United States Air Force

Report to Congressional Committees

Joint Study on the Impact of Wind Farms on Weather Radars and Military Operations

October 2019

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SECRETARY OF THE AIR FORCE
WASHINGTON

Joint Study on the Impact of Wind Farms on Weather Radars and Military Operations

This report details Air Force engagement with the National Oceanic and Atmospheric Administration's National Weather Service to assess existing tools, latest data, and policies to improve weather radars. This report was completed using Department of Defense data from each Air Force Major Command, the Department of the Army, the Department of the Navy, and incorporated inputs from the Department of Commerce's National Oceanic and Atmospheric Administration's National Weather Service, Department of Energy, and Department of Transportation's Federal Aviation Administration, academia, and industry.

Sincerely,

Barbara Barrett

Introduction

This report is provided to the congressional defense committees as directed on pages 81-82, Section 318 of House Report 5515-2 to accompany the National Defense Authorization Act for 2019.

SEC. 318. JOINT STUDY ON THE IMPACT OF WIND FARMS ON WEATHER RADARS AND MILITARY OPERATIONS.

(a) IN GENERAL.—The Secretary of Defense shall enter into an arrangement with the National Oceanic and Atmospheric Administration to conduct a study on how to improve existing National Oceanic and Atmospheric Administration and National Weather Service tools to reflect the latest data and policies to improve consistency in weather radars, with a focus on a research and development and field test evaluation program to validate existing mitigation options and develop additional options for weather radar impact, in collaboration with the National Weather Service, the Department of Energy, and the Federal Aviation Administration, and with input from academia and industry.

(b) ELEMENTS.—The study required pursuant to subsection (a) shall include the following:

(1) The potential impacts of wind farms on NEXRAD radars and other Federal radars for weather forecasts and warnings used by the Department of Defense, the National Oceanic and Atmospheric Administration, and the National Weather Service.
(2) Recommendations to reduce, mitigate, or eliminate the potential impacts.
(3) Recommendations for addressing the impacts to NEXRADs and weather radar due to increasing turbine heights.
(4) Recommendations to ensure wind farms do not impact the ability of the National Oceanic and Atmospheric Administration and the National Weather Service to warn or forecast hazardous weather.
(5) The cumulative impacts of multiple wind farms near a single radar on the ability of the National Oceanic and Atmospheric Administration and the National Weather Service to warn or forecast hazardous weather.
(6) An analysis of whether certain wind turbine projects, based on project layout, turbine orientation, number of turbines, density of turbines, proximity to radar, or turbine height result in greater impacts to the missions of Department of Defense, the National Oceanic and Atmospheric Administration, and the National Weather Service, and if so, how can those projects be better cited to reduce or eliminate NEXRAD impacts.
(7) Case studies where the Department of Defense, the National Weather Service, and industry have worked together to implement solutions.
(8) Mitigation options, including software and hardware upgrades, which the National Oceanic and Atmospheric Administration and the National Weather Service have researched and analyzed, and the results of such research and analysis.
(9) A review of mitigation research performed to date by the Government and or academia.
(10) Identification of future research opportunities, requirements, and recommendations for the SENSR program to mitigate energy development.

(c) SUBMITTAL TO CONGRESS.—Not later than 12 months after the date of the enactment of this Act, the Secretary shall submit to the congressional defense committees a report on the study conducted pursuant to subsection (a).

Executive Summary

The American Wind Energy Association offers that the US wind industry added 7,588 megawatts of new wind capacity in 2018. There are now over 56,800 wind turbines with a combined capacity of 96,488 megawatts operating in 41 states, Guam, and Puerto Rico. US wind power has tripled over the past decade, and today is the largest source of renewable-energy generating capacity in the country. Furthermore, the American Wind Energy Association offers that 35% of the current wind fleet operates within 50 miles of a military facility, which includes operating within 50 miles of various Next Generation Weather Radar (NEXRAD) sites.

The NEXRAD (also known as the Weather Surveillance Radar-1988 Doppler (WSR-88D)) is a key system that supports the tri-agency efforts of the Department of Commerce's National Weather Service, Department of Defense, and Department of Transportation's Federal Aviation Administration to track weather and make life, property, and military operational risk assessment decisions. NEXRAD data also supports operations of other government agencies, private industry, and the public. Currently, there are 159 operational NEXRAD systems, of which the Department of Commerce owns 122 systems, the Department of Defense owns 25 systems, and the Department of Transportation owns 12 systems.

Tri-agency NEXRAD program roles and responsibilities are outlined in the Interagency Operation of the WSR-88D Agreement approved 24 March 2008. In accordance with this agreement, the National Weather Service operates, but does not maintain, 21 Department of Defense weather radar sites, exceptions being the Vandenberg AFB, CA; Kadena AB, Japan; Kunsan AB, Republic of Korea; and Camp Humphreys Republic of Korea NEXRAD sites. The Department of Defense maintains its 25 radars. Furthermore, the Air Force Director of Weather acts as the Department of Defense Executive Agent to the NEXRAD program. The National Oceanic and Atmospheric Administration's Radar Operations Center maintains operational support responsibilities for all 159 NEXRAD systems in accordance with the Memorandum of Agreement for the Interagency Operation of the WSR-88D. The National Oceanic and Atmospheric Administration's responsibilities include performing systematic and coordinated analyses of the day-to-day operations and maintenance of WSR-88D units to determine the need for improvement, and for providing both immediate and long-term support during the WSR-88D life cycle; analyzing, developing, testing, evaluating, and approving proposed changes to the radar hardware/software configuration, materials, techniques, procedures.

The expansion of the wind energy industry across the U.S. continues to pose increased challenges to tri-agency members of the NEXRAD network. Communication and early engagement with wind energy developers serves as one of the most vital first steps toward developing cooperative wind development-NEXRAD solutions. However, as a tri-agency program, the National Oceanic and Atmospheric Administration lacks the same legal engagement and siting clearinghouse opportunities afforded to the Department of Defense under the 2018 National Defense Authorization Act, which hinders developers receiving a holistic, NEXRAD impact response.

This report was drafted in collaboration with all military services within the Department of Defense, the Department of Commerce's National Weather Service, and the Department of Transportation's Federal Aviation Administration, and incorporates input from the Department of Energy, academia and industry.

Report

(1) The Potential Impacts of Wind Farms on NEXRAD Radars and other Federal Radars for Weather Forecasts and Warnings used by the Department of Defense, the National Oceanic and Atmospheric Administration, and the National Weather Service.

Rotating wind turbine blades can impact the NEXRAD system in several ways, to include the radar base data (products used to detect precipitation, evaluate storm structure, locate boundaries, determine hail potential, estimate wind speed and direction, locate severe weather signatures, and identify suspected areas of turbulence), algorithms, and derived products when the turbine blades are moving and in the radar's line-of-sight; and, if turbines are sited very near to the radar, their large nacelles (cover housing that contains all of the generating components in a wind turbine, including the generator, gearbox, drive train, and brake assembly) and blades can also physically block the radar beam or reflect enough energy back to the radar to damage the radar's receiver hardware.

- Radar Receiver: The NEXRAD radar has a very sensitive receiver. The radar's Receiver Protector prevents damage from strong reflected signals; however its upper power limit is 53 decibel-milliwatts. Large objects sited very near the radar (< 4 kilometers), such as turbine nacelles, have the potential to return signals that exceed the limit of receiver protector and render the radar inoperable.

- Beam Blockage: If sited within a few kilometers of the radar, wind turbines can partially or fully block the radar beam. This beam blockage attenuates the strength of the beam and impacts data beyond the wind farm, causing shadows or spikes in the data through the entire range of the radar (460 kilometers for reflectivity data, and up to 300 kilometers for velocity and spectrum width data (product used to estimate turbulence associated with mesocyclones and boundaries)).

- Ghost Echoes: Ghost Echoes are erroneous reflectivity and velocity returns in the radar data beyond the location of the wind farm due to the scattering of the radar's signal by the turbines. This typically occurs when wind turbines are located within 25 miles (40 kilometers) of the radar site. Depending on proximity, these ghost echoes can occur 30-40 miles (48-65 kilometers) beyond the location of the wind farm. An example of the impacts of ghost echoes on the NEXRAD data can be seen by reviewing the impacts of a March 2017 wind turbine development south of the Hastings, Nebraska NEXRAD site. There, wind turbines were built less than 3 miles (5 kilometers) from the NEXRAD site. Figure 1. shows radar imagery prior to the buildup of wind farms south of the NEXRAD site. Figure 2. shows the increased clutter to the south of the NEXRAD site which has caused "ghost" echoes/erroneous weather returns. These "ghost" returns give the false appearance that precipitation is occurring, masks precipitation that is actually occurring, and impacts a weather forecaster's ability to assess weather conditions and provide credible notifications ahead of severe weather, including weather watches and warnings.

