result in unique insights, as phenomenology will be similar across these variables. Consistent with the statement of task, the report discusses key issues around WTG

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design and deployment impacts, with a primary focus on planned and future U.S. OCS deployment. The report's discussion reflects these points and, as the reader will see, conveniently enables the report organization to follow the committee's approach to information gathering.

Chapter 2 of this report provides background information on the navigation and safety issues associated with marine vessel operation in and adjacent to offshore wind facilities, common MVR designs and operation strategies for commercial maritime and fishing vessels in the United States, and electromagnetic characteristics of WTGs. This information clarifies the scale, scope, and nature of WTG impacts to MVR, which are also outlined in this chapter. Chapter 3 details mitigation solutions for WTG effects on MVR, including methods related to operational procedures, wind turbine design and deployment, radar design, signal and data processing, and other combined approaches. Chapter 3 also presents a general assessment of the feasibility of those methods. Lastly, Chapter 4 of this report provides a summary of key conclusions and recommendations resulting from the findings of the study committee, highlighting future directions for further consideration. Biographical information for committee members and definitions of acronyms used throughout the report may be found in Appendix A and Appendix B, respectively.

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2
Impacts of Wind Turbine Generators on Marine Vessel Radar

NAVIGATION AND SAFETY USING MARINE VESSEL RADAR

The Marine Transportation System (MTS; the waterways, ports, and land-side connections integral to moving people and goods to and from water[10]) is extremely important to the global economy, transporting about 90 percent of the world's goods.[11] In 2019, marine economy sectors contributed approximately $397 billion to the U.S. gross domestic product and grew faster than the nation's economy in its entirety (NOAA, 2021). Furthermore, while there are multiple government agencies who regulate different aspects of or actively use the MTS, safety of navigation throughout the system is of paramount importance to all parties.

In general terms, navigation is defined in this report as the art or science of plotting, ascertaining, or directing the course of a ship, and safety is considered freedom from harm or danger. To promote safety is to protect against failure, breakage, or accident. To that end, anything that potentially adds additional risk to the MTS warrants investigation by relevant stakeholders to determine the level of risk presented and the means to reduce or mitigate that risk.

The placement of wind turbine generators (WTGs) into the marine environment will result in changes to the MTS, which could impact navigation safety. The placement of these structures in the MTS will, in some cases, alter the traditional path followed by certain mariners. Although areas of the waterways may be designated as shipping safety fairways and formal routing measures, which will prohibit the construction of wind turbines in certain locations, the presence of wind farms adjacent to these shipping safety fairways and navigational routing measures will still provide new risks for the mariner to consider while safely navigating. Of the many tools a mariner leverages for safe navigation, the marine vessel radar (MVR) is one that is heavily relied upon or, in many cases, required. Therefore, any adverse impacts that WTGs have on MVR may have an adverse impact on the safety of navigation.

Navigation safety is also the fundamental duty of *all* mariners. While the concepts mentioned below should be observed by all operating in the offshore environment, they are required to be practiced in a much more formalized manner by commercial mariners. They consist of proper voyage planning (also known as passage planning), establishing proper watchkeeping arrangements, and observing proper watchkeeping principles (Standards of Training, Certification and Watchkeeping [STCW] Regulation VIII/2) (IMO, 2018).

Voyage planning can be broken down into four parts: appraisal, planning, execution, and monitoring. These actions are described in further detail in the points summarized below from International Maritime Organization (IMO) Resolution A.893(21) (IMO, 1999):

- Appraisal—all relevant information should be considered including but not limited to
    - the condition of the vessel, its equipment, and operational and maneuvering data including limitations or restrictions;

[10] See https://www.maritime.dot.gov/outreach/maritime-transportation-system-mts/maritime-transportation-system-mts.

[11] See www.ics.org.

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- any special characteristics of the cargo;
- a competent and well-rested crew;
- appropriate, accurate, and up-to-date charts, light lists, and mariners' routing guides and passage planning charts;
- up-to-date climatological and hydrographic data;
- existing ships' routing and reporting systems, vessel traffic services (VTS), and environmental protection measures;
- traffic information throughout the voyage;
- available port information; and
- any other pertinent information deemed necessary.

As summarized from the requirements listed in IMO Resolution A.893(21), with the information listed above, an appraisal should be made providing clear indication of all areas of danger and areas of safe navigation. For the purposes of this discussion, IMO defines VTS as any shore-side systems providing services including the provision of simple information to ships, such as position of other traffic or meteorological hazard warnings, or the extensive management of traffic within a port or waterway.[12]

- Planning—based on the appraisal, a detailed voyage plan should be prepared covering the entire voyage from berth to berth. The plan should include the plotting of the intended route indicating all areas of danger, existing ships' routing and reporting systems, VTS, and any areas where marine environmental protection considerations apply. The main elements to ensure safety of life, safe and efficient navigation, and protection of the environment during the voyage should include but are not limited to
  - safe speed, considering the proximity of navigation hazards and the maneuvering characteristics of the vessel;
  - positions where a change of machinery status is required;
  - course alteration points, taking into account the vessel's turning circle and the effect of wind and currents;
  - the method and frequency of position fixing, including primary and secondary options, and the indication of areas where accuracy is critical and where maximum reliability must be obtained;
  - use of vessel routing and reporting systems and VTS;
  - considerations relating to the protection of the marine environment; and
  - contingency plans.
- Execution—the voyage should then be executed in accordance with the plan. Factors that may necessitate a departure from the plan include
  - a change in the reliability of the vessel's navigation equipment;
  - meteorological conditions such as periods of low visibility and weather routing alerts;
  - conditions affecting position fixing accuracy such as daytime versus nighttime passing of danger points; and
  - traffic conditions.

[12] This and other definitions can be found at www.imo.org.

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It is the responsibility of the master (the captain of the ship) to determine whether circumstances introduce an unacceptable hazard to the safety of the voyage and whether that portion of the voyage will be attempted under those circumstances. The master also considers when additional personnel may be needed during the voyage.

- Monitoring—the progress of the vessel in accordance with the voyage plan is to be continuously monitored. Such monitoring includes accurately determining one's position, course over ground, other traffic in the area, obstructions nearby, weather conditions, sea state, and a host of other variables. Watchstanders endeavor to maintain this "situational awareness" at all times. As stated in the Navigation Rules (see below) one must use "all available means" when determining, among other things, risk of collision. Mariners routinely use every available "tool" in their toolbox to maintain situational awareness and therefore navigation safety. No one tool is to be relied upon exclusively when navigating a vessel.

Constant monitoring of the vessel's position and risk of collision is critical to ensuring a vessel is being navigated safely. MVR is an essential tool to accomplish this goal, especially in a coastwise environment. For the purposes of this report, the committee will be focusing on impacts of WTGs to MVR. However, other radar systems that contribute to safe navigation, such as weather, shore-based marine radar used by VTS, and surface high frequency (HF), may also be affected by wind turbines (e.g., Trockel et al., 2018a,b; Kirincich et al., 2019).

MVR is a vital component of a mariner's toolbox that can help the mariner "see" in reduced visibility, in darkness, and at great distances, and to determine the following information:

- Position—by taking bearing and distance of several known fixed objects and plotting them, similar to visual bearings.
- Course over ground—by taking and plotting the vessel's position (as outlined above) several times over a given period of time, connecting those positions, and monitoring via parallel indexing. For any parallel indexing technique, the intended track of a ship in relation to a radar-conspicuous fixed target is plotted in advance on the radar display.[13]
- Maneuvering—maneuvers, such as constant radius turns, can be planned and monitored.
- Other traffic and obstructions—by tracking targets and determining risk of collision or allision. If risk does exist and evasive maneuvers are taken by either vessel, further monitoring must be undertaken to determine if they were successful and do not create another unsafe situation.
- Weather conditions—by tracking rain or snow in the area that may affect visibility and be accompanied by strong winds and high seas.

The training and assessment of persons operating and working on the vessels forecast to be within areas that will also contain WTGs varies from none to that mandated and recommended by the STCW Convention and Code (IMO, 2018). Many, but not all, states require the completion of a boating safety course to operate motorized recreational craft. The U.S. Coast Guard requires

[13] Smith and Mulroney (1979) provide a full explanation of parallel indexing techniques, which is accessible via the National Academies Transportation Research International Documentation Database at trid.trb.org.

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Wind Turbine Generator Impacts to Marine Vessel Radar

anyone operating a vessel for hire (carrying passengers and/or goods or towing) to be licensed and therefore assessed (see Title 46 of the U.S. Code of Federal Regulations [CFR] subchapter B[14]). Internationally, the STCW Convention and Code describe the training, assessment, and competency requirements of those serving on board seagoing ships and fishing vessels (see Articles II&III STCW and STCW-F respectively) (IMO, 2018).

Certain vessels are required to carry MVR per Titles 33[15] and 46[16] of the U.S. CFR and Safety of Life at Sea (SOLAS) Chapter V Regulation 19. The training and competency requirements of the persons operating that equipment are laid out in Title 46 of the CFR and the STCW Code-Regulations I/14 and II/1, 2, and 3. The criteria for evaluating competence (IMO, 2018) include the following:

- Information obtained from radar is correctly interpreted and analyzed, taking into account the limitations of the equipment and prevailing circumstances and conditions.
- Action taken to avoid a close encounter or collision is in accordance with the Navigation Rules (IMO, 2018).
- Changes to course or speed are in accordance with accepted navigation practice and maintain safety of navigation (as noted in STCW table A-II/1 column 4[17]).

Multiple international agreements and U.S. law place requirements on vessels and operators in an effort to ensure safe navigation within the marine environment. Carriage and use of MVR is one such requirement. The International Navigation Rules formalized in the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (72 COLREGS), were officially adopted by IMO in 1977.[18] The 72 COLREGS were subsequently adopted by the U.S. Congress that same year, thus requiring all U.S. flagged vessels and all foreign vessels operating within U.S. waters to adhere to the rules. Additionally, the United States enacted the Inland Navigation Rules Act of 1980, unifying various inland rules with the 72 COLREGS throughout the Inland Waters of the United States. Both the International and Inland rules specifically address use of MVR in Rule 6, Rule 7, Rule 8, and Rule 19. For these four rules, the language for both the International and Inland Rules is identical. As such, the applicable excerpts from the International Navigation Rules are referenced throughout this chapter. In addition to the Navigation Rules, certain inspected vessels are required to carry and operate radar per U.S. regulations. These requirements are detailed in Titles 33 and 46 of the CFR.

Rule 6 requires vessels to "proceed at a safe speed [in order to] take proper and effective action to avoid collision and be stopped within a distance appropriate to the prevailing circumstances and conditions." In regards to operating at a safe speed, the rules further state in section (b) additional considerations for those vessels with operational radar. The rules require vessels with radar to consider "(i) the characteristics, efficiency and limitations of the radar equipment; (ii) any constraints imposed by the radar range scale in use; (iii) the effect on radar detection of the sea state, weather, and other sources of interference; (iv) the possibility that small vessels, ice and other floating objects may not be detected by radar at an adequate range; (v) the

[14] See https://www.ecfr.gov/current/title-46/chapter-IV/subchapter-B.
[15] See https://www.ecfr.gov/current/title-33.
[16] See https://www.ecfr.gov/current/title-46.
[17] See https://www.edumaritime.net/images/docs/stcw-table-a-ii-1.pdf.
[18] See https://www.imo.org/en/About/Conventions/Pages/COLREG.aspx.

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number, location, and movement of vessels detected by radar; and (vi) the more exact assessment of the visibility that may be possible when radar is used to determine the range of vessels or other objects in the vicinity" when determining safe speed.[19] As identified in this report, WTGs can interfere with a clear radar picture and, therefore, possibly impact the determination of safe speed when transiting in or adjacent to a wind farm.

Rule 7 discusses risk of collision. The rule states, "(a) Every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists. (b) Proper use shall be made of radar equipment if fitted and operational, including long-range scanning to obtain early warning of risk of collision and radar plotting or equivalent systematic observation of detected objects. (c) Assumptions shall not be made on the basis of scanty information, especially scanty radar information."[20] As a tool, the MVR is one of the most valuable in helping determine risk of collision. The capability provides the mariner critical information on a radar target's movement, especially range, that helps determine if the combined relative motion of the target and vessel could result in a collision. Some MVRs also provide the mariner the capability to visualize trial maneuvers that will forecast how movements of the vessel would alter the relative motion of the target. If the impacts of the WTGs prohibit the ability of the radar to accurately provide the range and relative motion of a target, and thus provides the mariner "scanty radar information," this valuable tool could be rendered ineffective in determining a risk of collision.

Rule 8 further references use of MVR when taking action to avoid a collision: "Any alteration of course or speed to avoid collision shall, if the circumstances of the case admit, be large enough to be readily apparent to another vessel observing visually or by radar.[21]" The presence of WTGs could block an MVR's ability to properly track a smaller vessel operating within a wind farm. Consequently, this could impact the ability of a large vessel operating adjacent to a wind farm to determine if the smaller vessel operating within a wind farm has sufficiently altered course or speed to avoid collision.

The mariner's visual paradigm is often described as "window, radar, chart." When operating in the vicinity of restricted visibility this model is reduced to the latter two. In these instances, a mariner's reliance on the MVR is more pronounced. Rule 19 provides guidance for the conduct of vessels in restricted visibility. Section (d) of the rule states, "A vessel which detects by radar alone the presence of another vessel shall determine if a close-quarters situation is developing and/or risk of collision exists. If so, she shall take avoiding action in ample time, provided that when such action consists of an alteration of course, so far as possible the following shall be avoided: (i) An alteration of course to port for a vessel forward of the beam, other than for a vessel being overtaken; (ii) An alteration of course toward a vessel abeam or abaft the beam."[22] An effective radar with a clear display of radar returns is critical in these situations. If the presence of WTGs impacts the radar picture and degrades the mariner's ability to determine risk of collision in restricted visibility, safety of navigation is severely hampered.

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[19] See https://www.ecfr.gov/current/title-33/chapter-I/subchapter-E/part-83/subpart-B/subject-group-ECFRc711a0393c57020/section-83.06.

[20] See https://www.ecfr.gov/current/title-33/chapter-I/subchapter-E/part-83/subpart-B/subject-group-ECFRc711a0393c57020/section-83.07.

[21] See https://www.ecfr.gov/current/title-33/chapter-I/subchapter-E/part-83/subpart-B/subject-group-ECFRc711a0393c57020/section-83.08.

[22] See https://www.ecfr.gov/current/title-33/chapter-I/subchapter-E/part-83/subpart-B/subject-group-ECFR65e97d0e33f25e3/section-83.19.

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MARINE VESSEL RADAR DESIGN AND OPERATION

MVRs have been in use for marine navigation since the late 1940s (Briggs, 2004). They have become an indispensable instrument in navigation and in collision avoidance, especially in restricted visibility. MVRs nominally operate in one of two frequency bands centered on 3 gigahertz (GHz) in the S-band and 9.4 GHz in the X-band. Based on the SOLAS international conventions set forth by IMO, all ships of or above 300 gross tonnage and all passenger ships (regardless of size) are required to be fitted with an X-band radar to assist in navigation and in collision avoidance (SOLAS Chap. V, Reg. 19.2.3.2). All ships of 3,000 gross tonnage and upward are required to have an S-band radar or a second X-band radar that is functionally independent of the first radar (SOLAS Chap. V, Reg. 19.2.7.1). Because of their lower operating frequency and longer wavelength, S-band MVR antennas are physically larger than those at X-band. Consequently, S-band MVRs are typically found on large vessels. However, due to smaller attenuation loss at lower frequencies, S-band MVRs can penetrate better through adverse weather conditions such as rain and fog than those operating at X-band.

Marine Vessel Radar Design

The standard design for MVR uses a magnetron source as its transmitter. The front-end antenna is a slotted waveguide array, which comprises a linear array of slots cut along a metal waveguide. The antenna is designed to radiate and receive horizontal polarization (i.e., the electric field of the electromagnetic wave is parallel to the sea surface). The radiated beam of the linear array is a fan-shaped beam, with an elevation beamwidth of 20–30 degrees and an azimuth beamwidth of 1–2 degrees. This ensures good azimuth resolution while providing sufficient elevation coverage to overcome the pitch and roll motion of the vessel on which it is mounted. In addition to having a narrow azimuth beam, an MVR antenna is designed to exhibit low azimuth sidelobes in its transmission (and reception) pattern outside the main beam, on the order of 23–30 decibels (dB) below the main peak.

The antenna, also referred to as an "open array," is rotated in the azimuth direction by a motor while repeatedly transmitting short radio-frequency pulses at several thousand times a second. Each short pulse is partially reflected by scatterers in the illuminated scene, with each reflection having a time delay proportional to the scatterer's distance from the radar. These reflected pulses travel back to the radar and are received by the antenna and detected by the receiver. The received signal from each transmitted pulse thus forms a reflectivity map of the scene versus distance (or range) from the radar at one particular azimuth angle. The pulse width, which is typically between tens of nanoseconds to a few microseconds, determines the range resolution of the radar. When the reflectivity versus range information is collected for a full rotation of the antenna, a plan position indicator (PPI) display is formed. A PPI display is a polar plot of the reflectivity map of the scene (with the radar at the origin) versus the range and the azimuth bearing. In magnetron-based MVRs, only the amplitudes of the return pulses are detected. The phase information between the transmit and receive pulses is not captured by the receiver, and the term "non-coherent radar" is sometimes used to describe such systems (Briggs, 2004). Magnetron-based MVRs transmit up to tens of kilowatts of power, with a theoretical maximum range of up to 100 nautical miles (nmi). However, as will be discussed later, the practical maximum range of MVRs for target detection is usually much shorter due to the Earth's curvature that limits the radar horizon.

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The raw range-bearing information is displayed on a raster scan PPI display. Modern MVRs include a set of tuning knobs that permit manual control by the operator. For example, the radar gain control sets the minimum signal strength that can be detected by the radar receiver. Increasing the gain has the effect of enabling weaker signals to be displayed. Conversely, decreasing the gain can often suppress background clutter but at the expense of suppressing weaker targets. In addition to the gain control, built-in filters can be applied to remove common types of clutter due to rain or the sea surface. Moreover, there are automatic modes such as "harbor," "coastal," "offshore," and "bird" for different operating scenarios. They help maintain a clear PPI display for optimal situational awareness. With increased computer processing power, modern MVR displays also incorporate automatic target tracking capabilities to aid mariners in collision avoidance. The automatic tracker is known as the Automatic Radar Plotting Aid (ARPA). It provides a set of standard functionalities for collision avoidance. ARPA capabilities include automatic target acquisition, target track creation, target course determination, and the calculation of the closest point of approach (CPA) as well as the time to closest point of approach (TCPA). For example, the system can be set up to provide an audio warning when the TCPA falls below a user-set threshold. More recently, multifunction displays have been introduced that can simultaneously display not only the PPI from an MVR but also information from Global Positioning System chartplotters, fishfinders, and other onboard sensors.

Marine Vessel Radar Market and Recent Developments

As of 2019, MVR constitutes about 40 percent of the $5 billion marine electronics market (Technavio, 2020). Well-known MVR brands include Furuno, Raymarine (FLIR Systems), Garmin, SimRad (Navico), JRC, Kongsberg Gruppen, Sperry Marine (Northrop), and Kelvin Hughes (Hensoldt UK). The market can be segmented by end users into merchant marine, fishing vessels, recreational craft, and military naval. While MVRs are used primarily for navigation and collision avoidance, there are also specialized needs depending on the application arena. For instance, small target detection and tracking are critical functions for navies, lifeboats, and coast guards. Another example is that commercial fishermen often use MVR to find reflectors placed on fishing nets or track flocks of birds to find schools of fish. The MVR market has a high barrier to entry, with strong competition among established vendors (Technavio, 2020). Cost is a dominant consideration in the design and manufacture of MVRs, especially for the commercial market (Acland, 2021; Haynes, 2021). A subset of MVRs are type-approved systems that pass a certification process established by government entities in various countries (e.g., the U.S. Coast Guard, the U.K. Maritime and Coastguard Agency, and the Maritime Bureau of Japan). Due to the cost of certification, type-approved systems tend to be higher-end products that meet performance standards set by IMO (IMO Resolution MSC.192(79)) and the International Electrotechnical Commission (IEC 62388). Non-type-approved MVRs are more commonly found on smaller vessels, such as those used for recreational boating.

While the standard MVR design has been in use for more than 70 years, several new developments have taken place. An alternative to the open array, in the form of a fully enclosed "domed antenna," was introduced in the 1990s (e.g., Furuno, 1993,1999). The antenna takes the form of either a reflector or a microstrip patch array. Such a domed antenna is smaller and thus is attractive for applications where a small form factor is important (e.g., on the mast of a sailboat). However, domed antennas sacrifice the beamwidth performance of an open array, as they have a broader azimuth beamwidth of 5 degrees or greater.

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A major trend in the MVR industry in the past decade is the move toward solid-state technology. The first solid-state radar for marine applications was introduced by Kelvin Hughes in 2006[23] (Kelvin Hughes, 2008; Acland, 2021). In a solid-state MVR, the magnetron is replaced by solid-state transistors in the transmitter stage. This provides greater frequency stability and enables fully coherent detection of the received signal. When detecting distant targets, solid-state radars transmit a stretched chirp pulse and use a pulse compression processing technique at the receiver to generate a reflectivity profile of the scene. This results in a range resolution comparable to that from a shorter pulse. By applying this approach, the same amount of incident energy on the target can be realized with a much lower peak power on transmit while maintaining the same long-range detection performance of magnetron-based radars. Consequently, solid-state MVRs use a much lower transmit power (tens of watts versus tens of kilowatts) but have much higher duty cycles. In addition to this key advantage, the frequency stability of solid-state transmitters also enables other more sophisticated processing techniques to be implemented. They include Doppler processing to measure the instantaneous radial velocity of moving targets with respect to the radar and Doppler beam sharpening to improve the cross-range resolution of stationary targets, such as bridges and other fixed obstacles (Wehner, 1995).