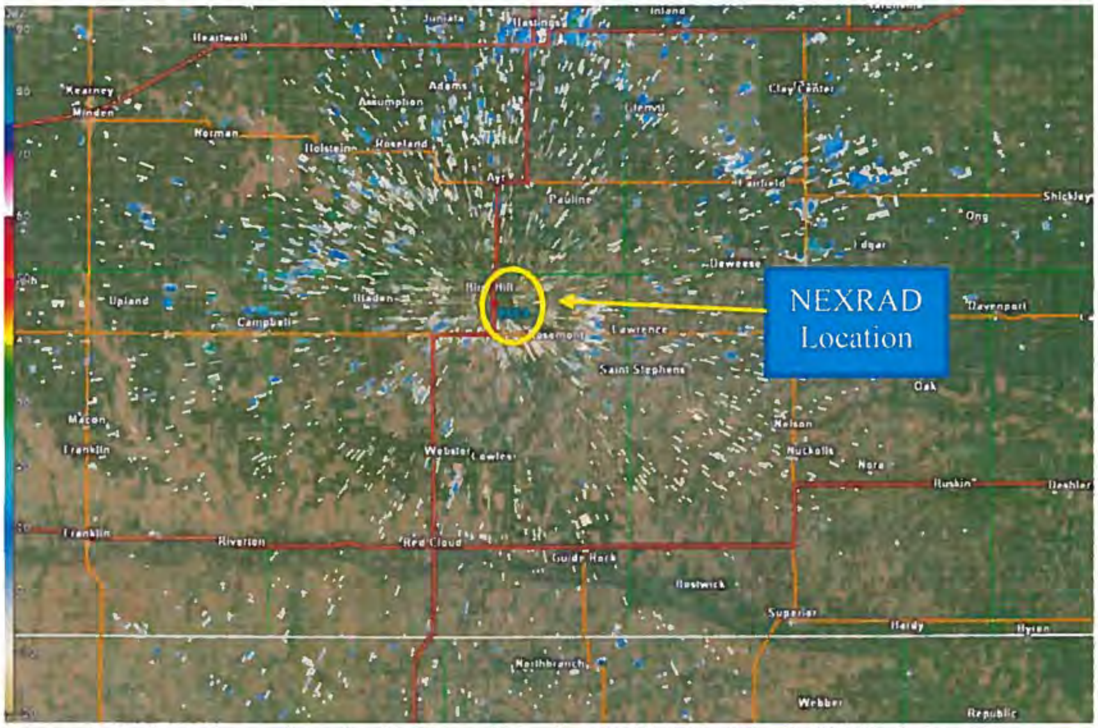

Figure 1. Radar imagery from the Hastings, Nebraska NEXRAD in March 2017 before turbines were constructed south of the radar site.

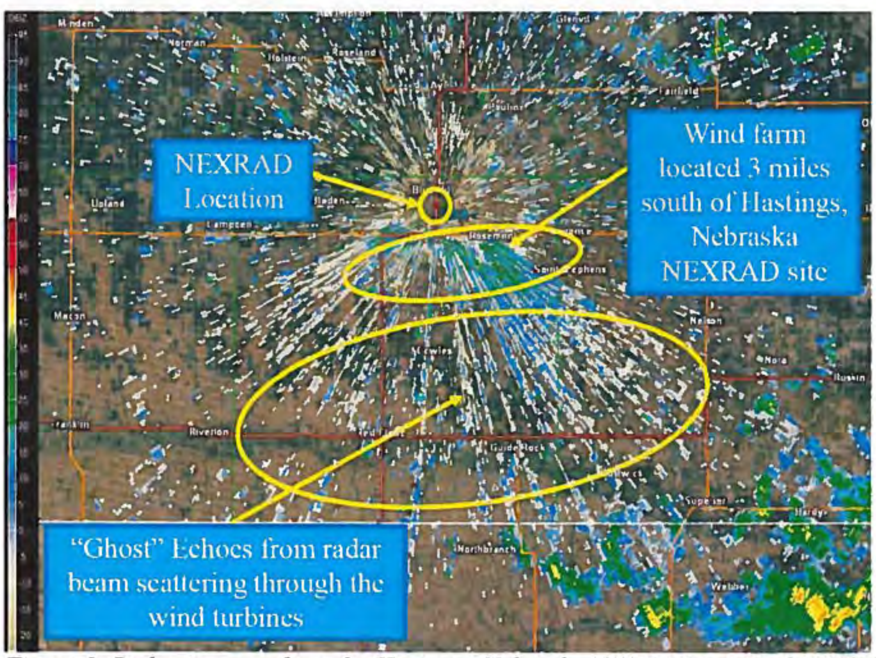

Figure 2. Radar imagery from the Hastings, Nebraska NEXRAD in March 2018 depicting "spikes" and clutter from newly constructed wind turbines to the south of the radar site within 3 miles.

- Radar Base Data: Turbines in the radar's line-of-sight can reflect energy back to the radar and visually contaminate the reflectivity, velocity, and spectrum width data. Weather forecasters look for certain "signatures" in the data that indicate the severity of the storms. The wind farm clutter can sometimes look just like showers and thunderstorms, or can alter the appearance of a storm by masking severe weather signatures. This visually corrupted data adds uncertainty to the analysis and could cause forecasters to delay/miss a severe weather warning or to provide an unnecessary weather warning.

The next five figures illustrate how a wind farm's contamination caused a tornado signature (wind detection capability) to be masked for about 15 minutes. On the left are radar reflectivity images. On the right are wind velocity images. Notice how the velocity signature was masked as the supercell traversed the area downstream of the windfarm.

December 1, 2018 – 6:11 pm

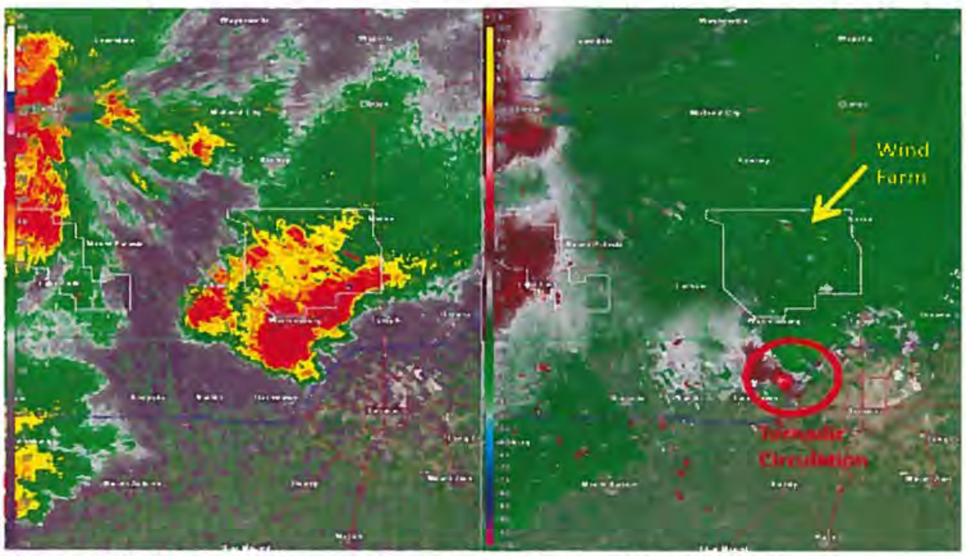

Figure 3. 6:11 pm - A strong rotation is seen northeast of Harristown, IL.

December 1, 2018 – 6:18 pm

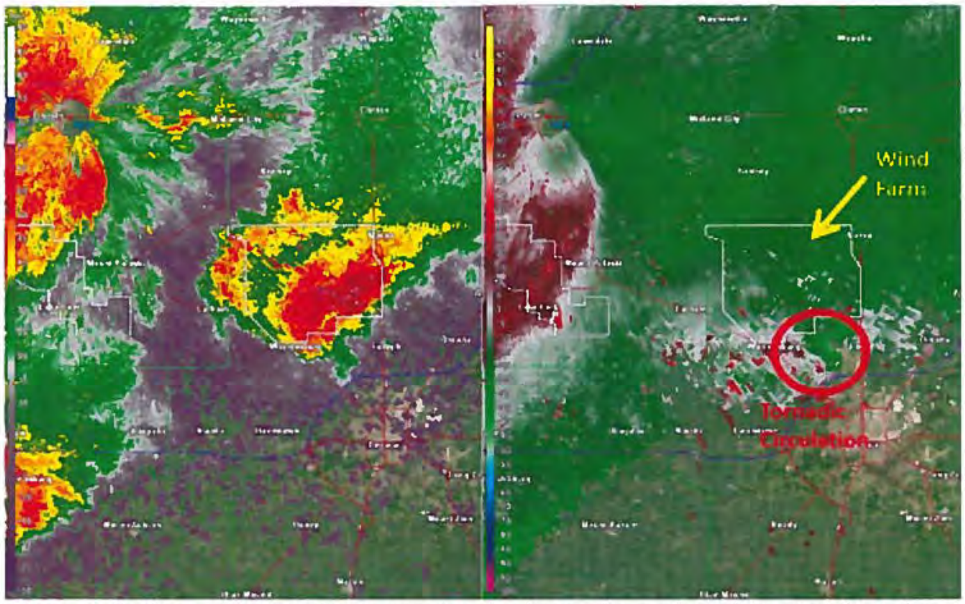

Figure 4. 6:18 pm - The rotation is entering the far southern edge of the wind farm, but is difficult to locate.

December 1, 2018 – 6:22 pm

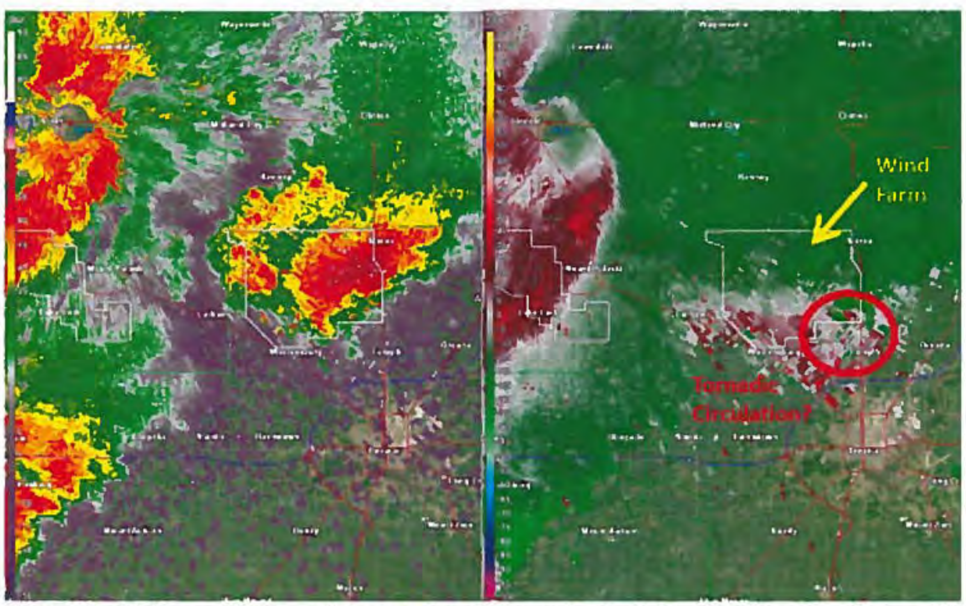

Figure 5. 6:22 pm - No sign of the rotation due to velocity field contamination. Supercell is in eastern part of wind farm.

December 1, 2018 – 6:30 pm

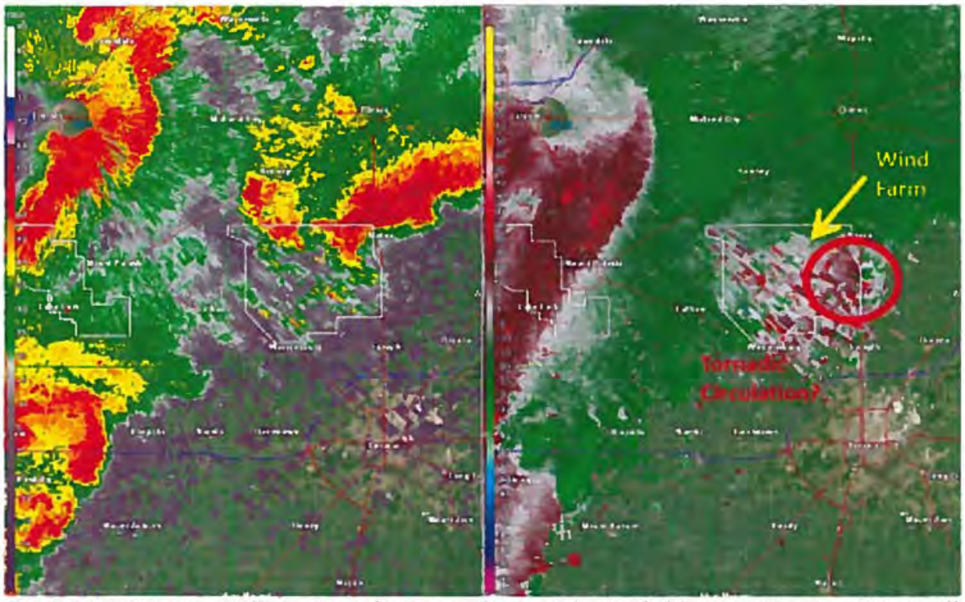

Figure 6. 6:30 pm - Still no sign of rotation due to velocity field contamination. Supercell is in northeast part of wind farm. A damage survey indicated an EF-1 tornado was developing at this time 3 miles south of Maroa, IL.

December 1, 2018 – 6:34 pm

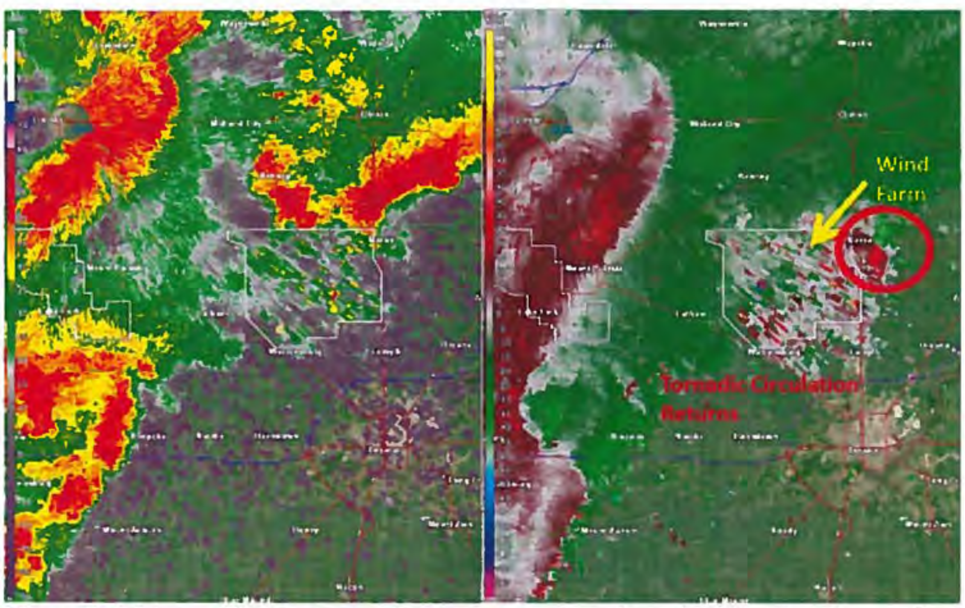

Figure 7. 6:34 pm - The strong rotation reappears since the radar beam is only traveling through the extreme northeast corner of the wind warm. EF-1 tornado is in the dissipating stage, but the rotation is still strong.

The top left panel of Figure 7. shows a tornadic circulation, red and green colors in a small area close to each other, moving from southwest to northeast over a time period of 49 minutes. Notice how the circulation disappears as it moves through the wind farm, approximately 20 miles (32 kilometers) southeast (approximately 120 degrees clockwise from North) of the Lincoln, Illinois radar indicated by a black circle in the northwest corner of the frame. Wind farm clutter obscured the tornadic circulation for approximately 15 minutes at the 0.5 degree elevation scan, approximately 1,200 feet above the ground. The circulation is also obscured on the 0.9, 1.3, and 1.8 degree elevation scans approximately 2,000, 3,000, and 4,000 feet above the ground, respectively. The loss of 15 minutes of credible weather radar data resulted in a decreased amount of time for the National Weather Service to issue warnings, thus decreasing the amount of time for communities to take emergency precautions. This supercell produced 13 tornadoes during its life cycle, including an EF-3 tornado in Taylorville, IL. This storm was dangerous and required careful monitoring by forecasters to determine if the tornado had dissipated and/or redeveloped. The radar data contamination from the wind farm made that task more difficult. The images are from the 0.5 degree elevation scan from KILX, which is the most desirable elevation to see rapidly developing tornadic circulations. Because of the contamination of the wind farm, forecasters had to look nearly 7,000 feet above ground to view uncontaminated data, which significantly hindered their ability to view the developments in the lowest portion of the atmosphere.

- <u>Algorithms and Derived Products</u>: The base reflectivity, velocity, and spectrum-width data are also used by many algorithms in the radar processor to detect certain storm characteristics, such as mesocyclones, relative storm motion, hail, turbulence, etc. Corrupted base data can cause the radar algorithms to generate false weather alerts or missed weather alerts. Figure 8. provides a visual representation of a wind farm's close proximity to the Dodge City, KS NEXRAD in which the wind farm created erroneous returns and provided forecasters with the false appearance/radar alert that a tornado was occurring. The radar also generates many additional products using this base data, such as wind profiles and rainfall estimates. Wind turbine clutter can impact the accuracy of these derived products.