Solid-state radars also offer several practical advantages over magnetron-based radars. For instance, unlike a magnetron-based radar that requires several minutes of warmup time at turn-on, a solid-state radar can be operated immediately upon a cold start. The much lower transmit power needed for a solid-state radar means less continuous drain on the boat battery. The lifespan of a solid-state transmitter tends to be longer than that of a magnetron-based transmitter. With all these features, most MVR vendors have been adding solid-state MVRs to their product line, resulting in a growing market share for solid-state radars. That being said, the majority of the MVRs in operation today are still magnetron-based systems (Haynes, 2021). The adoption of solid-state radars across many different types of existing users will likely be a gradual process due to the cost of replacement, long life cycle of existing MVRs, and lack of regulations that require the functionality provided by solid-state radars.

Marine Vessel Radar Installation and Operation

MVRs are typically mounted at high locations on vessels to achieve an unobstructed view of the surrounding scene, such as the top of the wheelhouse or on a mast. Instead of the theoretical maximum range of a radar supplied by the vendor (which depends on the transmit power and the antenna gain, among other parameters), the common limit to the practical, maximum range for target detection is the height of the radar and the height of the target from the sea surface. An approximate formula to estimate the maximum radar horizon due to the Earth's curvature (Skolnik, 1990) is $R_{max}=1.23*[\mathrm{sqrt}(h)+\mathrm{sqrt}(H)]$, where R_{max} is the maximum range (in nmi), h is the height of the radar (in feet), and H is the height of the target (in feet). For example, an MVR mounted at a height of 20 feet above water can see a surface target out to 5.5 nmi (or a 20-foot-high boat out to 11 nmi). The mounting height of the MVR will also impact its minimum range for detection due to the elevation beamwidth, BW_EL, of the radar (Figure 2.1). This is given approximately by $R_{min}=h/\tan(BW\_EL/2)$. For example, an MVR with BW_EL=25 degrees mounted at h=20 feet above the sea surface would have difficulty seeing a target closer than R_{min}=90 feet. Therefore, there is a compromise between the maximum and the minimum range—raising the radar in order to see a distant target will also sacrifice its ability to see close-in targets. Moreover, a higher

[23] See https://uk.hensoldt.net.

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antenna position will lead to larger sea clutter returns and the range over which they are detected. All of these tradeoffs need to be taken into consideration when choosing a proper antenna height.

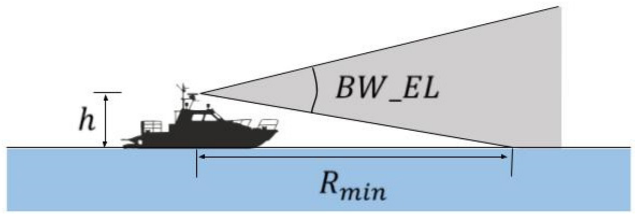

FIGURE 2.1 Illustration of how the mounting height, *h*, of a marine vessel radar affects the minimum detection range, R_{min}, due to its elevation beamwidth, *BW_EL*.

In addition to the height of antenna placement, having an unobstructed view from the antenna of the surrounding environment is also important to the quality of radar returns. When MVRs are mounted on vessels, other close-by structures such as masts, stanchions, and funnels can cause blockage and spurious echoes. These structures lead to deleterious phenomena, including (1) blind sectors in which the radar experiences complete blockage, (2) shadow sectors in which the radar can still see targets at longer range but the antenna pattern has a degraded beam and/or higher sidelobes, and (3) spurious echoes from large objects in other directions due to multiple scattering from onboard obstructions. While these effects are well known and often explicitly mentioned in MVR operator's manuals,[24] MVRs are nonetheless mounted in the midst of topside obstructions due to practical space constraints. During the 2007 Kentish Flats trial in the United Kingdom, Marico Marine (on behalf of the British Wind Energy Association) identified shipboard radar mounting issues to be a main cause of spurious echoes from offshore wind turbines (Marico Marine, 2007). This will be discussed further in the section on WTG impacts on MVR at the end of this chapter.

OFFSHORE WIND TURBINE GENERATOR CHARACTERISTICS AND DEPLOYMENT

The standard design for offshore WTGs—three-bladed, upwind, horizontal axis—is the same as that for onshore WTGs. However, because offshore wind turbines do not have the same transportation infrastructure limitations of onshore wind turbines where blade size is limited (e.g., by the roads that trucks can take and the radius of the turns, and the capacity of the cranes used in construction), they tend to be relatively larger machines (Hartman, 2021). Figure 2.2 illustrates the global trend to increase both the hub height of the turbine and the rotor diameter. To date, the offshore wind developers that have submitted a Construction and Operations Plan (COP) with the Bureau of Ocean Energy Management (BOEM) all indicate that they are considering WTGs with hub heights above 450 feet (137 meters [m]) and rotor diameters greater than 700 feet (213 m), with the maximum of 525-foot (160 m) hub height and 853-foot (260 m) rotor diameter (BOEM, 2021).

[24] For example, see manuals provided by Furuno USA at https://www.furunousa.com/en.

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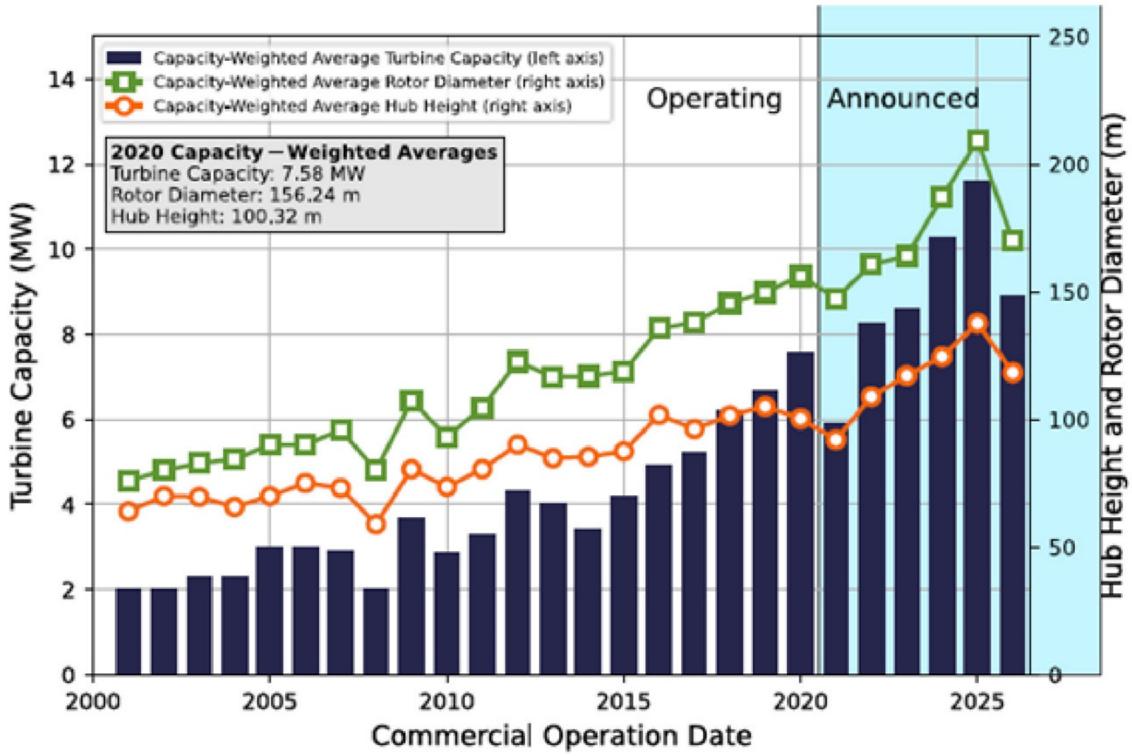

FIGURE 2.2 Global average offshore wind turbine capacity, hub heights, and rotor diameters. SOURCE: Musial et al. (2021).

These offshore machines are designed using the same materials as the onshore WTGs for the tower, nacelle, and blades. The towers are tubular structures that are typically tapered toward the top and are constructed from steel. The idea of constructing WTGs with concrete towers has been around for some time, with renewed interest in its use for offshore WTGs. Spain's ELICAN Project recently deployed a 5-megawatt (MW) offshore WTG with a concrete tower. This change in construction material will impact the large radar cross section (RCS) of WTGs, likely leading to a reduction as compared with those that have steel towers. However, more radar modeling, data collection, and verification are needed.[25]

The design of wind turbine blades is a topic of much research (Marlay et al., 2020), with the ultimate goal to capture as much energy from the wind as possible while taking into consideration operating criteria such as extreme loading, material fatigue, tip deflection, and weight and cost. Blades are made from a combination of lightweight wood (usually balsa), fiberglass, and, now more commonly, carbon fiber (Figure 2.3). These materials provide the required stiffness-to-weight ratio. WTGs are also commonly equipped with systems to protect sensitive and costly electrical equipment in the event of a lightning strike. WTG blades often have lightning receptors embedded in the surface of the blade, which are connected via a metal cable to the hub of the WTG and then down to ground (Crocker, 2020).

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[25] See https://esteyco.com/projects/elisa/index.html.

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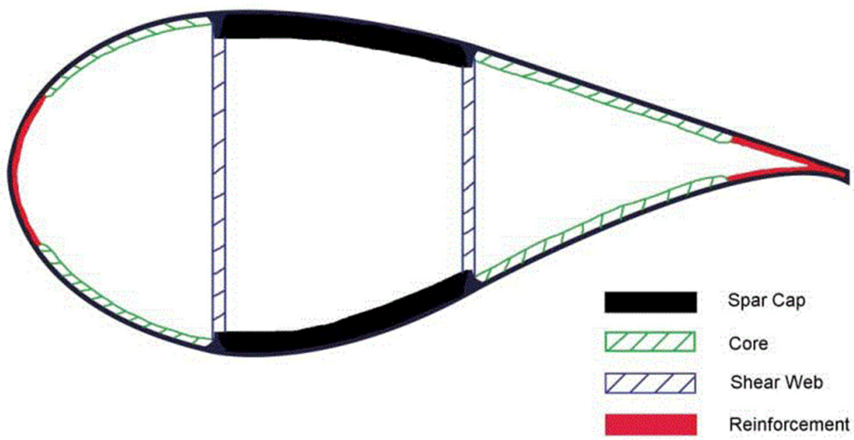

FIGURE 2.3 Composite wind turbine blade cross section. SOURCE: Griffith and Ashwill, 2011.

The nacelle of a WTG sits atop of the tower and houses components such as the generator and gearbox, if used. The nacelle cover functions to protect these components from the elements and is typically constructed from a fiberglass composite to reduce the weight of the nacelle.

There are also more novel offshore WTG designs being explored in the United States from vertical axis wind turbines (VAWTs) to designs consisting of multiple turbines deployed on a single tower (Figure 2.4). VAWTs may hold promise for the offshore environment owing to their insensitivity to the wind direction and the lower center of gravity of the machines, with the generator and gearbox located at the base of the turbine rather than housed at the top of the tower. However, these designs are yet to be proven economical and are still in the research and development phase. For this reason, the committee has focused this report on the impacts from the standard three-blade, upwind WTGs. If research and development leads to a lower levelized cost of energy for other WTG designs, this may warrant new research on the electromagnetic signatures and the impact of those new WTGs on MVR.

Offshore WTGs can also employ many different substructure foundations. The substructure type is largely dependent on the water depth at the WTG location. Fixed-bottom monopile foundations are the dominant technology for the proposed offshore WTG installation for the eastern United States (Musial et al., 2021). This is in part because of the shallower waters on the Outer Continental Shelf off the East Coast of the United States and because it is a mature technology. This may change for fixed-bottom foundations where jacketed or gravity-based foundations may become more prevalent. As the offshore market develops further and projects proposed off the West Coast of the United States and in other areas such as the Gulf of Maine, the Gulf of Mexico, the Great Lakes, and farther off the Atlantic Coast move forward, it is likely that other floating foundation types will be employed, such as the semisubmersible substructure. Whereas fixed-bottom substructures such as monopiles are fixed to the sea floor providing a rigid tower, a floating foundation WTG has added complexity for MVRs due to the sea state which can induce heave, yaw, surge, roll, sway, and pitch (Figure 2.5). These floating WTGs can have translational movements (surge, sway, and heave) and may not always remain at the same position, moving 20–50 m around a center point, depending on the design of the mooring of the WTG. The floating WTGs will be designed to minimize the vertical (heave) and the rotational (roll, pitch, and yaw) movements of the platform.

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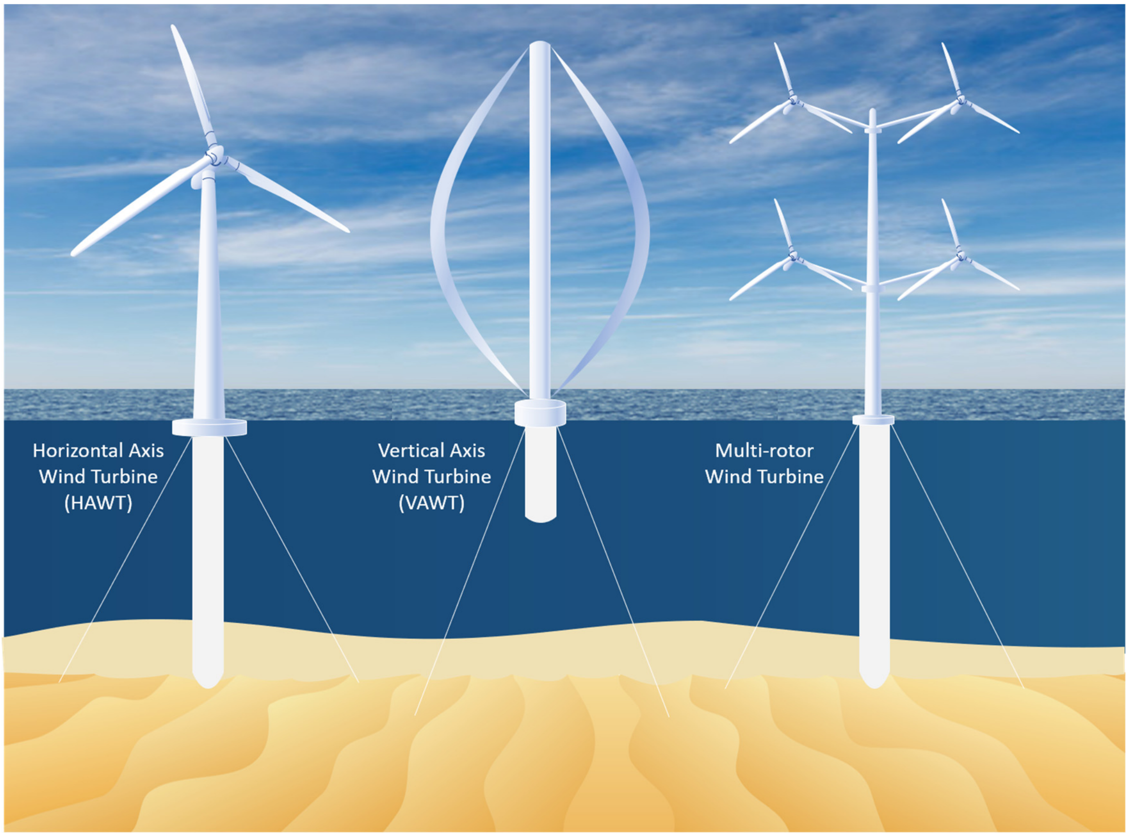

FIGURE 2.4 Examples of offshore wind turbine generators (WTGs). Left shows a horizontal axis wind turbine (HAWT), the standard and expected WTG design for the near to medium term. Vertical axis wind turbines (VAWTs) and multi-rotor wind turbines are being researched and would require additional analysis from the marine vessel radar point of view if deployed in the marine environment. SOURCE: Sandia National Laboratories.

Without terrain features that are present onshore, offshore wind farm developers can arrange the WTGs in a standard grid pattern. Data from BOEM show that a typical layout for a single offshore wind farm within the lease areas off the East Coast of the United States will include turbines spaced approximately 1 nmi × 1 nmi (BOEM, 2021). This distance between WTGs and the orientation of the WTG arrangement within an offshore wind farm may vary from developer to developer (e.g., Figure 2.6), but a regular grid arrangement can be expected. There has been some research into optimizing the micro-siting of WTGs in wind farm layouts (i.e., the distance and angle between one WTG and the next relative to the predominant wind direction) to reduce the wake effects created by upwind turbines on downwind turbines, which can lead to decreased wind speed and decreased power output (Hou et al., 2019). However, given the focus of this study to examine MVRs, which by their nature are moving relative to the WTGs (save for the spacing between the WTGs, which will be discussed in later sections), the orientation of the grid pattern of WTGs in an offshore wind farm is irrelevant. This statement may not be true for other land-based radar types used for air surveillance purposes or for HF radar systems used to track ocean currents, which are beyond the scope of this study.

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Wind Turbine Generator Impacts to Marine Vessel Radar

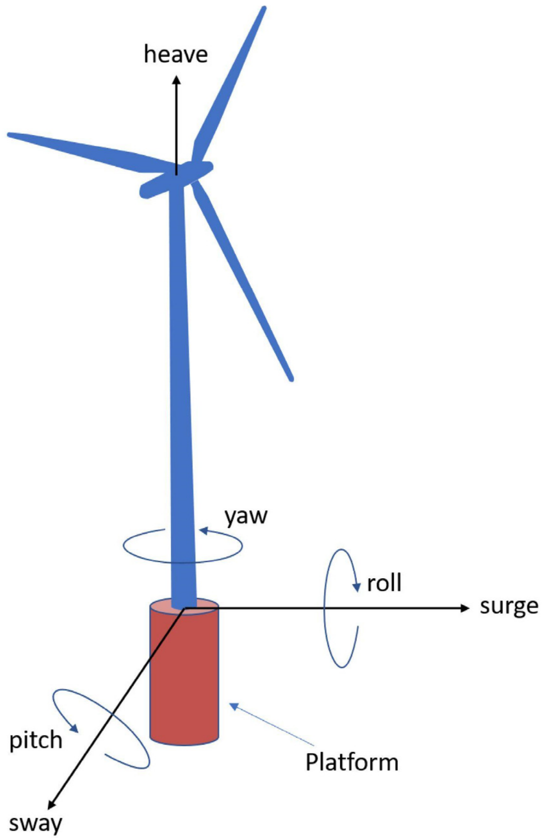

FIGURE 2.5 Representative system dynamics for a floating wind turbine generator. SOURCE: Griffith et al. (2018).

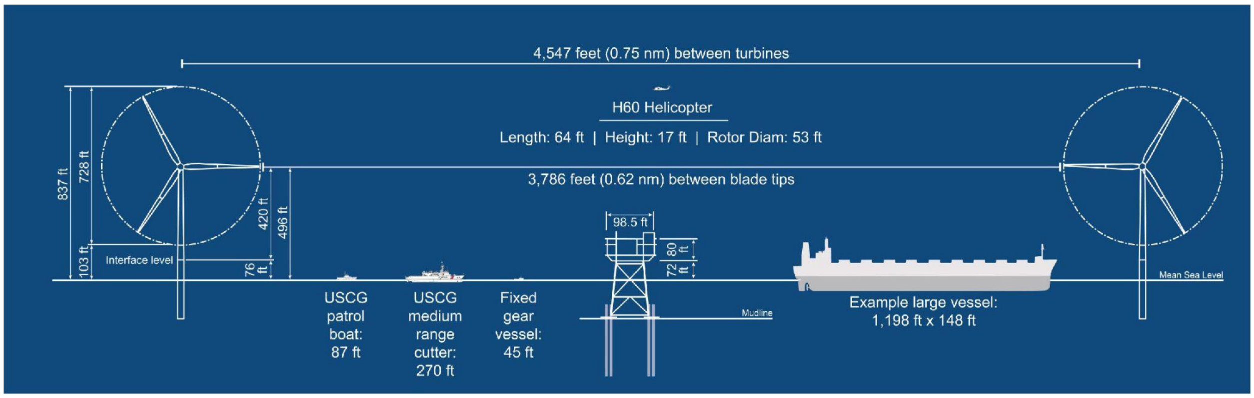

FIGURE 2.6 Scaled representation of vessels common to the Coastal Virginia Offshore Project Area relative to WTG wind turbine generator rotor diameter and 0.75 nautical mile spacing. (Figure 2.1-1 in the 2021 Construction and Operations Plan for the Coastal Virginia Offshore Wind Commercial Project). NOTE: USCG, U.S. Coast Guard. SOURCE: Dominion Energy Services, Inc. (2021).

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With offshore wind farms expected to be designed in a grid pattern, the number of turbines expected for a given project will be dependent upon the size of the offshore lease areas and the distances between WTG rows and columns in the layout, as well as other factors such as the power offtake agreements to the grid, the capacity of the interconnection transmission lines, and the power rating of the WTGs. The data from the COPs submitted by developers to BOEM show projects ranging from 15 WTGs to 174 WTGs per project (BOEM, 2021).