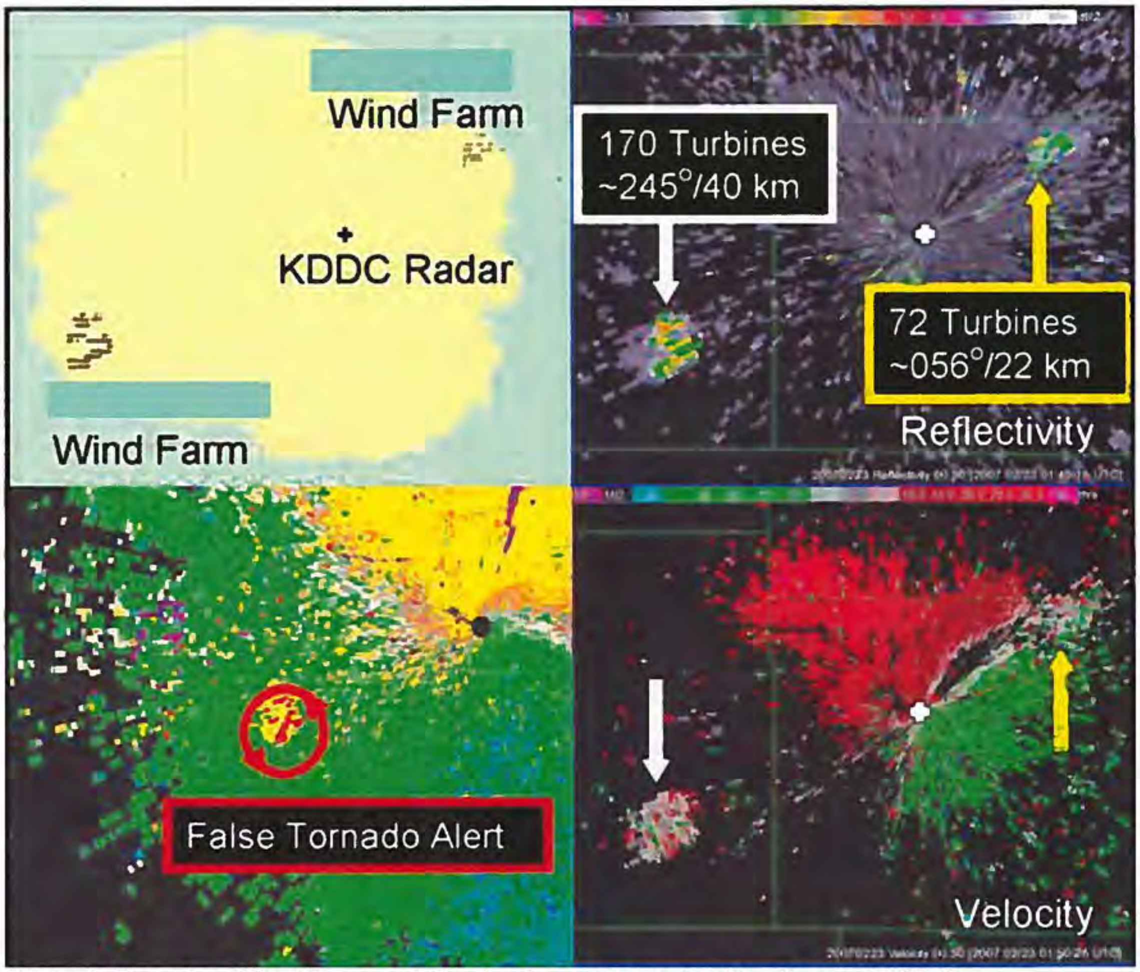

Figure 8. Example of Wind Farms and Weather Impacts to Dodge City, Kansas NEXRAD.

(2) Recommendations to Reduce, Mitigate, or Eliminate the Potential Wind Farm Impacts

Consultation with developers is the key to reducing, mitigating, or eliminating potential impacts to the NEXRAD system. This consultation is conducted by both the Department of Defense and Department of Commerce's National Weather Service via similar, but different Siting Clearinghouse processes. Developers are required to submit proposals through the Federal Aviation Administration's Obstruction Evaluation Database which provides the mechanism for the Department of Defense to assess wind farm impacts to the NEXRAD system. The National Weather Service relies on the optional notification process for developers to file proposals through the National Telecommunications and Information Administration. Through ongoing collaboration between the Department of the Air Force, Department of the Army, and National Weather Service Radar Operations Center, the National Weather Service is made aware of developments on all projects filed through the Federal Aviation Administration's Obstruction Evaluation Database. While the NEXRAD Program agencies have learned about many proposed wind farms via the Clearinghouse process, this only represents a subset of the wind farms being planned. Advance information on new planned projects, or expansions, would enable impact analysis and siting consultation earlier in the project lifecycle, potentially avoiding costly project changes.

In order to reduce, mitigate, or eliminate potential wind farm impacts, the Department of Defense and National Weather Service jointly utilize a four zone schematic developed by the National Weather Service Radar Operations Center that takes terrain, distance, and the number of NEXRAD elevation angles impacted into account. The four zones use terminology that communicates to wind farm developers the desired action. These zones, defined below, are: no build, mitigation (or "high impact zone"), consultation ("moderate impact zone") and notification ("low impact zone").

- <u>The No Build Zone</u>: a 4-kilometer radius around the NEXRAD. Developers should not build turbines in the radar's line-of-sight within 4 kilometer of the radar due to the potential for serious impacts, including turbine nacelles blocking the radar beam and potential receiver damage if sited in the radar's near field.

- <u>The Mitigation Zone ("High Impact Zone")</u>: the area between 4 and 36 kilometers, where a 160-meter turbine would penetrate more than one elevation angle. Wind farms sited within the mitigation zone have the potential for high impacts.

- <u>Consultation Zone ("Moderate Impact Zone")</u>: the area between 4 and 36 kilometers where a 160-meter turbine only penetrates the 1st elevation angle or when a 160-meter tall turbine will penetrate more than one elevation angle between 36 and 60 kilometers. Wind farms sited within the consultation zone have the potential for moderate impacts.

- <u>Notification Zone</u>: the area between 36 and 60 kilometers where a 160-meter tall turbine will only penetrate one elevation angle, or any area beyond 60 kilometer that a 160-meter tall turbine is in the radar line of sight. Wind farms sited within the notification zone have the potential for low impacts.

Figure 9. shows an example radar line-of-sight map generated using the Federal Aviation Administration's Obstruction Evaluation Database or National Oceanic and Atmospheric Administration's NEXRAD Screening Tool for a wind farm analysis. Four hypothetical proposals: A, B, C, D, and E are described below.

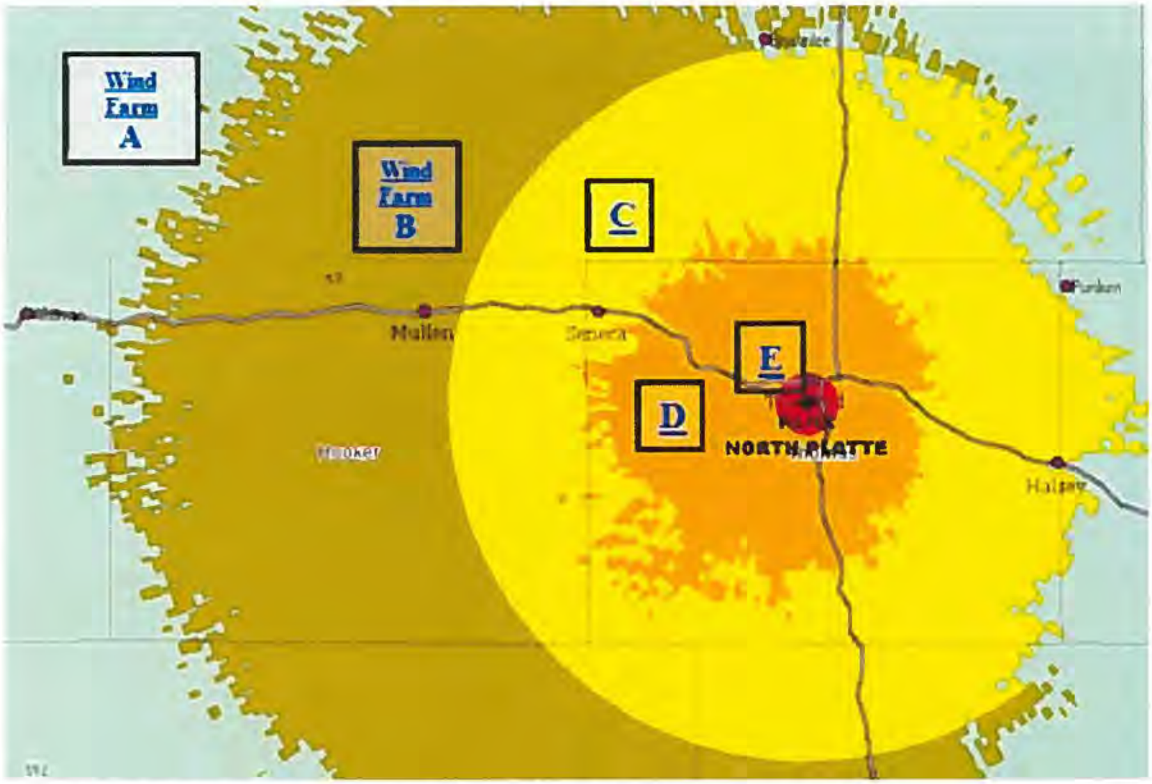

Figure 9. Radar Line of Sight Analysis for the North Platte, North Dakota NEXRAD.

- Wind Farm A: clearly out of the radar's line of sight, would have no impact on the radar data, except in some anomalous propagation conditions, in which case impacts would be low. A wind project proposal at this location would be considered radar neutral.

- Wind Farm B: Notification zone – low to minimal impact on the radar data if turbines were built in the proposal area. Recommendations to reduce, mitigate, or eliminate the potential impacts would include the developer locating most/all wind turbines in the western portion of the proposed area (as far away from the radar as practical).

- Wind Farm C: Consultation Zone ("moderate impact zone") – impacts increase the closer the turbines are built to the radar. Recommendations to reduce, mitigate, or eliminate the potential impacts would include the developer locating most/all wind turbines in the western portion of the proposed area lowering turbine heights, aligning the turbines radially, and/or siting the turbines as far away from the radar as practical.

- Wind Farm D: Mitigation Zone ("high impact zone") – high impacts on the radar. Recommendations to reduce, mitigate, or eliminate the potential impacts would include consulting with the developer to determine if there is flexibility to consider impact mitigation techniques (such as curtailing turbine use prior to expected severe weather events), discussing lowering the turbine heights and/or eliminating turbines from the project that would cause the most severe impacts, and communicating with developers to ensure they are aware of potential impacts on forecast/warning/impacts to Department of Defense operations.