ELECTROMAGNETIC CHARACTERISTICS OF WIND TURBINE GENERATORS

The electromagnetic characteristics of WTGs relevant to MVR are related to their geometries and their material compositions. The largest component of the WTG is the tower, which is nominally constructed of steel to provide structural strength. Since the steel is electromagnetically conductive, the tower is the main source of MVR returns. This is because its physical extent makes it extremely electrically large compared to the operating wavelength of the MVR, thereby creating a very strong radar return. The nacelle is a smaller and more complex mechanical structure, housing the generator and gearbox for the WTG, housed in a fiberglass enclosure to protect the machinery from the elements. The fiberglass enclosure is non-conducting and will allow incoming radar signals to pass through it, while the inner metallic machinery presents a complex electromagnetic scattering profile. Any radar signals that penetrate the fiberglass enclosure will largely be scattered incoherently and not reflected back to the radar source, which translates to a much lower effective RCS than that of the tower, where RCS is a measure of the strength of the backscattered signal from a target to the radar and has units of square meters (specifically, the product of incident power and RCS yields the power of the signal reflected back to the radar). The wind turbine blades are commonly composed of lightweight materials engineered to provide mechanical robustness while capturing wind energy efficiently. These materials may include wood, fiberglass, and carbon fiber composites. The complex dielectric permittivity of these materials determines how well each material absorbs and reflects incoming electromagnetic waves; therefore, the blade composition, construction, and position during operation all affect the degree to which the blades contribute to the WTG's overall RCS. It should be noted that the frequency of the radar has a strong influence on the reflectivity of the blade surface. For example, it has been reported that the lightning protection cable inside the blade can be a dominant contributor to the blade return in the HF band (3–30 megahertz) (Crocker, 2020). However, this is not the case at MVR frequencies, as radar imaging measurements carried out on a utility-class wind turbine (Li et al., 2016) clearly showed that the exterior of the blade gave rise to the dominant radar signature in the frequency range 3.1–5.3 GHz.

When evaluating the total RCS of a turbine, a coordinate system is centered on the turbine viewed from above, with 0 degrees designated as the direction of the front broadside view of the turbine (Figure 2.7). The RCS of a single horizontal axis turbine, dominantly a result of the tower, can be as high as 40 decibels relative to a square meter (dBsm) at S-band frequencies and 45 dBsm at X-band frequencies (Kent et al., 2008) when measured in the electromagnetic near field defined by a range closer than 2*L^2/ λ, where L is the tower height and λ is the radar wavelength. The nacelle's RCS is maximum mainly in the 90-degree and 270-degree directions but is considerably lower than that of the tower. Maximum blade RCS occurs in the 0-degree and 180-degree directions, with Doppler signatures arising from blade rotations (blade flashes) that are maximized in the edge-on radar views (90 degrees and 270 degrees). Blade rotation creates a time-varying

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Doppler signature depending on the speed of rotation of the blades as well as the shape and position of the blades (Naqvi et al., 2010).

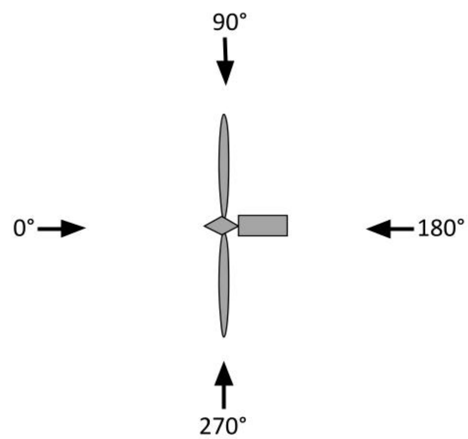

FIGURE 2.7 Aspect angle definitions with respect to the top view of a wind turbine generator.

Past efforts to characterize the RCS of WTGs have led to a thorough understanding of the electromagnetic scattering phenomenology of WTGs. For instance, the Air Force Research Laboratory (AFRL) conducted a comprehensive measurement campaign in 2006 on a land-based wind farm in Fenner, New York (Buterbaugh et al., 2007; Kent et al., 2008). Dynamic radar signatures were collected on a number of 1.5-MW WTGs with a tower height of 65 m and a blade length of 34 m. Subsequently, simulation results were generated by applying the ray-tracing code XPATCH (Hazlett et al., 1995) to a high-fidelity computer-aided design model and compared with the measurement data, thus establishing a level of confidence on the use of simulation tools for predicting WTG signatures.

The anticipated offshore wind facilities in the United States over the next 15 years are considerably larger than those at Fenner, New York, with tower heights ranging from 135 m to 158 m and blade lengths ranging from 105 m to 128 m. Therefore, it is natural to ask how the RCS of these larger turbines will scale and whether they may pose a greater challenge to the operation of MVRs. While it is possible to simulate the RCS of these larger structures to provide turbine-specific data, some general observations can be made based on our current understanding of the WTG scattering physics.

First, based on the physical-optics theory, it is expected that the RCS of a turbine tower will scale linearly as a function of its diameter and quadratically as a function of its height. This means doubling the tower diameter and the tower height will lead to a 2*(2^2) = eight-fold (or 9 dB) increase in RCS (Figure 2.8A). However, in scenarios where the MVR is operating sufficiently close to or even inside the wind farm, several research groups have argued that a taller tower may not give rise to the high level of RCS predicted under the standard far-field condition. This argument, first discussed in Van Lil et al. (2009) and later explored in greater detail in Grande et al. (2014), is that the large RCS predicted by physical optics is due to the constructive interference achieved along the entire length of the tower. However, when the radar is in the near-field region of the tower (as defined by a range closer than 2*L^2/λ, where L is the tower height and λ is the radar wavelength), the portion of the tower farther from the radar does not contribute to the RCS

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(Figure 2.8B). Therefore, the expected RCS under such conditions is considerably less than the far-field RCS. Figure 2.9 shows that the RCS in this region is independent of the height of the tower and actually decreases as the radar gets closer to the turbine. It is expected that most MVR encounters with WTGs fall within this region. Therefore, the actual RCS experienced by an MVR will be much less than that predicted under the far-field condition.

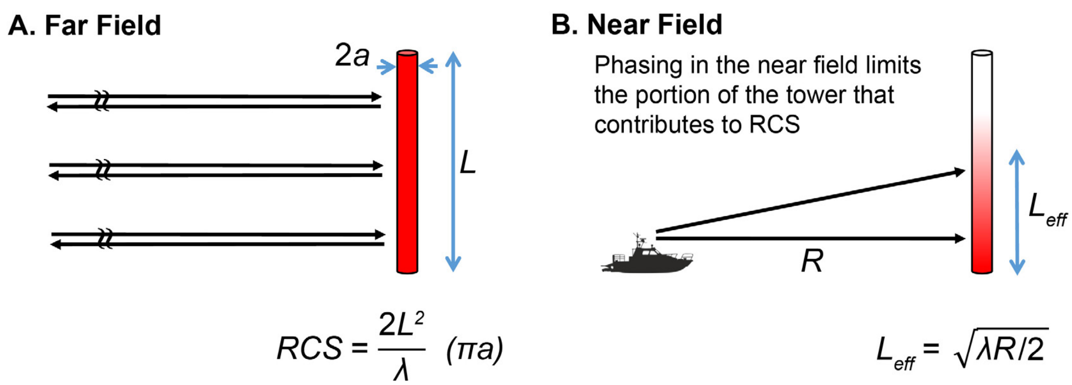

FIGURE 2.8 Illustration of how the radar cross section (RCS) of the tower (modeled as a long conducting cylinder) varies as a function of its length (L) and radius (a) under (A) the far-field condition where the radar is much farther away than the range R=2L^2/λ, and (B) the near-field scenario where the phasing of the incident wave along the cylinder causes the effective length L_{eff} to decrease as a function of range.

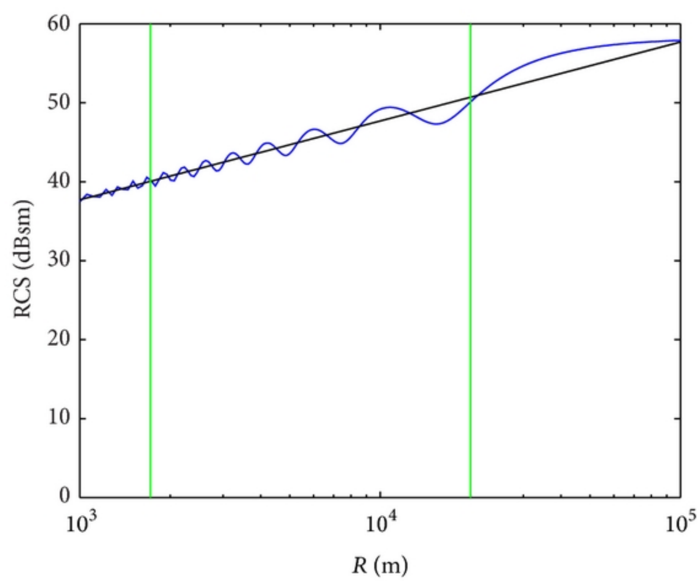

FIGURE 2.9 Radar-cross-section (RCS) values of a tapered cylinder at 3.08 gigahertz, as a function of the distance to the radar (R) in meters (m). Comparison of the proposed method (black line) and the theoretical expression from Welsh and Link (1988) (blue line). Green lines delimit usual distances for offshore wind farms from the coastline (Arapogianni, 2013). SOURCE: Grande et al. (2014).

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Wind Turbine Generator Impacts to Marine Vessel Radar

Second, the turbine blade RCS will likely exhibit the same kind of near-field effect as the tower. A "blade flash" is typically observed in the far field when the blade becomes perpendicular to the radar line of sight. When this occurs, all the points along the blade add coherently in phase. However, if the blade is too long for the radar to be in its far field, near-field phasing effects will limit the region of the blade that contributes to the flash. As the blade continues to rotate, the region moves along the blade and creates a diffused flash in time. In other words, a longer blade does not lead to a stronger flash, but a more extended flash, in the near field. This phenomenon has been observed in field measurements in Li et al. (2016). Additionally, the rotating blades give rise to a time-varying RCS and a corresponding Doppler signature. Even though longer blade lengths are planned for future WTGs, the maximum tip speed of turbine blades is not expected to exceed ~100 m per second (Ennis, 2021). Therefore, the maximum Doppler frequencies are expected to top out at 6.3 kilohertz (kHz) at X-band and 2 kHz at S-band.

Third, larger spacing between turbines will lead to less electromagnetic interaction between turbines. Consequently, it is expected that spurious echoes due to multiple scattering between turbines will lessen as turbine spacing increases. During the 2007 Kentish Flats trial (Marico Marine, 2007), multipath echoes attributable to turbine–turbine scattering were sometimes observed. In that case, the turbine spacing was approximately 0.38 nmi. For larger turbine spacing, spurious echoes due to multiple scattering between turbines will be less prominent.

To summarize, simulation tools exist that can accurately characterize the RCS of larger turbines to be deployed in the next 15 years. Without carrying out such detailed simulation, it can be argued, based on the academic community's current understanding of the electromagnetic scattering characteristics of WTGs, that (1) the RCS of larger WTGs may not scale up as drastically as one may expect from the standard far-field physical optics theory due to near-field phasing effects, (2) the Doppler signature due to longer blades will stay bounded owing to the anticipated limit on blade tip speed, and (3) multiple interactions between WTGs may lessen due to the larger planned spacing between WTGs.

WIND TURBINE GENERATOR IMPACTS ON MARINE VESSEL RADAR

The impact of WTGs on MVR performance is influenced by a number of factors, such as the following:

- MVR design choices, including operating frequency, antenna characteristics, transmitter type, receive processing approach, and ARPA design.
- Characteristics of the WTG deployment, including the RCS of the WTG's constituent components; size and separation of the WTGs; extent of the WTG farm; and blade size, composition, orientation, and tip speed.
- The operating environment, including target RCS, radial velocity, spatial distribution, and course; propagation characteristics, such as anomalous propagation due to ducting, shadowing, and multipath; and sea state affecting clutter signal strength and spectral distribution.

As described above, MVRs typically operate within two distinct frequency bands, depending on vessel size. Larger vessels commonly use S-band (in the vicinity of 3 GHz) systems, as this frequency provides better propagation characteristics in adverse weather. Smaller vessels favor X-band (9.4 GHz), as antenna gain—proportional to effective area divided by wavelength-

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squared—improves for the smaller antenna sizes operating at higher operating frequency. The MVR antenna design incorporates narrow azimuth beamwidth (typically of 1–2 degrees) and very broad elevation patterns (around 20–30 degrees) to compensate for vessel pitch and roll (Acland, 2021; Haynes, 2021; Kunz, 2021). Additionally, the majority of fielded MVRs employ a magnetron-based transmitter and corresponding non-coherent signal processing receive chain. Solid-state transmitters are gaining in popularity, providing better reliability and reduced operating costs; solid-state transmitters provide stable frequency operation, thereby enabling coherent Doppler signal processing on receive. It is currently estimated that roughly 80–90 percent of MVRs are magnetron-based (Haynes, 2021), with the expectation that 50 percent of new MVR sales will be solid state in the future (Acland, 2021; Haynes, 2021; Kunz, 2021).

Magnetron-Based Radar

In the case of magnetron-based MVR, the radar transmits and receives a pulse at the specified operating frequency for a given azimuth. The antenna rotates with typical rates of 24–45 revolutions per minute (Acland, 2021; Haynes, 2021; Kunz, 2021). Range resolution equals the speed of light times the pulse width divided by two, where pulse width is variable and depends on the operating environment. Objects at differing, resolvable ranges experience a time delay from the moment of transmission nominally equal to twice the distance from the radar to the object divided by the speed of light. A processor compares the strength of the received pulses at a given angle and range to an operator selectable threshold (inversely related to receive gain identified in earlier sections); returns that cross the threshold are declared targets. The strength of the return is proportional to the RCS of the reflective object divided by range to the fourth power. While published values for the RCS of a marine WTG vary, sensible numbers are approximately 40 dBsm at S-band and 45 dBsm at X-band, with the RCS of the blades changing as a function of aspect with respect to the nacelle and representing the dominant component of the return from the frontal aspect (Danoon and Brown, 2013; Ling et al., 2013; Hao Ling, personal communication, 2021). In a magnetron-based radar, the composite RCS influencing the strength of the echo return is the result of the complex interaction of all the components of the WTG, where the return from the tower generally dominates for most aspect angles. By way of comparison, the RCS of a small boat is on the order of 0 dBsm, whereas a medium-size ship has an RCS of roughly 40 dBsm, and a larger shipping vessel can have an RCS approaching 60 dBsm (Williams et al., 1978; Nathanson, 1999). Thus, the strength of the return pulse from the WTG is significant and can be about the same as that from a medium-size ship. This means that the radar display of returns over range and angle, referred to as the PPI, is cluttered with WTG returns in the absence of mitigating techniques.

Figure 2.10 shows an illustrative example of a PPI for magnetron-based MVR operating in the vicinity of the Kentish Flats Wind Farm. As seen from the captured PPI display, there are numerous returns from the WTG farm, including the anomalous returns designated by indicators A, B, and C, as well as the regular grid of returns in the lower right part of the display. A number of phenomena complicate a detailed understanding of this PPI display, including multipath between the vessel and radar, as well as sidelobe antenna effects.

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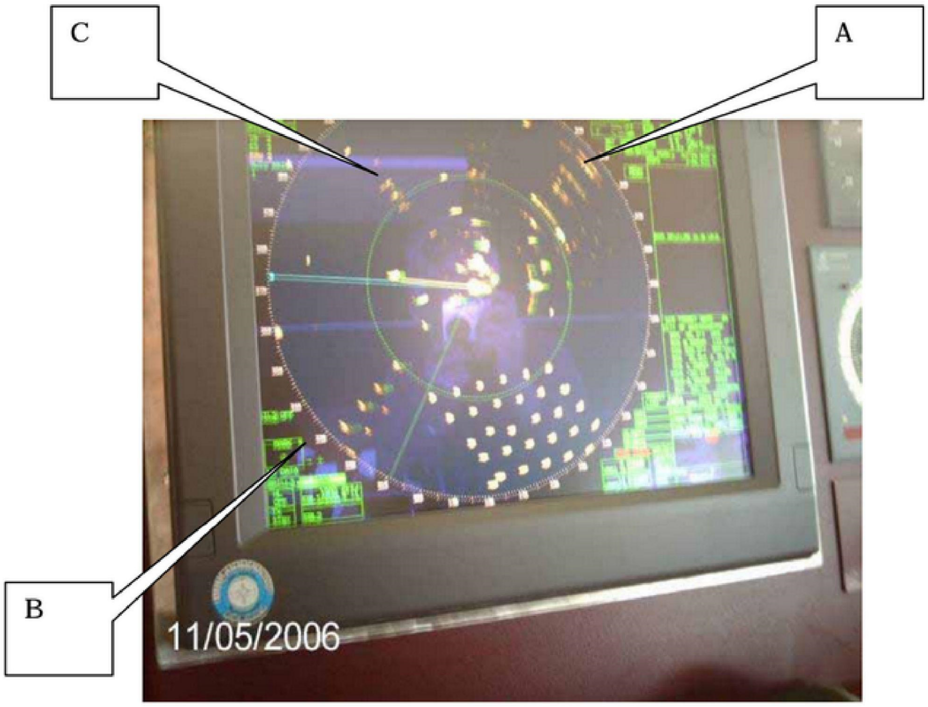

FIGURE 2.10 Illustrative plan position indicator display for magnetron-based radar from the Kentish Flats experiments, where the points A, B, and C highlight the phenomena of multiple target echoes due to wind turbine generator–radar interaction. SOURCE: Marico Marine (2007).

Radar detection typically involves binary hypothesis testing (Skolnik, 1980): the radar must determine which of two models—the null hypothesis or the alternative hypothesis—led to the observation. The null hypothesis is the case of additive interference plus noise, indicating no target. Interference essentially is anything that is not the sought-after target, leading to an important adage in radar: one person's clutter is another's target (Richards, 2005). In contrast, the alternative hypothesis is the case of target plus interference and noise. Different radar designs and modes are capable of distinguishing desired from undesired objects with a high degree of efficacy, depending on the complexity of the system.

Oftentimes, the radar threshold is set algorithmically to meet a desired probability of false alarm —the probability of choosing the alternative hypothesis when no target is present—while maximizing probability of detection (Levanon, 1988). In the case of MVR, the processor simply applies a detection threshold to the receive pulse, which if crossed, leads to the declaration of a target at that range and angle position. For this reason, the typical MVR design appears much more reliant on operator control of the threshold setting than, for example, radar systems used for air traffic control or military applications.

Given the copious detections shown on the MVR display in Figure 2.10, a natural operator response is to adjust the detection threshold upward (reduce the receive gain) to "declutter" the PPI. Unfortunately, the unintended consequence of an increased detection threshold is the suppression of weaker returns from smaller vessels or objects, such as buoys, that "fall under" the detection threshold setting. This undesirable consequence was acknowledged by MVR

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manufacturers, who further indicated that small vessels were primarily the domain of coast guards, navies, and search and rescue (SAR) operators. Moreover, in the context of navigation, it was suggested that smaller boats could easily maneuver out of the way of larger ships. Such statements are concerning, however, as the complexities of multiple ships traversing a large WTG farm may complicate the perceived ease with which small craft can maneuver from harm's way, or the corresponding impact on other vessels responding to attempts to navigate free of collision.

Other factors complicate the interaction between radar and WTG, including propagation-specific effects. Own vessel multipath is a significant concern (Haynes, 2021; Kunz, 2021). Specifically, the coupling between flat plate and modestly curved surfaces on the vessel and the radar leads to WTG detections appearing to come from ambiguous angles. In an environment with a dense population of WTGs, the many ambiguous returns on the PPI hold the potential to confuse operator interpretation of the environment. Additionally, these ambiguous returns will affect the ARPA and calculations of CPA and TCPA, since multipath yields false range and angle information and can affect tracking of more relevant targets.

Ducting is an anomalous propagation mode, whereby temperature inversion layers in the atmosphere result in stratified changes in the index of refraction and a corresponding waveguide effect. It occurs more commonly in marine and humid environments. Ducting can be a concern when interpreting radar returns, as the radar operating range extends beyond normal prediction. In the case of ducting, WTGs at long range can ambiguously enter the radar receive window and be mapped to closer, unambiguous ranges, thereby complicating the operator's understanding of the environment (Colburn et al., 2020; Colburn, 2021). Figure 2.11 depicts the impact of ducting on the radar's field of view. Specifically, ducting allows the radar to see the entirety of WTGs that normally appear beyond the radar line of sight (LOS) using the standard 4/3 Earth model. Ducting increases at lower operating frequencies. Additionally, the MVR's broad elevation pattern, used to mitigate vessel pitch and roll, exacerbates the ducting problem, as it provides high gain illumination out to the radar horizon. Figure 2.11 further suggests that MVR will see distant tops of WTG farms even under normal propagation conditions. The likely result is the inclusion of additional returns cluttering the PPI display.

Shadowing occurs when an object impedes the LOS between the MVR and other objects further in range. Depending on the orientation among radar, target, and turbine layout, WTGs can mask radar contact during the course of a target's trajectory. Targets lost in shadow do not appear on the PPI, nor figure into the ARPA calculations leading to CPA and TCPA. Figure 2.12 shows a transmission simulation of a 3-GHz radar within a 3 × 3 grid of WTGs with 3.3-m diameter towers; the streaks running from the lower left to upper right have null depths of ~6 dB and represent the shadowing effect. The radar's ability to detect targets passing through a shadow is diminished, but the shadows are very narrow. For the more likely case of larger diameter WTGs and a larger farm, the study committee expects shadowing effects to worsen. However, shadowing is a lower order effect on the MVR in comparison with other factors, such as strong reflections from the WTG tower and ambiguous multipath returns.