- Wind Farm E: Encroaches into No-Build Zone. High impacts on the NEXRAD with potential for mechanical damage to the radar in the red zone. Recommendations to reduce, mitigate, or eliminate the potential impacts would include consulting with the developer to ensure they are aware of the likely impacts to tri-agency missions, including impacts to forecast and warning operations of the Department of Defense and National Weather Service. Communications with developers would emphasize relocating or cancelling the development causing the most degraded impacts.

Mitigation strategies include negotiating with the developer to reduce turbine heights, or relocate/eliminate turbines of greatest concern, especially when located in the No Build, Mitigation ("high impact"), or Consultation zones ("moderate impact") zones. Another option is for developers to align turbines along NEXRAD radials. This strategy helps to avoid north/south or east/west spread of turbine contamination. Weather operators may also employ "real-time" mitigation strategies to reduce wind farm impacts on NEXRAD systems including temporary continuity of a storm using previous radar scans; spatial continuity of a storm using higher elevation scans; and using available adjacent NEXRAD systems. These "real-time" mitigation strategies may result in improperly assessing the severity of a weather phenomenon.

Wind energy developers may suggest other avenues to mitigate impacts to the NEXRAD system, such as relocating the radar or installing a commercial radar; however these options carry feasibility challenges. Even if developers paid the entire cost of relocation, including new land lease/purchase and communications, it would not ultimately solve the wind turbine issue. Furthermore, relocation may not be feasible to meet tri-agency requirements outlined in the "NEXRAD Radar Coverage and Siting Analysis" document. If turbine impacts cannot be mitigated at the current NEXRAD location, there would be no guarantee to prevent turbines from affecting the radar at the new location.

Wind energy developers may also suggest paying for the purchase and installation of a commercial radar. This proposal comes with a long list of concerns. Since the National Oceanic and Atmospheric Administration and the Department of Defense are not funded to purchase and maintain supplemental radar systems, the wind energy developer would have to cover all of those costs, including site surveys and environmental studies. The developer could pay for communication costs, any modifications to display systems, weather data processing, and ongoing maintenance. The National Oceanic and Atmospheric Administration's previous experience with commercial radars resulted in skyrocketing maintenance costs and ultimately the radar could not perform to NEXRAD standards. Developers are most likely only able to pay for routine maintenance for a specified amount of time, not for the life of the radar, and not to cover significant, costly or catastrophic repairs. Any agreement with a developer could include a service level agreement to ensure the maintenance and restoration of the radar occurred within a specified time. Furthermore, integrating any non-NEXRAD, non-Federal radars into the Department of Defense or National Weather Service operations presents significant challenges. There are starting and recurring costs associated with every connection. For example, communication lines and bandwidth would need to be upgraded and maintained to support effective delivery and display of the data. Integrating radars that are operated and maintained by third parties would encompass the National Oceanic and Atmospheric Administration and the Department of Defense receiving the data from non-Federal networks, which induces potential cybersecurity risks. While the maintenance and sustainment of these radars would not be the responsibility of the Department of Defense or the National Oceanic and Atmospheric Administration, there would be non-trivial recurring and one-time costs associated with every connection to third party radars. Integrating the data into the National Oceanic and Atmospheric Administration's Advanced Weather Interactive Processing System (AWIPS) or Air Force Weather's Data Analysis and Dissemination System would require external weather radar data to be processed through a supplemental radar product generator, which requires maintenance and sustainment of that software and hardware infrastructure. Ingesting data from non-NEXRAD weather radars induces increased cyber security threats and requires cyber security updates and monitoring. Requirements for any third-party weather radars must be established prior to ingesting the data, including data availability, quality, and reliability standards consistent with the operational needs of the Department of Defense and National Weather Service. The National Oceanic and Atmospheric Administration's additional concerns include the inability of accepting data from weather radars only in NEXRAD Level II format, data quality of sufficient level, reflectivity and velocity data available and dual polarization as high priority. These are neither inexpensive nor technically simple solutions, especially in light of the fact that NEXRAD data are the gold standard across the world for operational weather radar data.

Curtailment strategies include the developer agreeing to cease turbine operations during periods of severe weather or during military mission-limiting weather events. The Department of Defense formally documents agreements through a formal coordination process between the developer, military service department, and Office of the Secretary of Defense Siting Clearinghouse. It is the desire by the National Oceanic and Atmospheric Administration's National Weather Service to have a similar formal mitigation agreement process when any curtailment agreement includes NEXRAD-related wind farm impacts.

(3) Recommendations for Addressing the Impacts to NEXRADs and Weather Radar due to Increasing Turbine Heights

According to the Department of Energy 2018 Wind Technologies Market Report, the Federal Aviation Administration permit data suggests that near-future wind projects will deploy progressively taller turbines, with a significant portion (39% in 2018) of permit applications exceeding 500 feet (approximately 152 meters). Although some radars, such as air surveillance radars, can benefit from developers reducing the number or density of turbines in exchange for increasing turbine height, this is not the case for NEXRAD and other weather radars.

Increasing the height of wind turbines increases the negative impact on the NEXRAD radar data by contaminating a larger volume of the data. Shorter turbines may degrade radar data in the lowest one or two elevation angles, roughly equating to the lowest 2,000-3,000 feet of the atmosphere close to the radar. Meanwhile, taller turbines may degrade data in three or more elevation angles, negatively affecting radar data in the lowest 5,000 feet or more of the atmosphere close to the radar. Furthermore, as turbines increase in height, NEXRAD impacts increase. An increase in turbine blade height is directly proportional to an increase in radar's line-of-sight blockage (and thus contaminating of multiple radar level scans). A significant number of turbine proposals are now for heights of 180 to 200m, up from almost none five years ago. As developers repower older projects, they often reduce the number of turbines, but increase heights. For NEXRAD, any increase in height has an impact to the data regardless if the number of turbines decrease. The greater the number of elevation angles contaminated, the greater the impact.

The NEXRAD system performs 360-degree scans of the atmosphere with elevation angles between 0.5 degrees and 19.5 degrees. The NEXRAD samples up to 14 different elevations angles for each complete scan of the atmosphere. The radar beam increases in height and in diameter as it moves away from the radar, with most of the beam's energy at the beam center height. Figure 6. provides an illustration of the NEXRAD beam concept. The bottom and top heights of the beam are defined as the points where there is a 50% reduction in the transmitted energy. Below the beam bottom height and above the beam top height the energy drastically decreases. The area between the beam bottom and beam top is referred to as the "beam". There is reduced impact on the radar if the rotating blades are below the beam bottom, especially at "close" distances.

Figure 10. Illustration of the NEXRAD Radar Beam

Any object within the beam reflects energy back to the radar. The NEXRAD system uses a complex algorithm, called a clutter filter, to perform an analysis on the data to determine if the returned energy is from a desirable target (weather) or not (non-weather clutter). One factor used in the clutter filter process is the motion of the return. Clutter mitigation filters within the NEXRAD cannot filter rotating wind turbines due to the motion of the blades. When the turbines are close to the radar, they penetrate more of the beam, increasing the amount of energy returned to the radar, resulting in higher reflectivity values, potentially at multiple elevation angles.

The lowest elevation angles are the most critical because they show the lowest level of the storm, where the detection and monitoring of high winds, tornadoes, hail, or heavy precipitation is vital. Those same low elevation angles are affected by wind turbines distorting the radar information making it unusable to warn for severe weather.

Recommendations for addressing the impacts to NEXRADs and weather radar due to increasing turbine heights are limited. In order to address NEXRAD impacts due to increasing turbine heights, the Department of Defense and National Weather Service must continue to work with developers early and often to mitigate impacts through either the lowering of turbine heights, re-siting turbines, or developing curtailment options.

- When turbines contaminate the lowest elevation angle, 0.5 degrees at most radar sites, weather forecasters can use the next highest angle, 0.9, to compensate for the contaminated lower level data. The impact of this workaround is not negligible, however, as forecasters lose the ability to see as close to the ground as possible, but can generally still use other knowledge about the storm to issue timely and accurate warnings.

- The "Next Generation Weather Radar (NEXRAD) Siting Handbook" dated May 1983 states: "The Department of Defense requires area coverage and local coverage in the vicinity of the selected military bases. A useable range of 230 km from the NEXRAD site is required. Altitude coverage up to 21.3 kilometers (70,000 feet) is required. To meet the low-altitude coverage requirement of 1.5 kilometers (5,000 feet) over its bases, Department of Defense requires that radar sites be located within 40 miles (65 kilometers) of each base." For the National Weather Service, the Siting Handbook states: "The National Weather Service requires area coverage of the CONUS. A useable range of 460 kilometers for reflectivity data and 230 kilometers for radial velocity and spectrum-width data is indicated, and overlapping coverage is required in severe weather areas." When turbines contaminate the lowest two elevation angles, 0.5 and 0.9 at most NEXRAD sites, the forecaster's ability to accurately monitor and detect severe weather diminishes further. The forecaster must then look at the 1.3 degree elevation angle, which may be 1,500-2,000 feet off the ground close to the radar, in order to look for key features of severe storm or tornado development. Based on the Department of Defense and National Weather Service four zone schematic referenced in "Recommendations to Reduce, Mitigate, or Eliminate the Potential Wind Farm Impacts" (page 11 in this report), it is recognized that turbines can degrade radar data in the lowest two elevation angles within the critical threshold of 40 miles (65 kilometers) from the NEXRAD site.

- Once turbines contaminate the lowest three elevation angles (0.5, 0.9, 1.3 degrees at most radar sites), the National Oceanic and Atmospheric Administration and Department of Defense consider those impacts to the NEXRAD to be unacceptable. In order to view uncontaminated data, forecasters must look at well above the ground level, which can result in missed or delayed severe thunderstorm and tornado warnings. The impact is even more critical as distance from the radar increases. The impact can reach well above 10-15,000 feet or more rendering the data unusable. Critical weather occurs in the lowest levels of the atmosphere, such as rapid tornado development, downbursts imperative to aviation safety, and precipitation measurements necessary for accurate flash flood warnings. Those key weather features are missed when turbines contaminate three or more elevation angles. Under those circumstances, the National Oceanic and Atmospheric Administration can request wind energy developers to lower turbine heights or relocate proposed turbine locations, but cooperation is voluntary, and compliance has been very limited. In contrast, the Department of Defense can also request wind energy developers to lower or relocate turbines or develop other mitigation-type agreements (i.e. binding agreements) through the formal Mitigation Response Team process.

(4) Recommendations to Ensure Wind Farms Do Not Impact the Ability of the National Oceanic and Atmospheric Administration and the National Weather Service to Warn or Forecast Hazardous Weather

According to the National Oceanic and Atmospheric Administration and the National Weather Service, there is no technological solution to remove wind turbine clutter from NEXRAD data. Once turbines are constructed, the radar data are degraded and the National Weather Service warning performance threatened. If the National Oceanic and Atmospheric Administration's Radar Operations Center is aware of the project while it is in the planning phase, analysis can be done to determine which turbines will have the most impact on the radar data and provide recommendations to the developer to mitigate the impact and retain the life-saving data.

Unfortunately, specific requirements such as siting turbines a specific distance from radars or building turbines of a certain height, cannot be provided as a one-size-fits-all solution to all 159 operational NEXRADs. The impacts from turbines are dependent on many factors including the height of the radar tower, surrounding terrain, and other wind farm project specifics such as density, orientation, etc. Recommendations to reduce impacts at one NEXRAD site may be entirely different from recommendations at another radar site. Recommendations can even be different at the same NEXRAD site for different project proposals (height of turbines, location of turbines, etc.).

However, depending on project specifics, recommendations may include the following:

- Eliminating turbines from the project that are in close proximity to the NEXRAD (i.e. within 4 kilometers of the NEXRAD) or very tall (i.e. greater than 160 meters), causing clutter in multiple radar elevation scans
- Lowering turbine heights
- Moving turbines farther away from the NEXRAD system
- Aligning turbines along NEXRAD radials such that the east/west or north/south spread of clutter is reduced

- Developing a binding curtailment agreement, in which the developer legally agrees to cease operation of the turbines during specific weather conditions set forth by the National Weather Service (weather events such as severe thunderstorms, tornadoes, lake effect snow, etc.).

The key to all of these recommendations is that the developer works with the National Oceanic and Atmospheric Administration early on in the planning phase of the project and takes the recommended actions, neither of which is required by current law. In the 12 years of experience that the National Oceanic and Atmospheric Administration's Radar Operations Center has worked with developers on a voluntary basis, success is mixed. While some developers have established a good relationship with National Oceanic and Atmospheric Administration and work in good faith to reduce impacts, other developers have opted to reject any and all recommendations from the National Oceanic and Atmospheric Administration or outright refused to work collaboratively with the agency. The tri-agencies, including Department of Energy, must continue to engage with industry and academia on improving existing screening tools and determining weather radar wind turbine mitigation solutions. Establishing a joint interagency working group with AWEA and other wind industry participants could be valuable, provided industry is willing to address the concerns of all NEXRAD agencies.

(5) Cumulative Impacts of Multiple Wind Farms near a Single Radar on the Ability of the National Oceanic and Atmospheric Administration and the National Weather Service to Warn or Forecast Hazardous Weather

The vicinity of geography around many NEXRAD sites appears favorable for wind turbine developments. These radars include Fort Drum, NY; Dyess AFB, TX; Lincoln, IL; Dodge City, KS; and Amarillo, TX. At the present time, the Fort Drum, NY and Dyess AFB, TX NEXRAD sites are experiencing the most significant impacts from multiple existing and proposed wind farms due to close proximity and density of wind farms to the NEXRAD sites as well as siting wind turbines on hills that cause interference through multiple radar elevation angles.

While the impacts of one or two wind farms can be somewhat mitigated by forecasters using uncluttered radar data on either side of the project area, the increase in the number of wind projects around a single radar site is concerning because of cumulative impacts.

Figure 11. depicts the location of the Fort Drum NEXRAD (indicated by the blue star), nearly surrounded by current and proposed wind projects. If all of the proposed projects are built, the ability of the Fort Drum NEXRAD to detect and monitor hazardous weather would be greatly compromised. Degraded data associated with the turbines themselves and the down-range data artifacts, which are a result of tall turbines in close proximity to the radar, would prevent the radar from accurately detecting lake effect snow developing to the west of the radar, as well as severe weather (high winds, hail, and tornadoes) moving across the region.

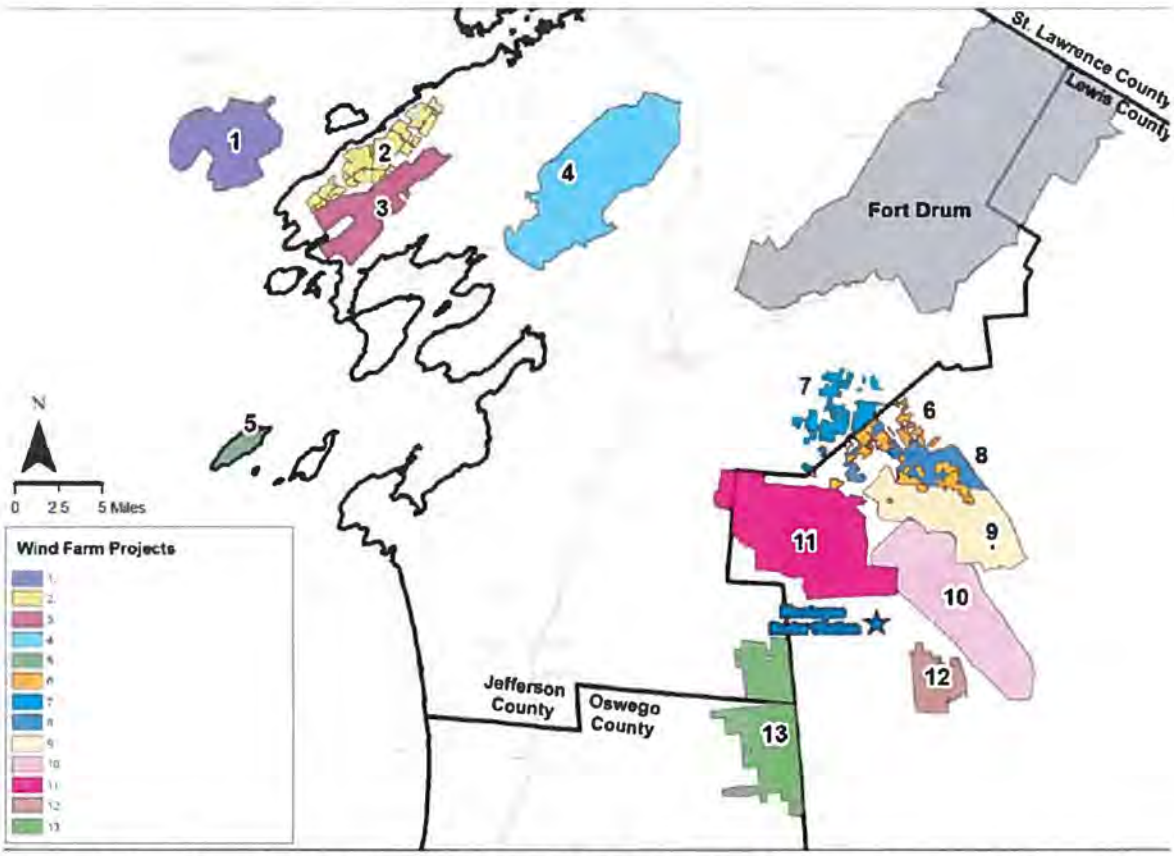

Figure 11. Fort Drum, New York NEXRAD indicated by the blue star. Current and proposed wind projects, referenced by numbers, are shown to nearly encircle the radar.

National Weather Service forecasters and Air Force Weather personnel at Fort Drum have already expressed concern in their ability to monitor and detect severe weather over the existing wind project to the northeast of the radar site. The addition of the proposed wind projects, nearly encircling the radar, would greatly hinder weather forecasters' ability to issue timely and accurate warnings and could greatly impact Army leadership's ability to make informed operational risk assessment determinations, including impacts to infrastructure, flying operations, and personnel training.

In the August 2017 severe weather event shown in Figure 12, a rapidly evolving storm approached the nearby wind farm. Both National Weather Service and Air Force weather forecasters at Fort Drum were concerned with this weather feature because of the possibility for a tornado to form quickly on the leading edge of the storm as it approached the wind farm. With the clutter and erroneous data returns from the wind farm still evident as the storm approached, it was difficult for forecasters to distinguish between real weather signatures of a developing tornado and clutter from the turbines.