Operation within the WTG farm will lead to additional effects on the MVR. Notably, within the WTG farm, concerns include receiver saturation due to large reflections from nearby objects; a highly complex multipath environment, including energy reflected from one WTG to another, and target returns reflecting from WTGs; and diversity of viewing angles to WTG blades leading to spatial variation in the WTG RCS.

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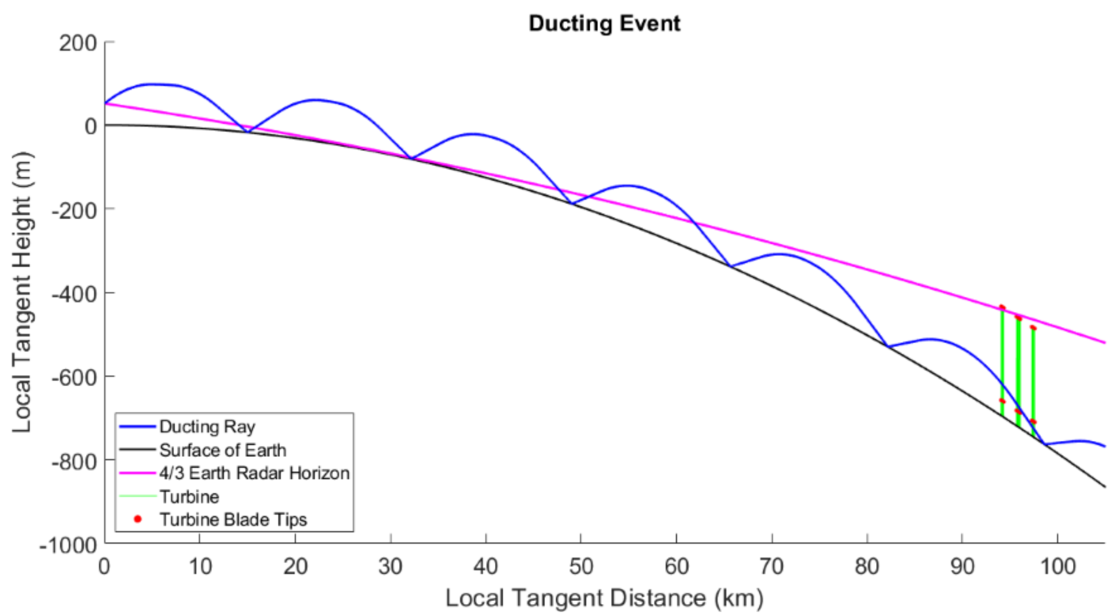

FIGURE 2.11 Ducting allows the radar to see objects below the radar horizon, bringing wind turbine generators at far range into the radar field of view and complicating the operating picture. SOURCE: Colburn et al. (2020).

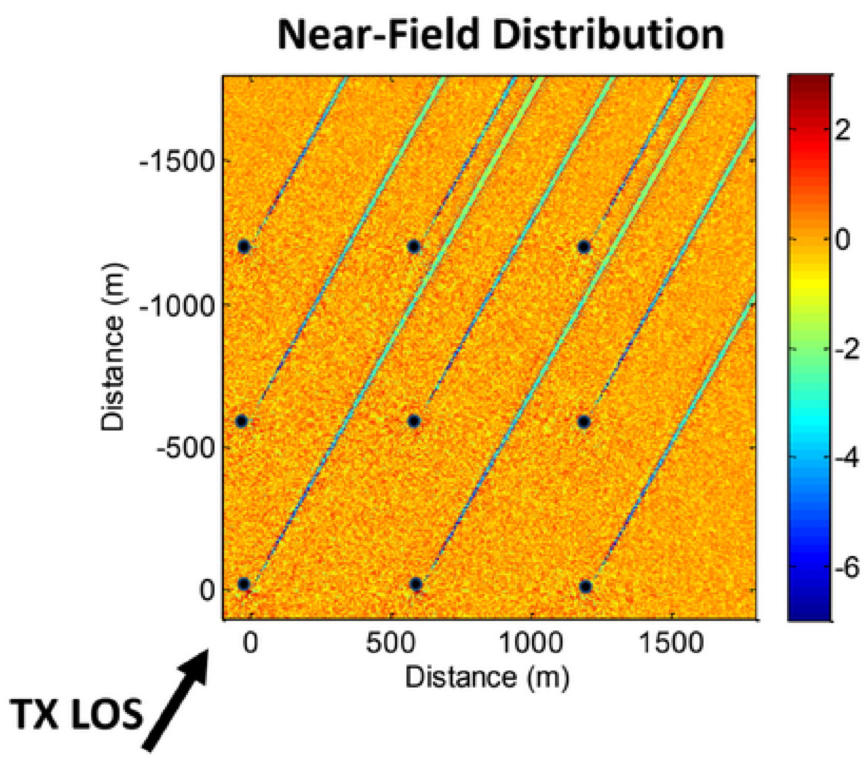

FIGURE 2.12 Shadowing effects within the wind farm (color bar in decibels), where the transmitter line of sight is denoted "TX LOS." SOURCE: Ling et al. (2013).

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At close range, the strength of the return echo may saturate the receiver amplifiers and exceed the dynamic range of the digitization stage, leading to distortion of the receive signal and further suppression of weaker targets. Distortion includes signal harmonics that degrade the radar scene with additional, spurious signals.

Multipath within the WTG farm can lead to additional echoes from a given WTG, with the multipath signal occurring at a later range. Multipath echoes contaminate additional range bins, appearing on the PPI as a multiplicity of anomalous detections, and can result from interactions with passing vessels, as shown in Figure 2.13; indicator A represents reflections from the Shivering Sands Towers, whereas indicator B identifies multipath reflections from a large vessel with flat sides.

FIGURE 2.13 Multipath example within proximity of wind turbine generators. SOURCE: Marico Marine (2007).

The RCS of the WTG blades is highly dependent on the aspect between the radar and the WTG nacelle, assuming a horizontal axis wind turbine, so as the vessel traverses the WTG farm, the performance of the MVR will vary dynamically and create a complex PPI display for operator interpretation. Figure 2.14 shows the variation of RCS for the case of smaller, land-based WTGs with 34-m blades and a 65-m tower; the RCS of the land-based WTGs is roughly 20–25 dB smaller than their marine-based variants since RCS is inversely proportional to wavelength and proportional to the square of the tower height times the tower diameter (Hao Ling, personal communication, 2021). The red lines in Figure 2.14 correspond to measurements under the AFRL Fenner data collection program, and the blue lines are simulated using a highly validated, computational electromagnetics code called XPATCH (Hazlett et al., 1995). The left-most panel

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in Figure 2.14 is shown for 1.5 GHz and the frontal incidence, so the response is relatively constant, whereas the right-most panel of Figure 2.14 is at 3.6 GHz and 137 degrees from frontal incidence, so that RCS varies substantially as the blade rotates. At X-band, the RCS will increase by roughly two orders of magnitude over the L-band result. The larger size of marine WTGs will also result in larger RCS values in general. The radar will commonly be in the near field of the WTG, resulting in variability in the effective RCS of the WTG. Thus, as previously stated, expected values for WTG RCS are approximately 40 dBsm at S-band and 45 dBsm at X-band.

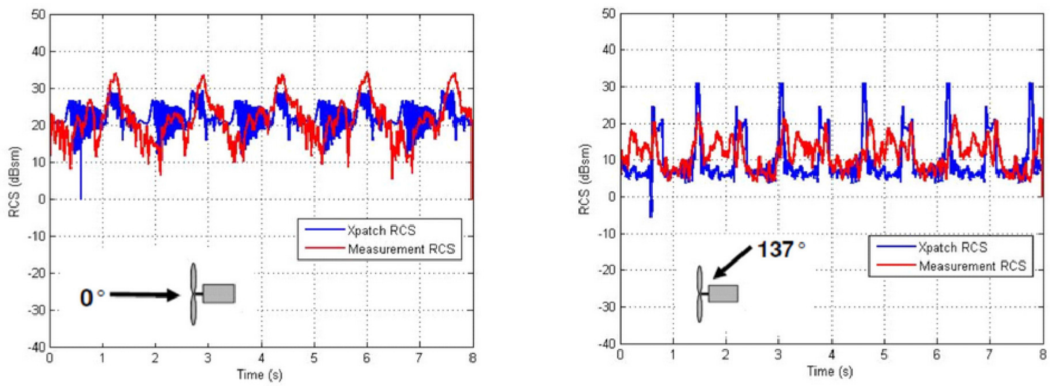

FIGURE 2.14 Measured and simulated radar cross section (RCS) for land-based wind turbine generator. The left panel shows a 1.5-gigahertz (GHz) example. The right panel shows a 3.6-GHz example. SOURCE: Ling et al. (2013).

A detailed assessment concerning the impact of WTGs on MVR requires, in part, physics-based modeling, simulation, and analysis combined with collection and interpretation of field test data anchoring the simulation software. An example for a simulated land-based radar operating in the presence of WTG interference was shared in a presentation to the committee (Figure 2.15). Using WINDTRX, which combines a highly validated U.S. Department of Defense radar model called ESAMS with a scatter-based model for a WTG, Figure 2.15 shows an example of signal-to-interference ratio (S/I) for a Federal Aviation Administration ASR-9 situated at the John F. Kennedy International Airport for a 0 dBsm target (Colburn et al., 2020; Colburn, 2021). The ASR-9 is a solid-state radar employing clutter suppression and Doppler filtering (Taylor and Brunins, 1985). While this scenario corresponds to a land-based, solid-state radar, the impact of the WTG on performance is evident and cautionary for MVR. Specifically, the region of low S/I (shaded blue in Figure 2.15) in the southeasterly direction is attributed to the unmitigated impact of WTGs on radar performance. In general, reliable detection requires an S/I of approximately 13 dB, so the region shown in blue in Figure 2.15 represents substantial degradation in detection capability, with expected detection rates of less than a few percent for returns from objects other than WTGs with RCS values less than 20 dBsm, and only ~25 percent for an object with RCS of approximately 30 dBsm. In the context of MVR, Figure 2.15 confirms that WTGs are significant sources of interference to detecting moving targets and smaller stationary objects, such as navigation buoys. To reiterate, this example does not apply bespoke methods to mitigate WTG interference possible with solid-state radar technology, a topic considered subsequently in the context of MVR.

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Doppler-Based Solid-State Radar

Solid-state radar was primarily introduced by MVR manufacturers for reliability improvements over magnetron-based systems. Solid-state radar provides a stable local oscillator, a prerequisite for pulse compression and Doppler processing, or what is commonly referred to as coherent radar signal processing. The terms "Doppler-based radar" and "solid-state radar" are used interchangeably in this section and throughout the remainder of the report. Pulse compression allows the radar to transmit energy over a long, coded pulse while achieving the resolution of a short pulse (Melvin and Scheer, 2012). Doppler processing further enables the radar to aggregate target reflected energy over multiple pulses, thereby increasing signal-to-noise ratio (SNR), and further allows separation of signal reflections with different range-rates relative to the radar LOS. The corresponding range-rate is a result of the combined motion of both the radar and the object under illumination, so even stationary objects—such as coastlines, bridges, and buoys—will have a non-zero Doppler shift depending on their angle relative to the marine vessel's velocity vector.

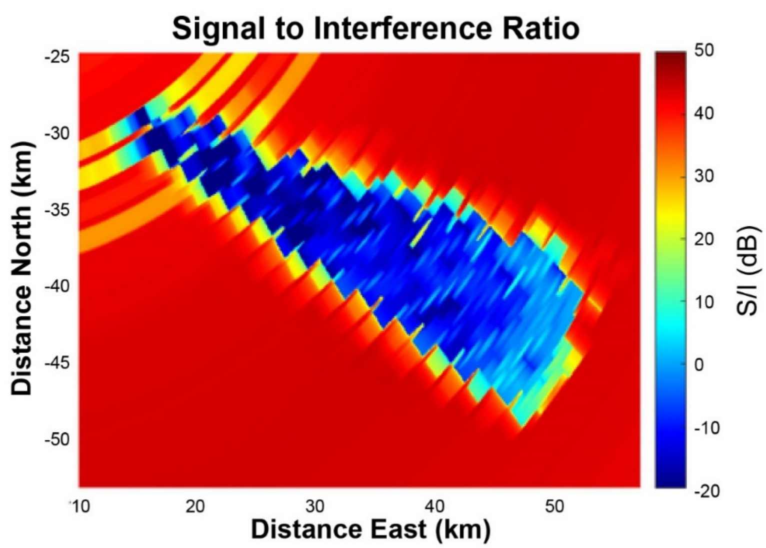

FIGURE 2.15 Signal-to-interference (S/I) ratio calculation for a 0 dBsm target near the John F. Kennedy International Airport, simulated using the WINDTRX model. SOURCE: Colburn et al. (2020).

Radar manufacturers increasingly offer solid-state radar with Doppler processing to their patrons (Acland, 2021; Haynes, 2021; Kunz, 2021). With Doppler processing, the radar can instantaneously determine whether a target is approaching or receding, and how quickly. Additionally, each Doppler filter has an angular beamwidth for stationary objects, which gets finer with longer dwells; this enables Doppler-based radar to more finely map out coastlines, docks, underpasses, etc. Conversely, Doppler-based radar can separate returns from stationary objects and moving objects, thereby improving the radar sensitivity to moving targets and smaller stationary objects since each target return only competes with the RCS of those returns within its Doppler filter, as opposed to magnetron-based radar where the target competes with the aggregate sum of all reflections within the range bin of interest.

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With the aforementioned in mind, the WTG impacts solid-state radar similarly to the magnetron-based radar systems, with the distinction that solid-state radar can separate objects by Doppler frequency. Stationary objects, such as the WTG tower or a buoy, appear at a fixed Doppler depending on the angle between the object location and the marine vessel direction of motion. Thus, WTG towers at different angles will have different Doppler shifts. Reflections from the WTG blades will generally yield returns over a continuum of Doppler frequencies, depending on the orientation of the radar to the blade motion. Figure 2.16 shows the simulated spectrum for a nominal WTG and an orientation where the blades appear to rotate toward the radar given the spread of the Doppler response (Colburn, 2021). The Doppler returns from the blades can lead the radar to determine the presence of approaching and receding targets (Haynes, 2021; Kunz, 2021). With many WTGs in the radar field of view, the operator will have to contend with a potentially confusing radar picture if relying on Doppler information and absent any mitigation strategies.

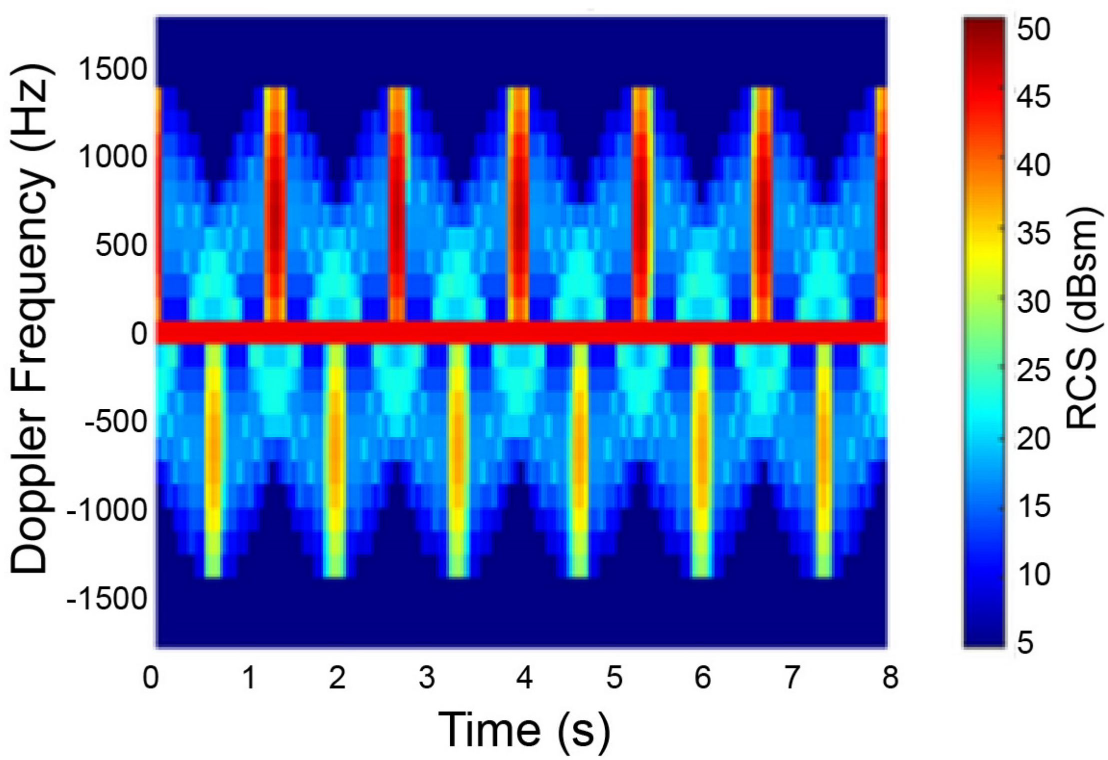

FIGURE 2.16 Wind turbine generator spectrogram (Doppler frequency versus time). SOURCE: Colburn et al. (2020).

A detailed description of how WTGs manifest in Doppler-based radar is given in Figure 2.17. Panel A of Figure 2.17 shows the geometry among a vessel with MVR, regularly spaced WTGs, and two moving targets. As seen, target T1 approaches the port side of the vessel carrying the MVR, whereas starboard target T2 moves away from the radar in the cross-track direction. Panel B of Figure 2.17 plots Doppler frequency versus the change in angle measured 90 degrees clockwise from the MVR's velocity vector (so, 0 degrees is nominally port side). This convention is chosen to place stationary objects orthogonal to the MVR's velocity vector at 0 Hertz Doppler

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and is often called the sidelooking radar case. Target T1 appears in the vicinity of 80 degrees, with the chosen convention that approaching targets are given positive Doppler frequency. Target T2, near 100 degrees, shows a Doppler frequency that is the result of the combined motion of both vessels; assuming both vessels move with similar velocities, the MVR appears to approach target T2, yielding a positive Doppler lower in frequency than target T1. It is important to note that Panel B shows the angle and Doppler response of targets and WTGs from different ranges; in practice, the radar further separates objects at different ranges based on time difference of arrival.

The Doppler frequency of a stationary object is strictly a function of angle between the MVR and the non-moving object; objects orthogonal to the velocity vector (at a change in angle of 0 degrees, 180 degrees, and –180 degrees) have zero Doppler, as there is zero range-rate with respect to the MVR. Stationary objects near the bow or stern, at 90 degrees or –90 degrees, approach with maximum positive and negative Doppler relative to other non-moving objects, as the radar moves with highest or lowest range-rate relative to these points. All other objects fall along the sinusoidal curve shown in Figure 2.17, as the Doppler is strictly given as twice the projection of the MVR's velocity vector onto a unit vector pointing toward the object of interest divided by the radar operating wavelength (Richards, 2005). In the absence of multipath reflections, the returns from the wind farm towers fall on the sinusoidal line, and any Doppler due to blade motion will extend off of the sinusoidal stationary return line. Thus, the blade Doppler falling off of the sinusoidal line will compete with returns from moving targets and can mask detection of smaller vessels. The differences in the vertical dashed lines corresponding to WTG Doppler suggest different amounts of Doppler spread based on orientation between radar and nacelle.

Range-Doppler sidelobes are another unique aspect of solid-state radar relative to its magnetron-based counterpart. Solid-state radar enables increased duty cycle waveforms yet achieves the resolution of short pulses using a matched filtering method colloquially called pulse compression. The range response of a standard linear frequency modulated waveform is a sinc (sin(x)/x) pattern, exhibiting a mainlobe and, depending on the weighting function, a sidelobe response that is nominally 40–60 dB below the mainlobe peak in the near sidelobe region, further diminishing away from the peak. As a result, a WTG may yield sidelobes in range appearing as additional detections or interference to weaker targets. A similar effect occurs with Doppler processing, where the radar coherently integrates multiple pulses to achieve the SNR of a longer pulse, and the resulting Doppler sidelobes for WTGs may appear as additional detections or can mask weaker targets in the absence of tailored signal processing methods. It is important to point out, however, that all of the energy returned from a WTG in magnetron-based radar competes with the target at that same range, whereas coherent range-Doppler processing generally minimizes those challenges so that primarily the weaker interference signal within the same range-Doppler cell competes with the target of interest. Figure 2.18 illustrates the range-Doppler response for a target and WTG, depicting each object's range-Doppler response, including the two-dimensional sidelobe response extending over the range-Doppler map. In comparison to Figure 2.16, the Doppler spread of the WTGs is variable over range due to changes in aspect between MVR and WTG nacelle. Additionally, Figure 2.16 does not depict the Doppler sidelobe responses, which spill off of the sinusoidal response in the vertical direction absent any mitigation.

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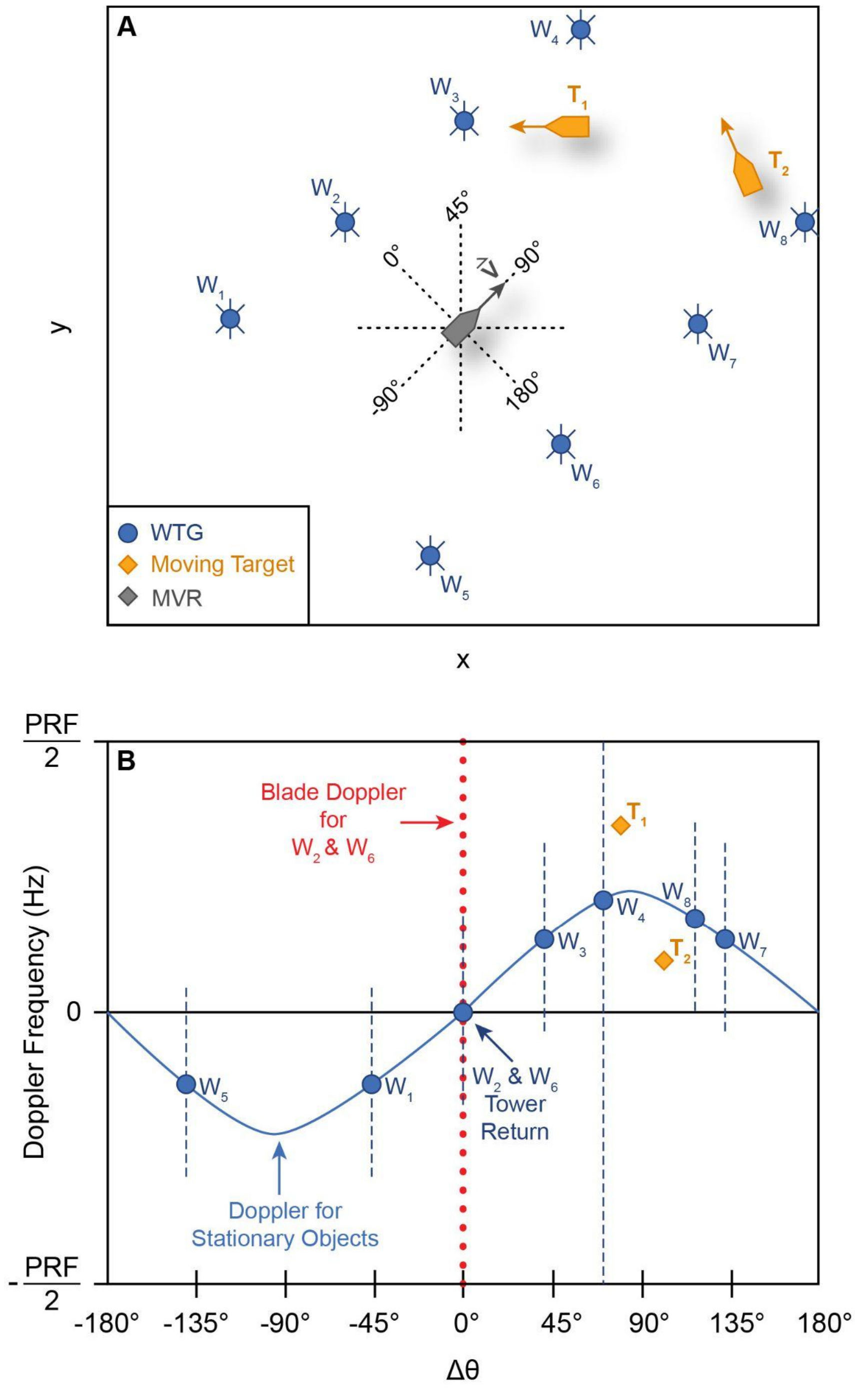

FIGURE 2.17 Description of solid-state radar Doppler processing in the presence of wind turbine generators (WTGs). In Panel B, PRF is defined as the pulse repetition frequency, or the rate at which the radar transmits and receives pulses. Δθ is defined as the change in angle measured starting 90 degrees to the portside and proceeding in a clockwise direction relative to the velocity vector (v) of the observer's shipboard marine vessel radar (MVR) (also referred to in this report as "own vessel") depicted in Panel A. This figure collapses returns from different range bins into the angle-Doppler domain.

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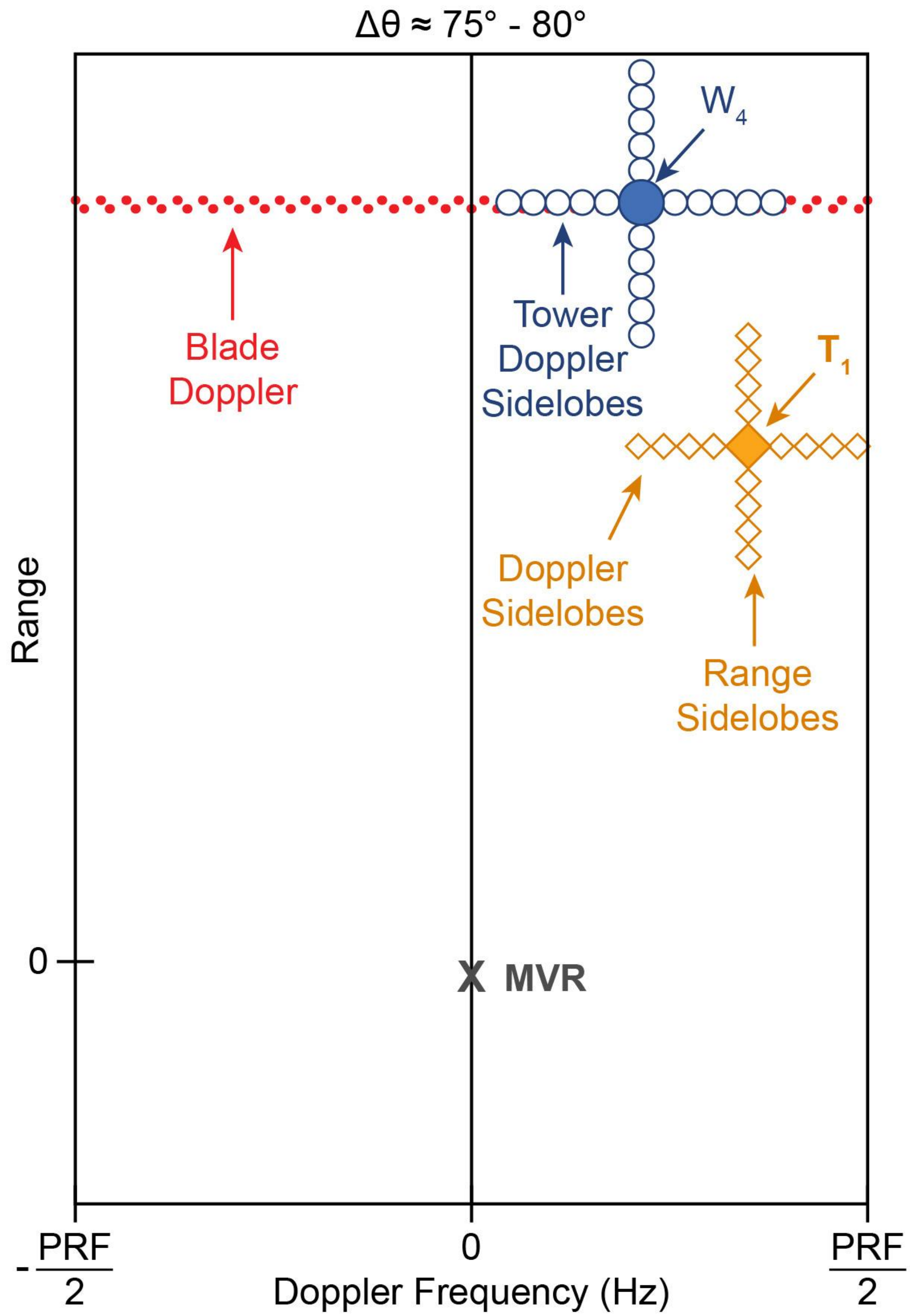

FIGURE 2.18 Range-Doppler response for wind turbine generators (W) and targets (T) of varying size, including sidelobes. PRF is defined as the pulse repetition frequency, or the rate at which the radar transmits and receives pulses. Δθ is defined as the change in angle measured starting 90 degrees to the portside and proceeding in a clockwise direction relative to the velocity vector of the observer's shipboard marine vessel radar (MVR), such that 90 degrees is the direction of travel.

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The impact of WTG on solid-state radar requires further assessment, as the majority of fielded radar, and hence collected data on WTG impacts, are magnetron-based. The well-known Kentish Flats Wind Farm results, for instance, correspond to a magnetron-based radar (Marico Marine, 2007). As reliability is the primary motivation for the introduction of solid-state radar, vendors have sought a direct replacement to magnetron transmitters. Thus, commercial vendors have not modified the processing chains of solid-state radar to exploit the full potential of Doppler-based radar to mitigate WTG effects. For currently available solid-state products, however, there is limited availability of data supporting strong assertions, one way or the other, concerning solid-state radar performance in a WTG environment. Although major developers of MVR acknowledge that WTG returns may affect the efficacy of their products, they assess the radar's overall performance as acceptable (Acland, 2021; Haynes, 2021; Kunz, 2021).

Both magnetron-based and solid-state radars generally use an ARPA to assemble radar measurements into target tracks. The ARPA determines CPA and TCPA for the operator and provides warnings if both quantities fall below a minimum specified value. The role of the tracker underlying the ARPA is to take target range and angle measurements and assemble a track for that object relative to the radar. The ARPA requires logic to identify priority targets. The impact of WTGs on the ARPA is a function of the ARPA algorithms and software implementation. In the committee's investigation, the impact of WTGs on ARPA performance was not evident. However, since the ARPA must draw on radar measurements to produce its core products, WTGs must have an impact. For example, WTGs can cause lost tracks as contacts are lost due to the aforementioned cases of shadowing or increased thresholding; spurious multipath can confuse any measurement-to-track association; and the multiplicity of returns from the WTG farm can overwhelm the tracker's computational capabilities.

In addition to navigation and collision avoidance, during the course of the committee's information-gathering sessions, it became evident that mariners employ MVR for a number of secondary uses, such as finding fishing nets, employing radar reflectors, and tracking birds to identify schools of feeding fish (Acland, 2021; Draher and Baker, 2021). WTGs will affect these specific radar uses more prominently than navigating in the vicinity of large marine vessels, given the generally low cross section of these objects. Similarly, WTGs may affect radar use for SAR operations, where WTG returns will compete with the reduced RCS of a person or disabled vessel. In general, WTGs will affect small target detection, thereby affecting MVR use by coast guards searching for illicit cargo on small boats, for navies searching for weak target returns in the conduct of their normal operations, and for SAR.

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3
Mitigating Solutions for Wind Turbine Generator Effects on Marine Vessel Radar

STAKEHOLDER NEEDS AND CAPABILITIES

When navigating in congested waters, the ability for a vessel to maintain a clear operating picture of other vessels, potential hazards, and obstructions is paramount, and requires an effective use of a mix of visual lookout and electronic sensors. A clear and understandable radar picture can provide the capability to see beyond the limits of the human eye, and provide the mariner an enhanced ability to safely navigate, appropriately respond to potential collision avoidance scenarios, and reduce risks associated with operating in the marine environment.

As previously discussed within this report, the Marine Transportation System (MTS) is grappling with a large growth in the development of Offshore Renewable Energy Installations (OREI), such as wind farms. While the U.S. Coast Guard is seeking to provide the mariner safe access to ports by designating shipping safety fairways and traffic separation schemes throughout the MTS, the location of the OREI in relation to these proposed shipping lanes may still pose risk to marine navigation. The presence of wind farms coupled with the subsequent shipping safety fairways is expected to funnel large, offshore commercial traffic into designated maritime traffic lanes. This consolidation of maritime traffic routes offshore in the vicinity of wind farms could potentially congest maritime traffic in previously unrestricted locations, and thus pose novel risks in the U.S. offshore maritime environment, highlighting the importance of reliable navigation systems aboard vessels operating in the U.S. Outer Continental Shelf (OCS) (Detweiler, 2021).

Concurrently, some smaller vessels are expected to transit through wind farms on a regular basis. Commercial fishing vessels are expected to transit through wind farms to their fishing grounds from their homeport, and passenger vessels may transit within the wind farms as a destination attraction (Salerno et al., 2019).

The consolidated sea space resulting from the presence of the wind turbines while navigating through a wind farm could reduce the maneuvering options that a vessel may have when a risk of collision exists. Furthermore, the presence of these turbines reduces a mariner's visual acuity by obscuring other vessels transiting through the wind farm. This reduction in visual acuity is exacerbated aboard larger commercial vessels transiting within the designated shipping lanes adjacent to the wind farms (Detweiler, 2021).

As detailed in this report, the operating picture provided by marine vessel radar (MVR) is also impacted by the presence and operation of wind turbines. If vessels are to operate both within and adjacent to offshore wind facilities, given these risks and the established international agreements and domestic regulations requiring the use of MVR for safe marine navigation, OCS stakeholders will need to determine mitigation strategies to address the impacts wind turbine generators (WTGs) can have on MVR. In contrast to investments by developers and operators of air traffic control[26] and military radar systems, compelling WTG mitigation techniques for MVR have not been substantially investigated, implemented, matured, or deployed. Within the following sections, the committee provides recommendations to mitigate the impacts of WTG on MVR.

[26] See https://www.faa.gov/air_traffic/technology/asr-11/.

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MITIGATION METHODS

Operational

Greater Utilization of Non-Radar Navigation Tools

If the effectiveness of MVR is degraded, vessel watchstanders will have to more heavily rely on other tools in order to maintain situational awareness at sea. Examples of supplementary tools that are available to vessel operators include additional watchstanders, Automatic Identification Systems (AIS), and the Electronic Chart System (ECS)/Electronic Chart Display and Information System (ECDIS). These tools can provide additional context to aid the operator's interpretation of the radar display but are not able to replace the instantaneous, active engagement with the environment of an MVR, especially considering the MVR's significant coverage in range and angle over diverse weather and light conditions.

Additional Watchstander(s)

Adding more eyes and ears to monitor the equipment, the vessel (position, course over ground, etc.), and the surrounding environment via additional watchstanders could assist mariners when navigating through or adjacent to a wind farm. As previously noted, both the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (72 COLREGS),[27] and the Inland Navigation Rules as published in Title 33 Code of Federal Regulations (CFR) subchapter E[28] require all vessels to "maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions," at all times. The number of personnel available to stand look-out varies depending on the size of the vessel and the subsequent crewing requirements delineated throughout Title 46 of the CFR.[29] Fatigue and the impairment it causes are of great concern in the maritime industry. To that end, Regulation VIII/1 of the Standards of Training, Certification and Watchkeeping (STCW) (IMO, 2018) sets out hours of rest requirements for seafarers with designated safety, security, and prevention of pollution duties, which would include watchstanders and lookouts. Consequently, adding watchstanders to a specific watch could prohibit those individuals from standing a subsequent watch. Additionally, the credentials and experience of the available personnel will vary depending on the size and class of the vessel. Not all members of a vessel's crew are required to have training as a lookout and a thorough understanding of 72 COLREGS or the Inland Navigation Rules, further limiting the available personnel to serve as an additional watchstander.

The U.S. Coast Guard has stated that it does not, in general, intend to designate OREI as areas to be avoided, and mariners are advised to navigate through at their own risk (Detweiler, 2021). As such, it is incumbent upon the mariner who chooses to navigate through or adjacent to a wind farm to determine if additional watchstander(s) would be needed (see Chapter 2 discussion on voyage planning). As noted above, the number and experience of available personnel will vary depending on the size and class of the vessel, making the mitigation method of adding watchstanders feasible in some instances but infeasible in others. Because navigating through or adjacent to a wind farm is a choice determined by the master of the vessel, and not a legal

[27] See https://www.imo.org/en/About/Conventions/Pages/COLREG.aspx.
[28] See https://www.ecfr.gov/current/title-33/chapter-I/subchapter-E.
[29] See https://www.ecfr.gov/current/title-46.

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requirement, mandating a new requirement through government regulation is unlikely. If such a requirement were to be pursued, crewing requirements would need to account for training and credentialing of the additional watchstanders to fulfill the regulatory requirement.

Automatic Identification Systems

AIS[30] are a shipboard broadcast systems that operates in the very high frequency (VHF) band, and consists of a VHF transmitter, two VHF Time-division Multiple Access receivers, a VHF Digital Selective Calling receiver, and standard marine electronic communications connections to the shipboard display and sensor systems. AIS can broadcast information such as the ship name, call sign, course and speed, classification, registration number, and Maritime Mobile Service Identities. Maneuvering information, closest point of approach, heading information, time to closest point of approach, course over ground, speed over ground, estimated time of arrival, and other navigation information can also be broadcast via AIS. Position and timing information is typically derived from a global navigation satellite system (e.g., Global Positioning System [GPS]) receiver. By monitoring AIS data, watchstanders will have the ability to receive information regarding other vessels, aids to navigation, and structures in the area.

Currently, there is no mechanism to ensure the accuracy and authenticity of AIS data. Therefore, it is imperative for mariners to exercise caution when relying on the information provided due to faulty GPS units either integrated into the AIS unit or attached to the AIS in addition to the AIS units not being set up properly and inaccurate information input. Although 33 CFR 164.46[31] describes which vessels are required to have a properly installed, operational AIS, the applicability of this regulation is currently only within U.S. Navigable Waters as defined in 33 CFR 2.36,[32] which only applies up to 12 nautical miles (nmi) offshore. Since a majority of the OREI will be developed outside 12 nmi on the U.S. OCS, use of AIS is not required on all vessels operating in the vicinity of WTGs. It is, however, feasible for the U.S. Coast Guard to pursue a regulatory change that would require AIS use out to 200 nmi. Additionally, the required minimum keyboard display is basic (Figure 3.1). The feasibility of using AIS to assist with safe navigation within an OREI would be dependent on capabilities of the AIS installed, its integration with other installed navigational equipment, and the accuracy of the information inputted into the system (Figure 3.2).

Existing AIS technology could allow OREI developers to install AIS transceivers on specified wind turbines and could assist the mariner when navigating through the wind farm. However, AIS transmitters would best be used sparingly to highlight particular WTGs important to maintain situational awareness such as the corners of a wind farm.

Electronic Chart System and Electronic Chart Display and Information System

Similar to AIS, ECS and ECDIS are not required on all vessels. ECDIS and ECS are navigational information systems, interfaced with other navigational equipment such as the GPS, Gyro, Radio Assisted Detection and Ranging (RADAR), Automatic Radar Plotting Aid (ARPA), and Echo Sounder. ECDIS is a high-quality ECS, which meets the requirement of the International

[30] A detailed overview of AIS can be found via the U.S. Coast Guard Navigation Center (NAVCEN) website, https://www.navcen.uscg.gov/?pageName=AISmain.
[31] https://www.ecfr.gov/current/title-33/chapter-I/subchapter-P/part-164/section-164.46
[32] https://www.ecfr.gov/current/title-33/chapter-I/subchapter-A/part-2/subpart-B/section-2.36

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Maritime Organization (IMO) performance standard and has been tested by an independent type-approval authority. ECDIS has several advantages over paper charts for navigation. For example, all information is processed and displayed in real time, alarms and indications are available to indicate dangers, charts can be customized to meet the needs of the voyage, features can be examined more closely via zoom capabilities, charts can be interrogated for detailed information, and other navigational equipment (e.g., AIS, ARPA) can be overlayed and integrated for display (Bhattacharjee, 2021).

While ECDIS facilitates passage planning, chart correction, orientation, review of navigational information, and other activities in support of safe navigation, it also has some limitations. The accuracy of the information received via AIS or other equipment interfaced with the ECDIS is only as good as the accuracy of the information transmitted to that equipment. Some sensors providing information may lack integrity with regard to accuracy. Additionally, the position of ships received on an ECDIS display may not be referenced to the same coordinate system. It is therefore imprudent for the officer of the watch to depend solely on the information on the ECDIS—an aid to navigation that does not replace the human quotient, which brings in the skill and expertise with experience that an ECDIS cannot provide (Bhattacharjee, 2021).

FIGURE 3.1 Furuno FA-170 Class A Automatic Identification Systems (AIS)–required minimum keyboard display (MKD). Only “Class A” AIS must have an MKD as part of the system. SOURCE: Furuno Electric Co., LTD (2021).

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Wind Turbine Generator Impacts to Marine Vessel Radar

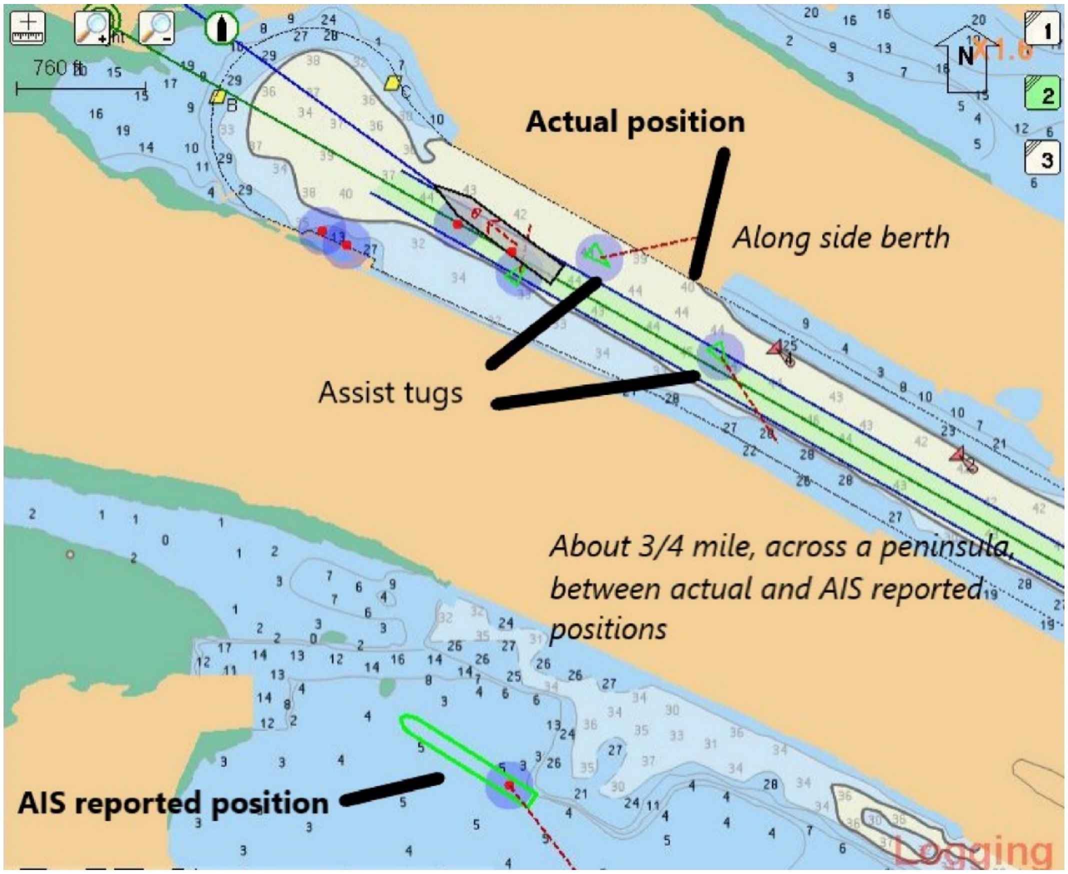

FIGURE 3.2 An example of erroneous data broadcast by Automatic Identification Systems (AIS). In this scenario, a vessel (situated in the area labeled "Actual position") was beginning to back away from the berth with two assist tugs (AIS positions are correct) with a draft of 35+ feet but shown in 4–5 feet of water (erroneous location is shown in green and labeled "AIS reported position").