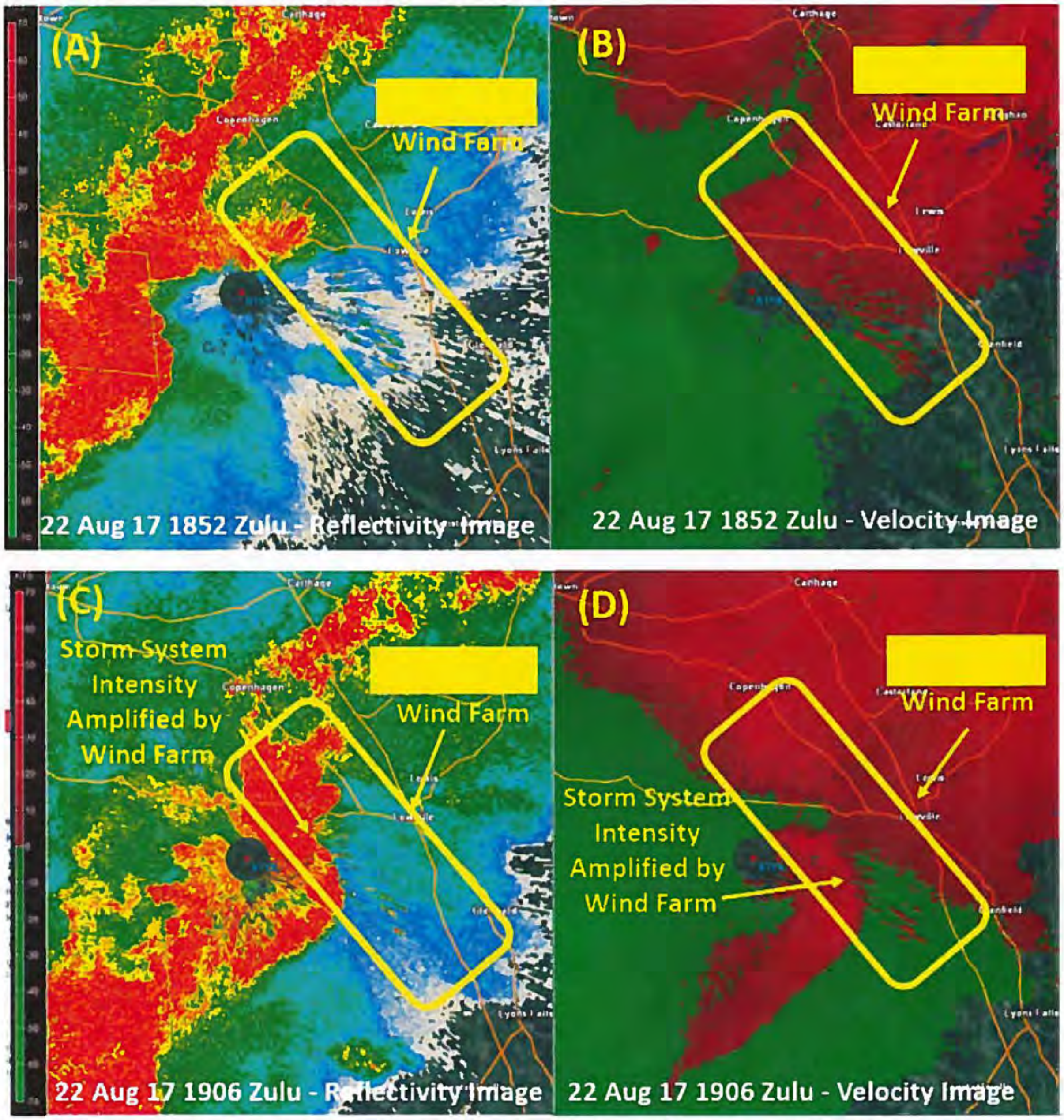

Figure 12. Reflectivity data (left) and base velocity data (right) from Fort Drum, New York NEXRAD on August 22, 2017 showing a line of severe thunderstorms approaching the wind farm (indicated by yellow rectangle). Figures A and B clearly depict the line of thunderstorms to the Northwest of the Fort Drum NEXRAD site as well as wind farm "clutter" depicted to the east of the radar. Figures C and D depict the line of thunderstorms intensifying as it crosses the wind farm location, making it difficult to determine whether tornadic development was "real" or falsely reported by moving wind turbines.

If wind developments similar to this project encircled the NEXRAD system (as shown in Figure 11.), it would become even more difficult for forecasters to effectively warn for hazardous weather and enable military leadership to make operational risk assessments in support of the assigned Department of Defense mission. The Dyess AFB NEXRAD is in a similar situation. Since Texas experiences a higher frequency of severe thunderstorms and tornadoes than New York, the concern is much higher for the negative effect of the cumulative impacts on National Weather Service warning capabilities.

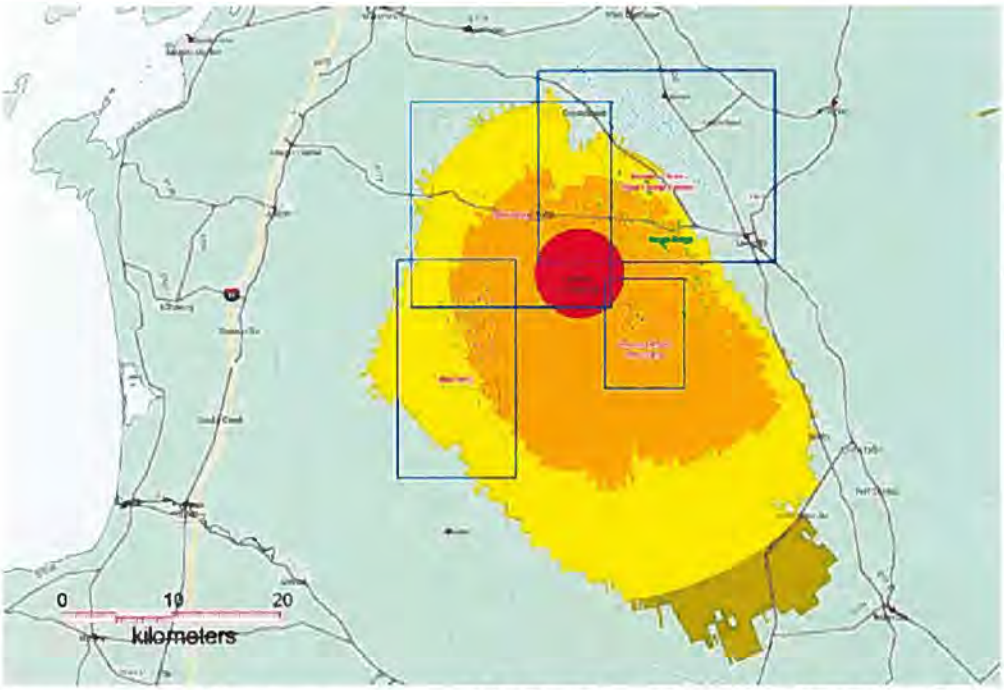

Figure 13. Wind turbine impact zones around the Fort Drum, New York NEXRAD site. The wind project, to the immediate northeast of the radar, has been present for about 13 years. The other projects indicated on the map are proposed as of early 2018. Note the number of proposed turbines within the orange "High Impact Zone" that, if built, will negatively impact the NEXRAD's capability to detect hazardous weather.

(6) An Analysis of Whether Certain Wind Turbine Projects, Based on Project Layout, Turbine Orientation, Number of Turbines, Density of Turbines, Proximity to Radar, or Turbine Height Result in Greater Impacts to the Missions of Department of Defense, the National Oceanic and Atmospheric Administration, and the National Weather Service, and if so, How Can Those Projects Be Better Sited to Reduce or Eliminate NEXRAD Impacts

Since 2006, the National Oceanic and Atmospheric Administration's Radar Operations Center has analyzed nearly 2,000 wind turbine projects for NEXRAD tri-agency partners. Out of those, the vast majority of projects are considered radar "neutral" or have little to no impact, or low impact. Low-to-minimal impact accounts for about 80-90% of the analyzed projects. Although the moderate-to-high impact projects are only about 10-20%, roughly 190 projects since 2006, they have the ability to result in major effects on the usability of the NEXRAD data.

Most wind turbine projects are far enough away from the radar to be considered "neutral". This means the wind turbines are below the radar's line-of-sight. Under normal atmospheric conditions, the radar would not "see" the turbines and the data would not be impacted. However, it is important to note that the atmosphere is rarely under what is considered normal conditions.

Figure 14. shows an example of a wind project far enough away from the NEXRAD to be considered radar "neutral." In this example, the wind project is approximately 98 kilometers (60 miles) from the Aberdeen, South Dakota NEXRAD site. Also shown in Figure 10. are the impact zones around the radar. It is crucial to note that these impact zones are unique to this NEXRAD site and to the height of the proposed turbines of this particular project. For shorter turbines, the impact zones are closer to the radar, while for taller turbines, the impact zones are larger. Furthermore, due to terrain such as plateaus, valleys, or mountains, the range of the impact zones could vary at other NEXRAD sites. Refer to the "Recommendations to Reduce, Mitigate, or Eliminate the Potential Wind Farm Impacts" section of this report for a review of the zone descriptions and impacts to the NEXRAD system.