New Technology

The integration of new technology onto vessels operating in and around offshore wind farms may enhance situational awareness in the event that radar systems are compromised. Infrared camera systems and Light Detection and Ranging (LiDAR) are not required to be carried, and are rarely seen on U.S. vessels, but may be useful in detecting targets missed by other means. Infrared maritime thermal camera systems are based on the principle that all objects emit thermal energy, and different objects can emit different thermal signatures. Sensors integrated into infrared detection systems can perceive and convert thermal energy emitted by an object above absolute zero into an electrical signal that can be processed to create an image.[33,34] Infrared systems can therefore provide vessel operators with the ability to sense targets in the infrared part of the electromagnetic spectrum, in total darkness and through solar glare, and with performance diminished in the presence of fog and smoke. Infrared thermal vision may bring improved clarity

[33] See https://www.lynred.com/blog/infrared-technology-and-thermal-cameras-how-they-work.
[34] See https://www.flir.com/about/about-flir/.

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to confusing and dangerous situations on the water. However, infrared thermal imaging on its own will not provide any range information. LiDAR operates at a longer range due to its three-dimensional laser scanner, with the potential to provide accurate and precise real-time position information for moving and stationary objects, infrastructure, and the coastline. LiDAR's ranging capability can provide advanced situational awareness information to ships during the day or night, with weather restrictions, and includes advanced functionalities to assist with collision avoidance. This includes the ability to discern individual ships when clustered together and to distinguish ship size, including detecting very small ships. LiDAR allows distance to obstacles on surrounding land or water to be accurately measured in real time, with reduced clutter and minimal returns off water to ensure accurate data collection under variable conditions.[35] Regarding the feasibility of integrating these technologies into MVR systems, the effective range of these systems is generally much shorter than MVR, especially in adverse weather and in the presence of smoke and other aerosols, and so their use in the marine environment requires careful evaluation and integration with other systems.

Steering Clear of Wind Farms if Possible

Shipping safety fairways, traffic separation schemes, and other ships' routing measures are being designated to ensure areas of the waterways are cordoned off to recognize the paramount right to navigation. The size, space, and location of these fairways and routing measures will be determined with input from multiple government agencies and all maritime stakeholders. By designating the appropriate space (determined by size and maneuverability of the vessel, visibility, etc.) for vessels to transit, it would be feasible for large vessels entering and exiting the major shipping ports along the Atlantic Coast of the United States to steer clear of the wind farms.

Additional Training

Credentialed mariners are required to be familiar with the proper operation of all installed navigation equipment. If this equipment is modified or replaced because of a new performance standard, training would need to be developed to assure watchstanders attain the competence to use that equipment effectively (46 CFR 15.405; STCW Regulation II in IMO, 2018). When new parameters are introduced into the operating environment, credentialing authorities and companies (STCW Regulation I-14) review training requirements to ensure that safe navigation through proper operation of required equipment can still be met.

Updating operator training to include specifics on WTGs could help mitigate navigation risks caused by WTGs. While WTG clutter on the radar display may look confusing and unmanageable at first, mariners could gain proficiency at distinguishing real targets from WTG clutter through training and practice. First-order scattering effects present a regular grid pattern on the display due to the wind farm layout and thus could be easily identified. Higher-order scattering effects are often less stable with respect to look angle and tend to be highly transitory when vessels move. Distinguishing them from real targets could be possible. During the 2007 Kentish Flats trial (Marico Marine, 2007), it was reported that experienced pilots were able to effectively track other vessels from both within and behind the wind farm area. The Maritime Institute of Technology and Graduate Studies (MITAGS) simulator facility in Baltimore, Maryland,[36] has taken a step in

[35] See For example, see https://www.neptectechnologies.com/marine-lidar/.
[36] See https://www.mitags.org/.

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this direction by implementing simulation capabilities to train pilots to navigate around and through specific wind farms.

While it is feasible for the mariner to receive training on proper methods to safely navigate through the wind farms using MVR, several potential bottlenecks are noted. First, the creation of new training courses is only likely if new manufacturing standards for MVR are adopted or credentialing requirements changed. With projected timelines of 5–10 years for standards bodies to approve updates, and an additional 5 years for U.S. government regulators to update CFR, formal training is unlikely feasible as a short-term solution. A more promising short-term solution is to encourage mariners to develop proper navigation skills for future wind farm installations. This may be accomplished if IMO issues a Maritime Safety Committee Circular or the U.S. Coast Guard develops a Navigation and Vessel Inspection Circular to address safety concerns when navigating in the vicinity of wind farms similar to the United Kingdom's Marine Guidance Note 372. Second, simulators are only effective if the underlying simulation models provide sufficient realism to emulate the actual phenomenology. Higher-order scattering effects leading to spurious echoes are much more challenging to model accurately. None of the existing signature modeling approaches for these effects have been validated against measurements. More realistic simulation capabilities will need to be further developed and tested for mariner training.

Enhancing the capabilities of training facilities requires an investment in representative user hardware, computing technology, and realistic interactions between the MVR and environment using simulation models. It is expected, however, that the corresponding investment is reasonable in comparison with the important benefits of offshore, renewable energy.

Wind Turbine Generator Design and Deployment

As discussed in Chapter 2 of this report, the standard design for an offshore WTG for the near term will be the three-bladed horizontal axis wind turbine. Hence, this section will focus on this WTG design.

Numerous techniques are being investigated to reduce the radar cross section (RCS) of WTG involving material choices (e.g., carbon fiber composites and radar absorbing materials [RAM]) for the WTG blades to mitigate clutter and shadowing for land-based WTG installations. The reduction of the clutter with new blade compositions will also be welcome for marine installations, though this reduction may only have noticeable effects in MVR returns in close proximity to or within the farms themselves, as a significant component of the radar return originates from reflections from the tower. The location of the blades well above the ocean surface from which the radar signals originate may make this approach less compelling as a motivating factor to improve performance of MVR.

These RCS reduction approaches have been the subject of at least three studies: "Stealth Technology for Wind Turbines," a report prepared by BAE Systems Advanced Technology Centre with Vestas Technology U.K. Ltd. for the Department for Business, Enterprise and Regulatory Reform for the United Kingdom in 2007 (BERR, 2007); "Radar-Cross-Section Reduction of Wind Turbines (Part 1)," prepared by Sandia National Laboratories in 2012 (McDonald et al., 2012); and "Stealth Wind Farm," a case study prepared by QinetQ in 2018 (QinetiQ Ltd., 2018).

The 2007 BAE Systems study examined the entirety of the WTG and aimed to reduce the RCS through a combination of RAM and the development of radar-friendly shape designs for the tower and nacelle. The study focused on the S-band radar frequency (2.7–3.1 gigahertz [GHz]), though the authors noted that RCS reduction in the X-band (9.1–9.41 GHz) is also desirable for

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MVRs. The BAE Systems study estimated that the total RCS of a WTG needed to be reduced by at least 25 decibels (dB) in order to successfully mitigate the impacts of WTGs on radar systems (BERR, 2007). BAE Systems researchers found that "the towers require the largest level of RCS reduction, of the order of 40 dB. Even so, the nacelle and blades also require up to 30 dB of RCS reduction." In partnership with the University of Manchester, the BAE Systems team modeled the North Hoyle offshore wind farm to generate a simulated plan position indicator (PPI) plot that mariners might see on their radar screens. The PPI was simulated with an initial assumed WTG RCS of 61.4 dB and then again after reducing the RCS of each WTG by 5, 10, and 20 dB. All cases, except the 20-dB reduction, showed some sidelobe or ghosting effect from the WTGs. The study did not move past the modeling phase to manufacture and construct a reduced RCS WTG that could be tested in the field to validate the modeled results.

The Sandia National Laboratories (Sandia) study investigated the incorporation of RAM into the fabrication process of WTG blades (McDonald et al., 2012). This study focused on the L- and S-band radar frequencies. The Sandia study looked solely at the reduction of the RCS for the blades and did not investigate the tower or the nacelle. This was because, as the authors of the study noted, that while the tower and nacelle produce larger radar returns than the blades, these stationary returns can be managed by similar techniques used to filter returns from large buildings like clutter maps. This is not the case for non-stationary MVRs.

Sandia National Laboratories developed a WTG blade design with integrated thin layers of RAM included in the blade structure (McDonald et al., 2012). Results from the Sandia study indicate that the integration of RAM in a WTG blade manufacturing process is feasible, and the modeling has shown that it can achieve 20 dB or greater RCS reduction at certain frequencies (McDonald et al., 2012). However, more research and development activities are needed to validate the modeling and understand the applicability to MVRs specifically.

A case study report released by QinetiQ in 2018 indicates that QinetiQ, partnered with the wind farm developer EDF, was able to reduce the RCS of a 35-WTG wind farm in France by 20 dB, as seen by a nearby weather radar using RAM (QinetiQ Ltd., 2018). No other information was available regarding the techniques used to achieve this reduction nor the applicability to MVRs.

Other approaches to reduce the overall RCS of WTGs involve altering the surfaces of the towers in order to provide a less persistent return to the illuminating radar, including coating with RAM or addition of faceted or "bumpy" surface treatments to the tower surface (e.g., Ueng, 2020). These kinds of approaches will likely be able to reduce the RCS of individual WTG towers in a farm but may result in additional clutter within the confines of and adjacent to the farm. Additionally, any non-smooth surface will present additional wind loading and opportunities for debris deposition on the surface, which could shorten the overall mechanical strength and useful lifetime of the tower.

The BAE Systems and Sandia studies have both shown that the reduction of RCS for WTGs is feasible (BERR, 2007; McDonald et al., 2012). However, a completely undetectable WTG is undesirable in the marine environment. In addition, questions remain about the applicability of these techniques to MVRs, which will require additional research and development. Lastly, the committee notes that floating offshore wind farms may pose additional challenges in the interpretation of their marine radar returns due to wave-related motions of individual WTGs.

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Radar Design, Signal, and Data Processing

To date, compelling WTG mitigation techniques for MVR have not been substantially investigated, developed, matured, or deployed. This is in contrast to U.S. Department of Defense and Federal Aviation Administration radar systems, where significantly higher investment has been made in characterizing impacts and actively developing solutions.[37] In this section, possible mitigation measures in MVR deployment and MVR design are discussed.

Marine Vessel Radar Deployment

As explained in Chapter 2, a large offshore wind farm presents a large cluster of radar reflecting objects to MVRs. This can result in (1) first-order scattering effects leading to clutter and shadow issues, thus making it more difficult to detect targets in and around a wind farm; and (2) higher-order scattering effects (multipath from the observer's own vessel, other vessels, between turbines) leading to spurious echoes and compounding WTG interference on MVR. The radar phenomena observed are not unique to WTGs but are exacerbated by their large RCS. Therefore, traditional approaches to dealing with clutter returns from large RCS objects can be considered. These methods include enhancing the RCS of small vessels that are difficult to detect and reducing own vessel scattering. These techniques apply to both magnetron-based and solid-state MVRs.

Radar Reflectors

To improve detection in the presence of large WTG clutter, one approach is to install radar reflectors on small vessels to increase their RCS. It was found during the U.K. trials that experienced pilots were able to use various radar controls (gain, sensitivity time control, pulse width) to detect small targets around wind farms, as long as target RCS was above established navigation buoys (Brown and Howard, 2004; Marico Marine, 2007). Therefore, boosting the RCS level of small vessels to above that of nearby buoys is a way to ensure they can be seen by MVRs on other vessels when navigating around a wind farm. In fact, Safety of Life at Sea (Chap. V, Reg. 19.2.1.7) already requires that all ships, if less than 150 gross tonnage and if practicable, have a radar reflector to enable detection from ships navigating by radar at both 9 GHz and 3 GHz. Corner reflectors, lenses, or active reflectors are commercially available for this purpose (Hodges, 2005). When mounted high on the vessel, they can boost the RCS level to several square meters for passive reflectors or lenses, and to more than 100 square meters for active reflectors. Although it was found that the RCS of these products might not be satisfactory for all look angles, they are a rather low-cost solution to enhance the detectability of small vessels by other MVRs. Passive reflectors are preferable over active reflectors, as they are easy to maintain and do not lead to spectrum management requirements as in the active reflector case.

Marine Vessel Radar Placement

Cutting down platform scattering can reduce spurious echoes arising from multiple scattering. This can be accomplished through better MVR placement on the vessel and/or RAM treatment of surrounding structures such as masts, funnels, stacks, or derricks. It was found during

[37] See https://windexchange.energy.gov/projects/radar-interference-working-group.

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the Kentish Flats trial (Marico Marine, 2007) that a large fraction of spurious echoes observed on PPI displays were traceable to own vessel obstructions. In particular, cylindrical shaped masts, stanchions, or funnels gave rise to spurious sectored echoes in the direction of the obstructions at the same range as the WTGs. Flat surfaces sometimes gave focused ghost images of the entire farm in the direction of these surfaces. If a vessel operates adjacent to or inside a wind farm, careful calibration and testing of its MVR could eliminate (or at least clearly identify) shadow or blind sectors due to onboard obstructions. Clearly labeling these sectors on the MVR will serve as a reminder to the pilot that artifacts in these directions are more likely, especially when navigating adjacent to or inside a wind farm. Use of RAM or coatings to treat the offending surfaces may also help reduce multiple scattering between large WTGs and these surfaces. Absorber sheets made of magnetically loaded rubber or silicone that are thin and flexible have been used on naval ships for this purpose (Cuming Microwave, 2015; TDK, 2021). They could provide an off-the-shelf solution to reduce spurious echoes due to platform structures.

In summary, attention to radar mounting and interaction with the MVR-carrying vessel is an important consideration. The approach taken will vary by vessel type and configuration, thereby requiring a level of customization. Identifying and treating reflective points on the vessel to reduce their impact on the MVR will yield substantial benefit. A downside is that the treatments will generally require regular maintenance.

Marine Vessel Radar Design

The majority of MVRs in operation today use magnetron technology. Solid-state radar is a relatively new technology. While gaining popularity, it still only currently occupies a small fraction of the installed base. Furthermore, the susceptibility or immunity of solid-state radar to WTG interference has not been established via rigorous in-situ testing. Earlier MVR measurement collections on WTG interference (Brown and Howard, 2004; Marico Marine, 2007) were done using magnetron-based radar exclusively. Therefore, assertions of the suitability of solid-state radar, or lack thereof, for operation in a WTG environment are inconclusive from these experiments. Nevertheless, solid-state radar offers a greater potential in overcoming WTG interference than magnetron radar. This is because solid-state radar is fully coherent and can detect Doppler information, which opens up an additional dimension for separating moving targets from WTG clutter. Below, the radar signal processing steps and the corresponding radar features from targets and clutter sources are discussed.

We now consider how coherent signal processing can be used as an advantage to filter unwanted WTG returns building on the prior discussion. Figure 3.3(A) illustrates a typical scene with four WTGs and two targets in the field of view of an MVR, which is located at the center of the scene. Figure 3.3(B) shows the raw radar I/Q data collected over fast time, slow time (or pulse number), and antenna bearing angle. In the first processing step, range compression is applied to the radar I/Q data along the fast time axis and results in a set of range profiles versus slow time and antenna bearing, as shown in Figure 3.3(C). In the second step, a fast Fourier transform is applied along the slow time axis to generate a range-Doppler plot for different antenna bearing angles, as shown in Figure 3.3(D). Figure 3.3(E) shows the resulting Doppler versus bearing plot at a particular range cell, r_0. Due to the finite pulse repetition frequency (PRF) of the radar, the maximum extent in the Doppler dimension is limited by ±PRF/2. For this discussion, the antenna bearing angle is defined in a clockwise manner, starting from the front of the vessel. In the plot, returns from stationary objects (including land mass and towers of the WTGs) are mapped to a

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sinusoidal trajectory in the Doppler-bearing plane. The maximum Doppler of the sinusoid is proportional to the speed of the own vessel. Moving targets (e.g., Targets 1 and 2) are offset from this curve. WTG blade returns could also be present when the antenna is pointed in directions of the WTGs and are marked by dashed lines. They are spread out in Doppler because of the various Doppler components produced along the blade from the hub to the tip. From Figure 3.3(E), it can be seen that moving targets, stationary clutters (including both land and WTG towers), and dynamic clutters (due to WTG blade returns) all have rather distinct behaviors in the Doppler-bearing space. This makes it possible to devise an automated algorithm to filter out clutter and detect moving targets. To do so for a magnetron-based radar would be akin to trying to detect targets in clutter with the entire Doppler dimension collapsed to a line.

Several comments are in order:

1. The successful detection of targets from clutter depends on their separation in range, Doppler, and azimuth bearing. Therefore, such processing is still subject to the usual resolution limit and sidelobe leakage in the range, Doppler, and antenna beam dimensions. Improved resolution via shorter effective pulse length, longer dwell time, or narrower antenna beam will lead to improved target detection.
2. Spurious echoes emanating from own vessel, other vessels, or between turbines will not be mitigated by using Doppler filtering. For example, spurious echoes due to multiple scattering between a shipboard obstruction and a WTG tower will not obey the assumed sinusoidal trajectory in the Doppler-bearing plot for stationary clutter. They will still interfere with moving target detection.
3. The PRF of MVRs may be too low to capture the Doppler return from WTG blades without ambiguity. For example, the U.S. Department of Energy anticipates that the maximum tip speed of offshore WTG blades in the next 15 years will be in the range of 100 meters per second (Ennis, 2021). This corresponds to a maximum Doppler shift of 6.3 kilohertz at 9.4 GHz, which is above the typical PRF of MVRs. Consequently, the blade return may fold back into the Doppler extent dictated by the PRF. On the other hand, as discussed in Chapter 2, the blade return is prominent only when the blade is perpendicular to the radar line of sight. Therefore, the Doppler flash may not always be captured during the antenna dwell on the WTG. Even if it is present, the return is spread over multiple Doppler bins and is much weaker than the coherent return from the entire blade.
4. The WTG interference problem for MVRs is less difficult than what has confounded air traffic control and air defense radars. That is because all targets of interest are confined to the sea surface and the problem is essentially a two-dimensional one. This is in contrast to the case of air traffic control and air defense radars that have to detect and track targets in a three-dimensional space, thus making it very difficult to track aircraft flying over a wind farm (Karlson et al., 2014).
5. The ARPA takes radar measurements (detected objects at specific ranges and angles) and assembles them into tracks and predictions on approach points. Trackers rely on logic to initiate tracks, assign measurements to tracks, drop tracks, and determine track priority. As noted in Chapter 2, the many spurious measurements emanating from a WTG degrade ARPA performance. Developing, testing, and enhancing an ARPA mode for WTG operation is a data processing–centric approach to mitigate WTG effects and improve performance for the operator. For example, the tracker can

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incorporate knowledge of WTG locations to remove the resulting tower measurements and blade Doppler from further tracker consideration.

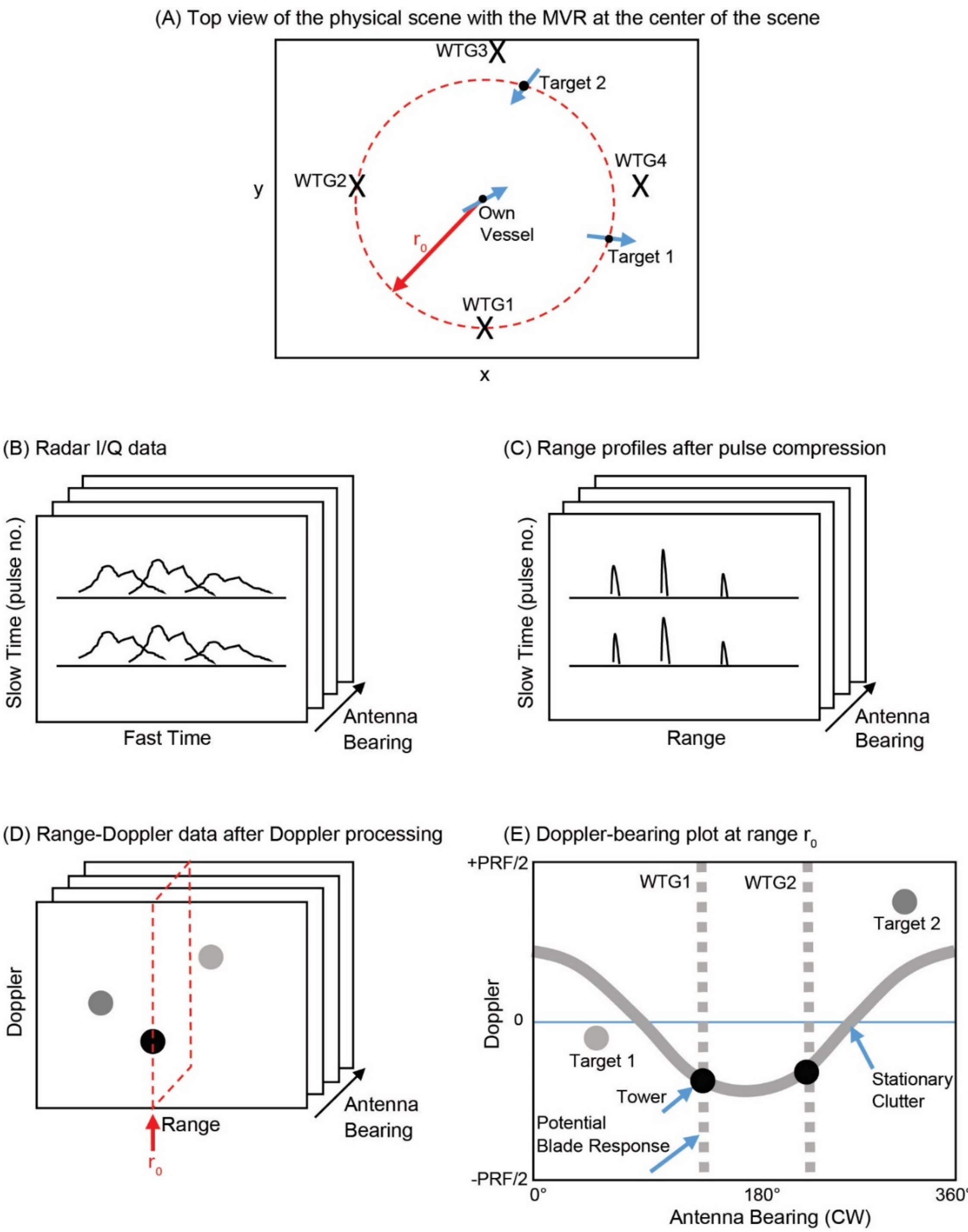

FIGURE 3.3 Illustration of marine vessel radar (MVR) signal processing. NOTE: PRF, pulse repetition frequency; WTG, wind turbine generator.

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6. Other filtering methods based on signal decomposition, model-based signal processing, and iterative deconvolution used in other radar systems may also be possible. The essential concepts are similar to Doppler filtering and involve suppressing those signal components that differ from targets of interest.
7. The elevation beamwidth of currently fielded MVRs exacerbates ambiguous signals. As mentioned, the wide elevation beamwidth accommodates vessel pitch and roll. It is possible to deploy antennas with narrower elevation beamwidth and the ability to switch beam positions based on vessel motion. Such deployments will require greater antenna area (along the vertical dimension) to reduce the elevation beamwidth, as well as inertial navigation measurements and electronics to switch elevation beam pointing appropriately. Antenna improvements can be made to both solid-state and magnetron-based radar, but consistent with our current discussion, application to solid-state radar will yield the most flexibility for system improvement in a WTG environment.
8. As solid-state radar supports a range of duty cycles, flexibility in waveform parameter selection is feasible. Incorporating available arbitrary waveform generator technology in future solid-state MVR designs enables waveform parameter optimization, thereby providing another degree of freedom that may prove useful in minimizing WTG interference. For example, the arbitrary waveform generator supports emerging techniques, such as phase tagged waveforms capable of separating range ambiguous clutter returns, an approach which may help suppress WTG returns from far ranges.

In summary, the committee finds that it is within the "realm of the possible" to leverage solid-state radar technology and apply coherent signal processing to filter out both static and dynamic WTG clutter signals and detect moving targets. Since this type of processing can be carried out in software, it may not require hardware changes to existing solid-state radar. In fact, it is conceivable that a "wind farm" mode can be created on future MVRs to suppress/filter WTG clutter automatically. Additionally, ARPA upgrades for a WTG mode primarily require software modifications; incorporating inputs from external sources, such as AIS, may require additional system modifications, though such information is likely available in modern, integrated navigation consoles. Software updates may require computer hardware updates; moreover, software updates require some degree of verification and validation before fielding. Finally, improved antenna technology is feasible, and may leverage current trends in the commercial sector, but certainly will add to the cost and complexity of the MVR.

Given the aforementioned discussion, the committee emphasizes that the susceptibility of the current generation of solid-state radars to WTG interference is unclear. This is the case largely because MVR manufacturers have leveraged solid-state technology mostly as a like-for-like replacement to the magnetron to improve reliability, with some added features not specifically addressing WTG interference. Extensive testing against future U.S. offshore wind facilities at the earliest possible stage would shed light on their impacts to solid-state radar.

Lastly, cost is a dominant consideration in the design and manufacture of MVRs, especially for the commercial market. Manufacturers may be unwilling to consider modifications to their current designs that can substantially improve MVR performance in the presence of WTGs unless required to do so by new regulations.

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Wind Turbine Generator Impacts to Marine Vessel Radar

Other Information Systems and Combined Methods

Radar navigational issues arising from the presence of WTGs will mainly be relevant in close proximity to or within WTG farms. The possibility of smaller vessels passing through the WTG farms and having their signatures masked by the close-in radar returns or shadowing from the WTGs and their clutter can make detecting small disabled vessels and vessels in distress a challenge. Shutting down WTG blade rotation during search and rescue (SAR) operations may provide some benefit, though strong returns from the tower and stationary blades remain a limiting factor. The feasibility of installing dedicated in-farm radars to provide situational awareness in and around WTG farms will be based on cost and system maintenance requirements. The installation would require dedicated connections to a Coast Guard watch station or the local substation. The radar and signal processing technologies already exist to enable such a system. The industry ecosystem in this space may readily support its design and development, given the increased deployment of marine wind farms over the coming decades that could create a market for such a system. This kind of technology may be even more important in floating WTG farms, where RCS clutter and variability will depend more heavily on sea state.

However, apart from the specialized application of prospective SAR operations, the case for in-farm radars and related systems is less compelling. While these systems could be fielded, it is much less straightforward to consider how these resources would be used to supplement shipboard MVR given that there is no established way to send such data to any vessel at sea. This situation may shift once wind farms of significant size are deployed, and the Coast Guard and other organizations have more data with regard to the need for real-time situational awareness in marine wind farms in general for SAR operations as well as routine navigation.

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4
Key Findings, Conclusions, and Recommendations

During this study, the committee organized its information gathering around six areas consistent with its statement of task:

- Navigation safety,
- Offshore wind turbine generator (WTG) characteristics and deployment,
- Marine vessel radar (MVR) design and operation,
- Electromagnetic characteristics of WTGs,
- The impact of WTGs on MVR performance, and
- Strategies to mitigate the impact of WTGs on MVR.

With this in mind, in this chapter the committee first summarizes all findings by the six aforementioned areas. Subsequently, the committee provides conclusions and recommendations addressing the impact of WTGs on MVR and mitigating strategies.

This section builds on prior discussion, with the intent of focusing the most important information consistent with the statement of task. *While the study committee carefully distinguishes performance between magnetron and solid-state classes of MVR, the corresponding general impact of WTG-induced degradation will be similar across radar height, radar range, vessel type and size, and other likely parameters, a point influencing the committee's deliberations and the corresponding discussion throughout the report.*

FINDINGS

Navigation Safety

Navigation involves directing a ship using all means possible to minimize the potential for collision, allision, or grounding within the Marine Transportation System (MTS). Navigation employs technical instruments as decision aids, of which MVR is a commonly used device. From earlier discussion, the presence of marine WTG farms affects the marine operating environment in a number of ways, thereby impacting navigation safety.

From the perspective of navigation safety, the U.S. Coast Guard is taking measures to ensure that safe passage to and from U.S. ports does not conflict with an offshore wind farm. The essential guidance from the U.S. Coast Guard involves designating areas of the various waterways as shipping safety fairways, traffic separation schemes, and other routing measures. Similar to the highway road network, safety fairways concentrate vessels into regular traffic patterns. However, the increased traffic density could increase the likelihood of a risk of collision situation occurring, due to reduced available sea space and by funneling vessels into a close proximity, as Finding 1.1 summarizes (see navigation safety findings in Box 4.1).While the fairways and routing measures may increase the likelihood of a risk of collision situation occurring, the designated waters are expected to increase the safety of navigation by providing a corridor free from structures. WTG

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developers are required to conduct Navigation Safety Risk Assessments when proposing deployment sites, used to assess the proposal but also as input when formulating safety measures.

MVR is a critical tool used to safely pilot vessels throughout the MTS and is generally required for all commercial vessels, as Finding 1.2 enumerates. Mariners employ MVR to navigate WTGs, and the role of MVR increases under adverse weather conditions where visual piloting is restricted. Thus, it stands to reason that factors affecting MVR performance impact navigation safety. Despite this assertion, the committee found that no standard approach to active radar deployment for operation in a WTG environment is available, as the latter part of Finding 1.2 indicates. The U.S. Coast Guard recognizes that addressing the general lack of understanding of how MVR will lose efficacy in a WTG environment, and the corresponding impact on navigation performance, requires in-depth testing and evaluation, a current gap identified in Finding 1.3.

In gathering information on navigation safety, the committee sought to understand the various technical options available to bridge potential performance gaps in the presence of WTGs. A line of reasoning that WTG locations are generally known, at least for monopile deployments, led the committee to understand the availability and use of Automatic Identification Systems (AIS) reporting vessel and WTG locations as a complement to the MVR. As Finding 1.4 indicates, the committee found that the capability to incorporate AIS into the radar display to enhance context is a standard requirement.

BOX 4.1
Findings: Navigation Safety

Finding 1.1: The U.S. Coast Guard's proposed safety fairways are intended to provide safe access to U.S. ports by guiding vessels safely past wind turbines but may cause increased traffic density and risk of collision with crossing vessels in the vicinity of wind farms.

Finding 1.2: MVR is an essential tool used by mariners to maintain situational awareness and avoid collisions and allisions. Moreover, MVRs are required on a multitude of commercial vessels for navigation safety. Mariners rely on MVR to navigate in and adjacent to wind turbine farms in diverse weather conditions. However, there is currently no standard system of active radar tailored to a WTG environment.

Finding 1.3: The U.S. Coast Guard sees the need for updated studies to assess WTG interference on MVRs, yet there is no concept in place despite planning for, and deployment of, new offshore wind farms in compliance with the recent Executive Order (No. 14008; United States, 2021) directing vast expansion of U.S. offshore renewable energy.

Finding 1.4: Current manufacturing standards require that radar systems have the capability to incorporate AIS into their product displays to provide additional context as a navigation aid (Haynes, 2021), but there is no regulatory requirement to integrate the AIS with radar systems.

Offshore Wind Turbine Generator Characteristics and Deployment

The characteristics of marine WTG farms determine the impact of corresponding interference on MVR. As discussed earlier in the report, the WTG tower and blade size, orientation, and spacing determine a number of electromagnetic effects, such as the WTG's

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effective radar cross section (RCS), Doppler signature due to the rotating blades, and multipath. The axial orientation and anchoring approach result in different properties affecting WTG interference. As Finding 2.1 indicates, the horizontal axis blade configuration is the current standard (Box 4.2). In this configuration, blade Doppler and composite RCS are highly dependent on the orientation of the MVR relative to the nacelle. There are other novel offshore WTG designs that are under investigation such as vertical axis wind turbines (VAWTs) and multi-rotor structures (Deign, 2019). Predictions about if and when these new offshore WTGs will become available to the market are difficult to make. However, any new WTG design will likely have a different radar signature than the typical three-bladed WTG and should be studied. For example, the signature return from a VAWT will be uniform over aspect, with blade Doppler omnipresent. In addition, in the shallower waters of the Atlantic Continental Shelf, the fixed foundation will be standard, indicating a stable WTG location. In the deeper waters of the Pacific, floating foundations with anchoring to the sea floor will predominate. The floating foundations will result in variability of WTG position, and may affect WTG spacing and safe passage to clear the resulting catenary. Finding 2.2 summarizes this latter point.

BOX 4.2
Findings: Offshore Wind Turbine Generator Characteristics

Finding 2.1: The three-bladed horizontal axis upwind WTG will be the standard marine deployment in the near term (10–15 years). New types of WTG designs are being investigated including VAWTs to take advantage of their lower center of gravity for deep water applications and may be deployed in the long term (15+ years).

Finding 2.2: Rigid fixed-bottom WTG support structures (monopile, jackets, gravity-based foundations) will be the standard for the East Coast of the United States in the shallow Outer Continental Shelf where waters are less than 60 meters deep. Floating WTG foundations will be the predominant substructure type for waters deeper than 60 meters off the Atlantic Coast and in the Pacific Ocean where fixed-bottom foundations cannot be accommodated.

Marine Vessel Radar Design and Operation

As Finding 3.1 indicates, the vast majority of MVRs are magnetron-based (see MVR design and operation findings in Box 4.3). Magnetron transmitters represent older technology, matured and proliferated during World War II. The frequency response of a magnetron lacks sufficient stability to reference return signals to a known phase reference response, thereby limiting the ability of the radar to separate different signal returns in angle and Doppler. Over the past 15 years, solid-state radars have penetrated MVR markets, primarily owing to their increased reliability. Solid-state radars employ stable frequency sources and hence enable coherent signal processing, whereby the radar processor can combine returns from a contiguous set of transmit pulses to filter objects according to Doppler frequency and inferred angle. Thus, solid-state radars provide functionality substantially exceeding that of their magnetron-based counterparts. Finding 3.1 further indicates that, despite better performance potential, adoption of solid-state radar will be slow, as there are no requirements driving the market. Finding 3.2 relates to the antenna

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characteristics of MVR; the antenna is a spatial filter, letting signals in from some directions while suppressing signals from others. The current MVR system has fairly narrow azimuth beamwidth but a broad elevation response to accommodate vessel motion. The broad elevation beamwidth allows strong WTG returns to enter the radar over a greater range extent, thereby exacerbating WTG effects.

MVR radars must detect WTGs to avoid allision but then reject the WTG response when looking for weaker targets. This is particularly true due to the thresholding effect discussed in earlier sections of the report: operators will lower the gain function (effectively raising the threshold) to clean up the radar display, at the expense of losing weak target detections. As Finding 3.3 states, MVRs have multiple needs to detect and track weaker targets, such as small boats, birds, and reflectors used to find objects such as fishing nets.

MVRs do follow certain guidance in the form of minimum requirements. These requirements do not address the complexity of the MTS and in present form do not accommodate the anticipated proliferation of WTGs. This latter point, summarized in Finding 3.4, is problematic due to the inertia of proposing, approving, and ultimately deploying new radar requirements. Moreover, the committee found that profit margins for MVR manufacturers are very tight, requiring strict control over the bill of materials to maintain competitiveness, as described in Finding 3.5. The committee further found that MVR manufacturers do not have financial or regulatory incentive to incorporate ameliorating designs into their product lines to address navigation in a WTG environment.

Electromagnetic Characteristics of Wind Turbine Generators

The electromagnetic characteristics of WTGs determine return signals seen by the MVR. There are two dominant effects: the strong return from the WTG tower, and the strong and Doppler-spread returns from the blades. Magnetron-based radar will see the composite return of tower and blade in a single range-angle cell, whereas the response seen in Doppler-based radar will vary with the processing approach. Concerning the latter, however, any Doppler processing will identify the Doppler return of the moving blades as a function of orientation with respect to the radar. A radar line of sight closer to the edge-on view of the WTG blades leads to more Doppler spread.

At present, the horizontal axis WTG is the primary deployment the community will see over the next 10–15 years. The so-called horizontal axis wind turbine (HAWT) configuration leads to variability in RCS as a function of aspect, primarily due to the orientation of the blades relative to the radar line of sight. Future deployments may use the VAWT configuration. If fielded, the VAWT configuration will lead to a more uniform radar signal response than the HAWT but one where Doppler will be present from virtually all aspects. Finding 4.1 summarizes these considerations (see findings on electromagnetic characteristics of WTGs in Box 4.4).

The committee further found that WTG RCS will vary substantially with geometry because of near-field phasing effects, as given in Finding 4.1. It is unlikely the radar will operate in the far field of the WTG, so the result of being in the near field is an increase in destructive interference with changing angle, thereby resulting in a broad range of anticipated WTG RCS values, which affects system performance assessment and mitigating strategies. Furthermore, as Finding 4.2 indicates, WTG height presents unique issues at or beyond the normal radar horizon presented by a surface vessel. A point of concern centers on range ambiguous returns from WTGs at far range that mask targets at near range or add to an already confusing operator picture: these ambiguous

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returns, while coming from a farther range beyond the expected horizon, will appear to the operator to emanate from near ranges. Similarly, at the horizon, the radar may only see part of the target, such as the mast, which is lower RCS than the whole ship, while the majority of a tall WTG in the vicinity will present itself fully to the radar, thereby degrading target detectability through masking effects.

BOX 4.3
Findings: Marine Vessel Radar Design and Operation

Finding 3.1: The majority of fielded MVRs are magnetron-based. However, newer offerings are solid state and enable coherent signal processing techniques such as Doppler filtering. Adoption of solid-state radar is expected to be slow due to cost of replacement, long life cycle of existing MVRs, and lack of regulation requiring enhanced functionality that solid-state radars provide over their magnetron-based counterparts.

Finding 3.2: MVRs employ antennas with low sidelobes, narrow azimuth beamwidths, and very broad elevation beamwidths (~25–30 degrees) to accommodate vessel pitch and roll. Larger vessels can accommodate a larger antenna, leading to narrow azimuth beamwidth useful when separating objects spatially.

Finding 3.3: Small target detection and tracking is a critical function for navies, lifeboats, and coast guards. Additionally, MVRs have secondary, commercial functions for fishers, such as finding small radar reflectors placed on fishing nets or tracking flocks of birds to find schools of fish.

Finding 3.4: Radar performance standards, such as IEC [International Electrotechnical Commission] 62388,[a] have been recommended by international bodies and required by domestic regulations, and serve as the primary driver in product design, performance, and cost, as well as adoption on marine vessels (Haynes, 2021). The process by which new marine radar functionalities are incorporated into standards and requirements is often very laborious and time-consuming and will create situations where MVR functionality lags mariner needs, especially in response to navigation adjacent to and within wind turbine farms.

Finding 3.5: The MVR commercial market is highly competitive, with very tight profit margins forcing manufacturers to exercise rigorous control over the bill of materials and forgo critical design considerations that may substantially improve MVR performance in the presence of WTGs. Radar vendors generally will not incorporate additional capabilities unless required by new regulations in the markets they serve or due to user demand.

[a] See https://webstore.iec.ch/publication/6967.

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BOX 4.4
Findings: Electromagnetic Characteristics of Wind Turbine Generators

Finding 4.1: Further analysis and measurements are necessary to determine RCS characteristics of marine HAWTs. Results indicate that larger turbines do not necessarily lead to a stronger signature due to near-field phasing effects leading to destructive interference of the return across the WTG, thereby reducing the effective RCS and otherwise leading to substantial variability in the strength of the WTG return (Grande et al., 2014). Similarly, as engineered systems become available, measurements and analysis are necessary to determine the RCS of the recently proposed VAWT blade configuration relative to the contemporary HAWT design.

Finding 4.2: The extreme height of the WTG tower leads to unique horizon effects. Specifically, a target close to the sea surface has a shorter radar horizon and is thus more susceptible to being masked by tall WTGs at similar ranges. Another concern is the reception of relatively strong WTG returns beyond the anticipated radar horizon resulting from the WTG height, leading to range ambiguous returns that complicate operator interpretation and mask unambiguous targets.

Finding 4.3: Concern for electromagnetic shadowing due to WTG towers exists in the MVR development community. The closer the radar is to the tower, the larger the angular extent of the electromagnetic shadow behind the tower and the deeper the shadow. This shadowing may make smaller craft in the area momentarily invisible to the radar.

Finding 4.4: The nominal blade tip speed of offshore WTG blades is 100 m/s, giving rise to a large Doppler shift (>6 kHz at X-band) for certain viewing geometries. The MVR PRF will generally be too low to unambiguously capture the corresponding Doppler information.

Finding 4.5: Higher-order scattering effects, such as those due to own vessel, other vessels, and multiple scattering between turbines, are much more challenging to accurately model, thereby leading to uncertainty in the nominal WTG signature. Current computational models are approximate and lack validation, including those used in simulators.

The proposed density of the WTGs as seen in the submitted Construction and Operations Plans raises some concerns about shadowing, as stated in Finding 4.3. The committee found that while shadowing will be present, it is a higher-order effect, and other factors play a more serious role in degrading MVR performance. Nevertheless, the issue was raised by members of the MVR development community.

As given in Finding 4.4, at a nominal blade tip speed of roughly 100 meters per second (m/s), the Doppler signature of the WTG can cover a broad range of frequencies. Close to the hub, the blade Doppler is virtually zero, whereas the response increases in Doppler to a maximum at the blade tip. The resulting Doppler at X-band is on the order of 6 kilohertz (kHz), thereby requiring a pulse repetition frequency (PRF) of 12 kHz to avoid signal aliasing. The higher PRF constrains the unambiguous range of the radar. At lower PRF, the maximum Doppler frequency of the blade will alias, filling up the Doppler spectrum at the corresponding individual WTG's range and angle location.

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Finally, the committee found that modeling and simulation of WTG interaction with radar use approximate models that may miss important, higher-order effects impacting the mariner's use of the MVR as a decision aid. Finding 4.5 identifies this matter and further notes a lack of detailed validation and documentation of WTG models.

Wind Turbine Generator Impacts on Marine Vessel Radar

From the committee's information-gathering sessions and collective experience, it is evident that WTGs decrease the effectiveness of MVR, and the sizes of anticipated marine WTG farms will exacerbate this situation. This decreased efficacy applies to both traditional, magnetron-based MVRs and as-fielded, solid-state MVRs, with some discriminating factors, as identified in Finding 5.1 (see findings on WTG impacts to MVR in Box 4.5). A combination of factors manifests as issues degrading effectiveness of MVR, as described in Finding 5.2, leading to lost contact with smaller objects, such as recreational watercraft and buoys, and presenting a confusing navigation picture. The large RCS of a WTG leads to a strong signal return, with own vessel multipath adding angle ambiguous returns. WTG blades also exhibit high RCS and will result in a strong Doppler return over a continuum of frequencies generated by both reflections along the extent of the blade and the varying geometry between the MVR and the multiplicity of WTGs in the MVR field of view. As identified in Finding 5.3 and Finding 5.4, a natural operator response to strong WTG reflections is to reduce the radar gain, effectively raising the detection threshold, with the consequence of losing detections of lower RCS targets. A combination of lost contacts, as well as shadowing effects, may complicate search and rescue (SAR) in proximity to the WTG farm. As Finding 5.4 indicates, there is currently no available bespoke WTG mode to facilitate improved use of MVR when operating in a WTG environment.

Comprehensive data collections will improve the stakeholder community's understanding of WTG effects on MVR. As identified in Finding 5.5, there is a lack of experimental data to inform the regulatory, investment, engineering, training, and operational constituents. This is especially valid over a range of parameters necessary to make the best-informed decisions. A good example of this latter point is given in Finding 5.6, where the committee notes that the well-known Kentish Flats experiments (Marico Marine, 2007) were limited in scope to only include magnetron-based radar: assertions on the impact of WTGs on Doppler-based radar from the Kentish Flats collections necessarily yield an incomplete perspective, since no Doppler radars were used to collect data at the time.

Consistent with several of the findings in this section, the lack of MVR tailoring to the WTG environment raises two findings related to radar data processing. Finding 5.7 asserts that post-processing methods to suppress range-Doppler sidelobes in Doppler radar, without customization for nuances presented by the WTG operating environment, will potentially lead to a loss of small object detections. Similarly, as Finding 5.8 indicates, the Automatic Radar Plotting Aid (ARPA) ingests measurements and outputs tracks and key predictions (i.e., closest point of approach [CPA] and time to closest point of approach [TCPA]); there was no evidence that ARPA design accommodates WTG effects, such as logic-based exclusion of WTG corrupted measurements or approaches to maintain custody of smaller RCS objects resulting from episodic or lost contacts due to WTG presence.

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BOX 4.5
Findings: Wind Turbine Generator Impacts on Marine Vessel Radar

Finding 5.1: WTG returns obfuscate the MVR picture for both magnetron-based and solid-state radar, thereby affecting navigation decision-making.

Finding 5.2: WTGs lead to interference in MVR, including strong stationary returns from the wind turbine tower, the potential for a strong blade flash return for certain geometries, and Doppler spread clutter generated along the radial extent of the WTG blade, which could obfuscate smaller watercraft or stationary objects such as buoys. Additionally, own vessel platform multipath is a significant challenge for returns from WTGs, leading to ambiguous detections and a potentially confusing operator picture.

Finding 5.3: When conducting maritime surface SAR operations in and adjacent to an offshore wind farm, use of MVR could be challenging because wind turbines can cause significant interference and shadowing that suppress the detection of small contacts.

Finding 5.4: There is no currently available “WTG mode” for MVRs, and operator control of detection threshold to mitigate strong returns will frequently lead to the unintended consequence of suppressing detections of small targets.

Finding 5.5: There is a paucity of field collected data to understand and evaluate the impacts of WTGs on currently deployed MVR models and support comprehensive development of ameliorating methods. Similarly, the impact of anomalous propagation and returns from range ambiguous regions on MVR is poorly understood due to lack of experimental data.

Finding 5.6: The Kentish Flats WTG data were collected using magnetron-based radar. No Doppler signal is measured in magnetron-based radar. Therefore, assertions of the suitability of Doppler-based solid-state radar, or lack thereof, for operation in a WTG environment are inconclusive from these experiments.

Finding 5.7: Automatic sidelobe suppression applied to the range and azimuth cells around a very strong target like a WTG may desensitize the radar and cause it to miss small targets.

Finding 5.8: Manufacturers of MVR systems employ range-angle tracking to calculate time to CPA and TCPA. There was no evidence of mechanisms within the tracker to mitigate measurements due to reflected energy from WTGs.

Mitigating Solutions for Wind Turbine Generator Effects on Marine Vessel Radar

The committee found that plausible options exist to improve MVR operating in the presence of marine WTGs. However, as Finding 6.1 indicates, there is no evidence of investments to support the development of mitigating methods for decreases in MVR effectiveness, in contrast to the attention given to military and Federal Aviation Administration radars operating in the vicinity of land-based WTGs (see findings on mitigating solutions in Box 4.6).

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Solid-state radar holds the potential to improve MVR performance in the presence of WTG interference. As Finding 6.2 identifies, the current generation of solid-state Doppler radars employs many strategies similar to the magnetron-based radars that they replace, leading to questions about their effective utilization. Specifically, the committee found that currently fielded, solid-state MVR can be used more effectively in a WTG environment, in addition to the currently touted benefits of better reliability and rapid identification of approaching and receding targets based on Doppler frequency. This observation leads to Finding 6.3, where the committee explicitly notes that solid-state radar holds the potential for improved performance due to its ability to separate and filter signals based on Doppler frequency (and, hence, angle for stationary objects, where angle and Doppler are dependent measurements), as well as provide measurements available to improve data processing and logic in a WTG environment. In general, it appears that software upgrades can enhance solid-state MVR performance, as filtering and data processing are software functions.

Modifications to the WTGs themselves to reduce radar signature are possible, as stated in Finding 6.4, where the use of radar absorbing materials and tower shaping will decrease the WTG radar signature.

BOX 4.6
Findings: Present State of Mitigating Solutions for Wind Turbine Generator Effects on Marine Vessel Radar

Finding 6.1: In contrast to investments by developers and operators of air traffic control and military radar systems, compelling WTG mitigation techniques for MVR have not been substantially investigated, implemented, matured, or deployed.

Finding 6.2: Questions remain about the effective utilization of current generation, solid-state Doppler radar and target trackers/analyzers in the presence of WTGs for currently fielded systems. In their present state, they may provide unique susceptibilities relative to magnetron-based radars. The full capability of solid-state MVR remains latent with regard to operations in a WTG environment.

Finding 6.3: It appears possible to leverage solid-state radar technology to apply coherent signal processing methods as a means of filtering and interpreting both static and dynamic WTG clutter to improve moving and stationary target detection and discrimination. Moreover, it may be possible to implement such features through software changes without requiring hardware upgrades.

Finding 6.4: Previous modeling and simulation efforts have shown that incorporation of radar absorbing materials and tower shaping can reduce the RCS of WTGs.

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CONCLUSIONS

From the findings presented in the prior section, the committee draws two primary conclusions.

Conclusion 1: Wind turbines in the maritime environment affect marine vessel radar in a situation-dependent manner, with the most common impact being a substantial increase in strong, reflected energy cluttering the operator's display, leading to complications in navigation decision-making.

WTGs cause interference to MVR, including strong stationary returns from the wind turbine tower; the potential for a strong blade flash return for certain geometries; and Doppler spread clutter generated along the radial extent of the WTG blade, which may obfuscate smaller watercraft or stationary objects, such as buoys. Additionally, multipath reflection from own vessel platform is a significant challenge for returns from WTGs, leading to ambiguous detections and a potentially confusing operator picture. As presently deployed, WTGs reduce the effectiveness of both magnetron-based and Doppler-based radar; however, similarities and differences exist between both radar classes as to the actual mechanisms leading to WTG-induced effectiveness loss. MVR strives to detect both moving and stationary objects to aid safe navigation. While vessel operators can control the radar detection threshold—via the receive gain function—to manage the number of targets shown on the plan position indicator (PPI) display and mitigate strong returns, this approach will frequently lead to the unintended consequence of suppressing detections of small targets in and around wind farms, thereby affecting navigation decision-making and situational awareness.

WTG interference decreases the effectiveness of MVR, and the sizes of anticipated marine WTG farms across the U.S. Outer Continental Shelf will exacerbate this situation. WTG interaction with MVRs at the scale of the proposed U.S. deployment will lead to unforeseen complications due to heightened effects of propagation, multipath, shadowing, and degraded ARPA performance. Navies, coast guards, and rescue vessels searching for smaller boats as their primary targets in the conduct of ordinary operations will experience a loss of contact with lower RCS vessels due to the various forms of identified WTG interference. Specifically, WTG interference will complicate MTS operations and is therefore particularly consequential when conducting maritime surface SAR operations in and adjacent to an offshore wind farm.

Conclusion 2: Opportunities exist to ameliorate wind turbine generator–induced interference on marine vessel radars using both active and passive means, such as improved radar signal processing and display logic or signature-enhancing reflectors on small vessels to minimize lost contacts.

MVRs are not optimized for operations in the complex environments of a fully populated continental shelf wind farm. There is no simple MVR modification resulting in a robust WTG operating mode. Solid-state radar technology makes it possible to apply coherent signal processing methods to filter out both static and dynamic WTG clutter returns to improve detection of moving targets and stationary objects such as buoys. It therefore offers greater potential in overcoming WTG interference than magnetron-based radar; however, assertions of the suitability of Doppler-based solid-state radar, or lack thereof, for operation in a WTG environment are inconclusive from

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previous experiments. Furthermore, adoption of solid-state radar is expected to be slow due to cost of replacement, long life cycle of existing MVRs, and lack of regulations requiring enhancements in radar capability.

In contrast to investments by developers and operators of air traffic control and military radar systems, compelling WTG mitigation techniques for MVR have not been substantially investigated, implemented, matured, or deployed. Approaches external to the MVR radar design successfully employed for other radar applications used elsewhere to deal with strong clutter returns from large RCS objects can, however, be considered as a low-cost or alternative means of mitigating WTG interference. These methods can include enhancing the RCS of small vessels or other objects that are difficult to detect, reducing topside scattering from the own vessel structure to reduce false returns, and improving operator training. These techniques apply to both magnetron-based and solid-state MVRs.

Finally, the environmental complexity that an offshore WTG farm presents to the MVR, its PPI display, and other output products highlights the need to carefully evaluate training and performance of MVR operators.

RECOMMENDATIONS

In light of the key conclusions, the committee offers the following recommendations:

Recommendation 1: The Bureau of Ocean Energy Management and other relevant federal agencies (e.g., members of the federal Wind Turbine Radar Interference Mitigation Working Group) should pursue any practicable opportunities to fill gaps in understanding of wind turbine generator impacts on marine vessel radars operated in and adjacent to wind farms, giving attention to

- **comprehensive test planning, data collection, and evaluation over a range of expected, operational conditions;**
- **innovative and collaborative approaches to facilitate data collection, such as the establishment of a marine vessel radar "sensor integration lab" for all classes or types of marine vessel radars and the development of a validated modeling and simulation capability;**
- **research, development, and characterization of a reduced radar-cross-section wind turbine generator for marine vessel radar;**
- **improvements to operator training models based on verification with physics-based models anchored by field collected data;**
- **data collection and analysis using prototype systems, preceding the full deployment of vertical axis wind turbines, if and when they become economically feasible for offshore applications, as a means of characterizing their impacts to marine vessel radars; and**
- **data collection and analysis on floating wind turbine generators, which may pose additional challenges for marine vessel radars through their wave-induced movement that will likely provide a less-consistent radar return overall and may also increase clutter and complicate Doppler return interpretation.**

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Wind Turbine Generator Impacts to Marine Vessel Radar

Recommendation 2: The Bureau of Ocean Energy Management (BOEM) and other relevant federal agencies (e.g., members of the federal Wind Turbine Radar Interference Mitigation Working Group) should pursue any practicable options to mitigate wind turbine generator impacts on marine vessel radar. BOEM and partners should give attention to the following:

- **The International Maritime Organization's Standards of Training, Certification and Watchkeeping (STCW) Knowledge, Understanding and Proficiency standards of competence to include operating in or adjacent to multiple structures at sea. Similar radar observer training should be considered for U.S. credentialed mariners not subject to STCW code who operate vessels equipped with radar in the vicinity of wind turbine generators.**
- **Updated requirements for vessels less than 150 gross tonnage to exhibit a radar reflector of suitable size and design while underway in or adjacent to a wind farm to improve their detectability when practicable.**
- **The deployment of reference buoys adjacent to wind farms to provide mariners a reference target to appropriately adjust marine vessel radar gain and other control settings to assist in the detection of smaller targets operating in the vicinity of wind farms.**
- **The evaluation and standardization of radar mounting procedures on marine vessels to mitigate the impact of near-field platform interference (i.e., multipath) on radar performance.**
- **The promotion of radar designs with increased immunity to wind turbine generator interference, such as new, Doppler-based, solid-state marine vessel radars with wind turbine generator resilience.**
- **Research and development to prove the performance and feasibility of fieldable material and structural wind turbine generator design components to reduce the radar cross section of wind turbine generators and mitigate their effects on marine vessel radar.**

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Appendix A
Committee Biographies

William L. Melvin
Chair

Dr. William Melvin is the Deputy Director for Research at the Georgia Tech Research Institute (GTRI), Director of the Sensors and Intelligent Systems Directorate at GTRI, a University System of Georgia Regents' Researcher, and an adjunct professor in Georgia Tech's Electrical and Computer Engineering Department. His research interests include all aspects of sensor technology development, systems engineering, developmental planning, autonomous and intelligent systems, and machine learning. Dr. Melvin has authored numerous papers and reports in his areas of expertise and holds three U.S. patents on adaptive sensor technology. He is the co-editor of two of the three volumes of the popular *Principles of Modern Radar* book series. Among his distinctions, Dr. Melvin was chosen as an Institute of Electrical and Electronics Engineers (IEEE) Fellow for his contributions to adaptive radar technology, is a fellow of the Military Sensing Symposium, and was awarded the 2014 IEEE Warren White Award for outstanding achievement in the field of radar. Dr. Melvin has served on the Board on Army Science and Technology through the National Academies of Sciences, Engineering, and Medicine; the Air Force Studies Board study on developmental planning organized through the National Academies; and other committees sponsored by the National Research Council. Dr. Melvin received the Ph.D. in electrical engineering from Lehigh University, as well as M.S.E.E. and B.S.E.E. degrees (with high honors) from this same institution.

Jennifer Bernhard
Member

Dr. Jennifer T. Bernhard is the Donald Biggar Willett Professor of Engineering and Director of the Illinois Applied Research Institute at the University of Illinois at Urbana-Champaign. She earned the B.S.E.E. degree from Cornell University in 1988 and the M.S. and Ph.D. degrees in electrical engineering from Duke University in 1990 and 1994, respectively. Dr. Bernhard has been a faculty member specializing in applied electromagnetics in the Electromagnetics Laboratory in the Department of Electrical and Computer Engineering at the University of Illinois since 1999, and served as the Associate Dean for Research in the Grainger College of Engineering from 2012 to 2019. Her academic research group focuses on the development and analysis of multifunctional reconfigurable antennas and systems, as well as high-security physical layer-based modulation schemes. Dr. Bernhard is an Institute of Electrical and Electronics Engineers (IEEE) Fellow and a Defense Science Study Group alumna, and a former member of the IEEE Board of Directors (2017–2018) and the American Society for Engineering Education Engineering Research Council Executive Board (2016–2019). She previously served as a member of the external review panel for the Radar Division of the U.S. Naval Research Laboratory (2010), the President's Council of Advisors on Science and Technology working group on Government-Held Electromagnetic Spectrum (2011–2012), and an assessment committee for the National Science Council (2015). Dr. Bernhard currently serves as the chair of the Engineering

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Review Committee for the Lawrence Livermore National Laboratory and on the Board of Directors for IEEE-USA.

Benjamin Karlson
Member

Mr. Benjamin Karlson has been a member of the Wind Energy Technology Department at Sandia National Laboratories since 2007. During this time Karlson has been involved with many projects that addressed wind energy power system integration, wind turbine reliability, and transmission planning. He currently leads the Wind Turbine Radar Interference Mitigation Working Group (WTRIM) activities for Sandia. The WTRIM effort is a multi-federal agency effort aimed at developing solutions that allow the continued deployment of wind energy while maintaining the nation's air space missions. Prior to joining Sandia, Karlson worked for the Federal Energy Regulatory Commission as an expert witness in electric rate filings. Karlson has a B.S. in electrical engineering from the University of New Mexico and an M.S. in electrical engineering from New Mexico State University, and was a registered Professional Engineer in New Mexico.

Hao Ling
Member

Dr. Hao Ling is the L.B. Meaders Professor Emeritus in Engineering at the University of Texas at Austin. His areas of research include antennas, wave propagation, and radar. Dr. Ling received his B.S. degrees in electrical engineering and physics from the Massachusetts Institute of Technology in 1982, and his M.S. and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana-Champaign in 1983 and 1986, respectively. He was on the faculty at the University of Texas for 31 years. From 2015 to 2017, he was also a program director at the National Science Foundation, and managed the Communications, Circuits, and Sensing Systems program. Dr. Ling was the lead principal investigator of a 2013 Department of Energy–funded study to assess the effect of offshore wind farms on sea surface, subsurface, and airborne electronic systems. He is a fellow of the Institute of Electrical and Electronics Engineers.

Andrew McGovern
Member

Captain Andrew McGovern has worked at the forefront of key issues affecting maritime safety for decades: technology, licensing, medical, navigation, and accident investigation issues as well as local, national, and international regulatory and legislative processes. Capt. McGovern served as President of the Pilots Association for six terms and is continuing to serve as the long-time Chair of the New York/New Jersey Harbor Safety Committee. He also served on the Port of New York/New Jersey Area Maritime Security Committee and the New York City Mayor's Waterfront Management Advisory Board. At the national level, Capt. McGovern has worked with agencies affecting the marine transportation sector—including serving on the National Oceanic and Atmospheric Administration's Hydrographic Services Review Panel and the U.S. Coast Guard's Merchant Marine Personnel Advisory Committee (almost 20 years as chair). He was also a member of the National Academies Transportation Research Board's Maritime Safety and

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Human Factors Committee. Internationally, Capt. McGovern has served on many delegations to the International Maritime Organization and several to the International Labor Organization addressing issues such as Standards of Training, Certification and Watchkeeping Code, the Maritime Labor Convention, and the International Ship and Port Security Code.

John Stone
Member

Commander John Stone, U.S. Coast Guard (Ret.), has more than 20 years of experience in marine navigation as an active-duty U.S. Coast Guard Officer, and an operational perspective on marine vessel radar operation. He holds a 100-ton Merchant Mariner license and has significant experience as a marine radar operator in multiple locations and climates. In his current role as a Marine Transportation Specialist at U.S. Coast Guard headquarters, Mr. Stone manages federal regulations pertaining to navigation safety and ship carriage requirements, and participates in Navigation Safety Risk Assessments associated with wind energy and other Offshore Renewable Energy Installation development. Previously, he also served as an assistant professor of mathematics at the U.S. Coast Guard Academy. Mr. Stone is a U.S. Coast Guard Academy graduate and holds an M.S. in computer science and an M.B.A. from the University of Rhode Island.

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Appendix B
Acronym List

AFRL	Air Force Research Laboratory
AIS	Automatic Identification Systems
ARPA	Automatic Radar Plotting Aid
BOEM	Bureau of Ocean Energy Management
BWEA	British Wind Energy Association
CFR	Code of Federal Regulations
COLREGS	Convention on the International Regulations for Preventing Collisions at Sea
COP	Construction and Operations Plan
CPA	closest point of approach
dBsm	decibels relative to a square meter
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
ECDIS	Electronic Chart Display and Information System
ECS	Electronic Chart System
GHz	gigahertz
GPS	Global Positioning System
GW	gigawatt
HAWT	horizontal axis wind turbine
HF	high frequency
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
kHz	kilohertz
LiDAR	Light Detection and Ranging
LOS	line of sight
m	meter
MCA	Maritime and Coastguard Agency
MITAGS	Maritime Institute of Technology and Graduate Studies
MKD	minimum keyboard display
MTS	Marine Transportation System
MVR	marine vessel radar
MW	megawatt

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nmi	nautical mile
OCS	Outer Continental Shelf
OREI	Offshore Renewable Energy Installations
PPI	plan position indicator
PRF	pulse repetition frequency
RAM	radar absorbing materials
RCS	radar cross section
SAR	search and rescue
S/I	signal-to-interference ratio
SNR	signal-to-noise ratio
SOLAS	Safety of Life at Sea
STCW	Standards of Training, Certification and Watchkeeping
TCPA	time to closest point of approach
VAWT	vertical axis wind turbine
VHF	very high frequency
VTS	vessel traffic services
WTG	wind turbine generator
WTRIM	Wind Turbine Radar Interference Mitigation Working Group

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