Wind turbine impacts increase greatly as wind turbines are sited closer to the radar, especially within 18 kilometers (assuming level terrain), as radar operator workarounds become more difficult. Turbines sited at least 18 km from the radar generally only impact the lowest radar scan at 0.5 degrees elevation, and clutter is confined to the wind farm area. Within 18 kilometers, wind turbines cause additional impacts including: clutter on multiple elevation scans above 0.5 degrees, multipath clutter down range of the wind turbines, and greater impacts to radar algorithms. Multipath scattering from wind turbines can extend the contaminated data up to 40 km beyond the wind farm. Turbines sited within 4 km of the radar may also cause significant (>10%) attenuation/blockage of the radar beam impacting data throughout the entire range (460 kilometer-reflectivity, 300 kilometer-velocity) of the radar. When turbines are sited within 200 meters, wind turbine construction or maintenance personnel may be exposed to microwave energy exceeding OSHA (Occupational Safety and Health Administration) thresholds. The above distances assume a level terrain and normal weather conditions. Therefore, actual impacts may occur closer or further away from the radar than this chart indicates depending on the terrain and current weather. Accurate determination of the radar's line-of-sight and impact distances requires a detailed site-by-site analysis.

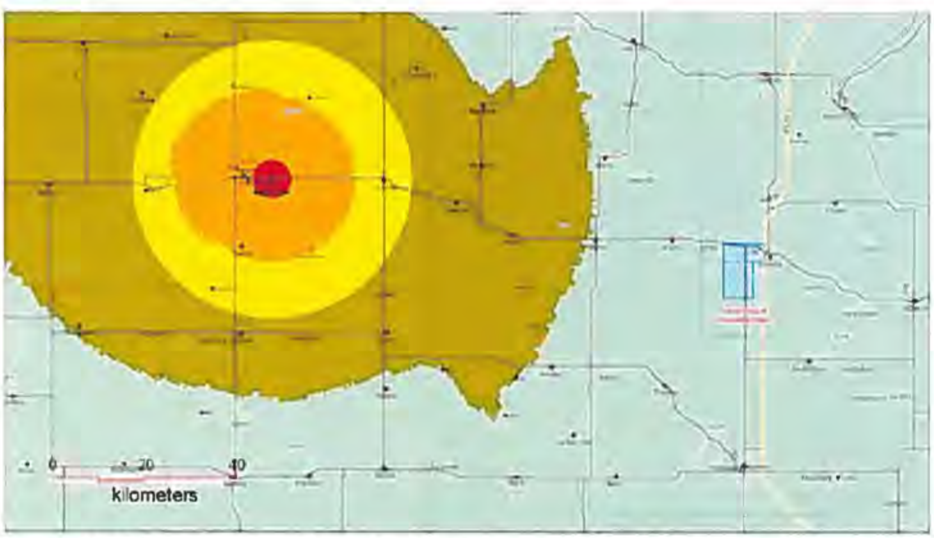

Figure 14. NOAA analysis of a wind project approximately 98 kilometers (60 miles) from the Aberdeen, South Dakota NEXRAD site.

Once turbines are built, there is nothing that can be done to remove the clutter from the weather signal. The best option is for developers to work with the Department of Defense and the National Oceanic and Atmospheric Administration to reduce impacts as much as possible. Refer to the "Recommendations to Reduce, Mitigate, or Eliminate the Potential Wind Farm Impacts" and "Recommendations for Addressing the Impacts to NEXRADs and Weather Radar due to Increasing Turbine Heights" sections for a complete description of current mitigation options. One example is aligning turbines with NEXRAD radials to reduce the azimuthal spread of the contamination. In Figure 11, the proposed wind project, to the west of the Fort Drum, NY NEXRAD radar site (indicated by the shaded green/#13 key reference) has a very broad north to south spread. This results in an extremely large area of data contamination, affecting nearly the entire western view of the NEXRAD. Reducing the density of turbines within a project can minimally reduce impacts, although the more important factors are turbine height, proximity to the radar, and east/west or north/south spread of the turbines.

As previously stated in the "Recommendations to Reduce, Mitigate, or Eliminate the Potential Wind Farm Impacts" and "Recommendations for Addressing the Impacts to NEXRADs and Weather Radar due to Increasing Turbine Heights" sections, there are several methods to reduce or eliminate wind turbine impacts to the NEXRAD system. Furthermore, there is an ongoing effort to lower elevation angles at NEXRADs where it is feasible to do so. Adding a supplemental low elevation angle below 0.5 degrees has great advantages to improved detection of hazardous weather at mountaintop and coastal NEXRAD sites. There has also been recent Congressional interest in lowering elevation angles at interior radar sites such as Minot AFB, ND to improve NEXRAD coverage over western North Dakota, as well as the NEXRADs surrounding Charlotte, NC; Greer, SC; and Columbia, SC. As this initiative spreads to NEXRADs across the country, it will further complicate the impacts from wind turbines. The benefits presented by lowering the elevation angle will be offset by the contaminated data from the wind turbines.

(7) Case studies where the Department of Defense, the National Weather Service, and Industry have Worked Together to Implement Solutions

The Wind Turbine Radar Interference Mitigation Working Group's Memorandum of Understanding between the Department of Energy, Department of Defense, the Department of Transportation's Federal Aviation Administration, and the Department of Commerce's National Oceanic and Atmospheric Administration has provided a key forum where multiple agencies have collaborated to develop wind turbine solution tools. A collaborative effort between Sandia National Laboratory and National Oceanic and Atmospheric Administration led to the development of a publicly accessible site that provides developers with access to produce dynamic, tailored wind turbine and NEXRAD impact assessments that are cropped to the county around the selected locations following the Tool for Siting, Planning, and Encroachment Analysis for Renewables (TSPEAR) model as seen in Figure 15. This publicly available tool provides a universal interface/tool for developers and federal agencies to assess wind turbine impacts on the NEXRAD systems early in the wind development siting process.

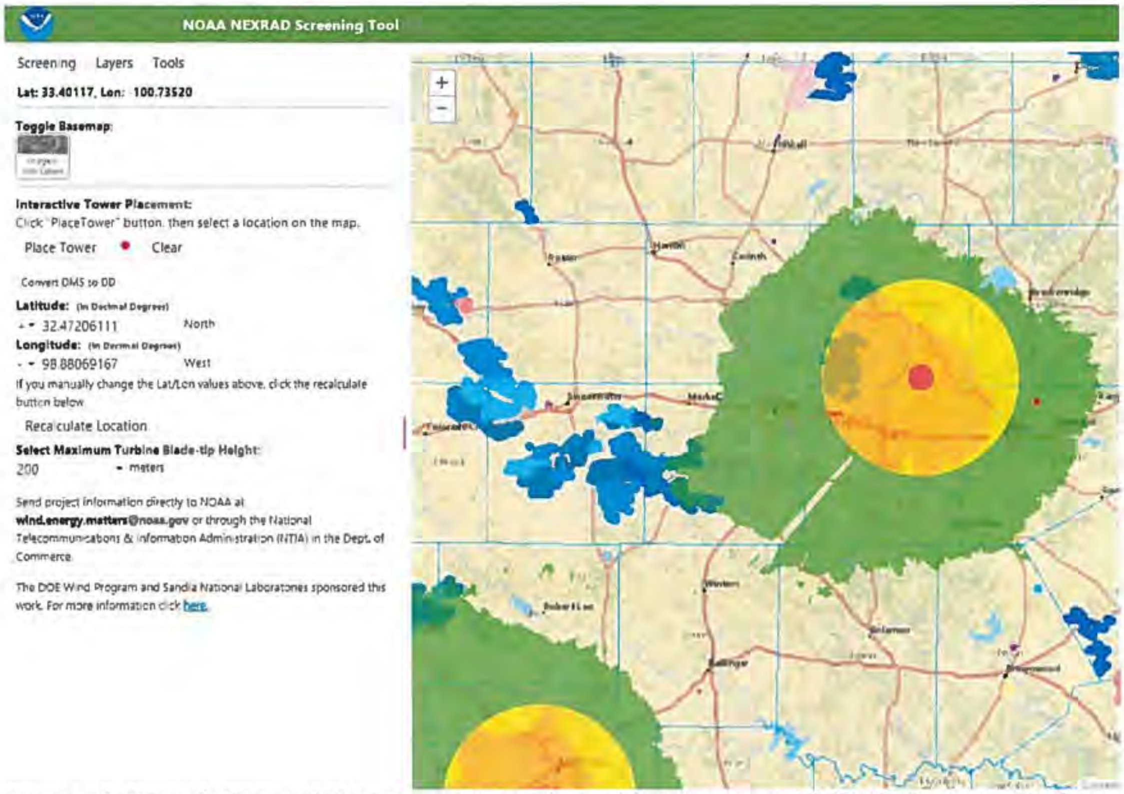

Figure 15. Example National Oceanic and Atmospheric Administration's NEXRAD Screening Tool Developed by Sandia National Laboratories via Department of Energy Wind Program and National Oceanic and Atmospheric Administration.

Furthermore, the Department of Defense works directly with the National Oceanic and Atmospheric Administration's Radar Operations Center to conduct joint/interagency technical reviews of any wind turbine project. Once the Department of Defense receives projects through its Siting Clearinghouse process (established in the 2018 NDAA), the Services utilize either the Federal Aviation Administration Obstruction Evaluation/Airport Airspace Analysis Department of Defense Preliminary Screening Tool (as depicted in Figure 16.) or the National Oceanic Atmospheric Administration NEXRAD Screening Tool (as depicted in Figure 15.) to determine a first-look assessment of whether a particular development will impact a NEXRAD site. If any turbines fall within the established four-scheme zone, the Department of Defense service representative sends the project information to the National Oceanic and Atmospheric and Administration's Radar Operations Center where personnel provide a case-by-case analysis of potential wind farm impacts on NEXRAD data and forecast/warning operations. The Radar Operations Center uses a geographic information system database that utilizes data from the Space Shuttle Radar Topography Mission to create a radar line-of-sight map with delineated areas corresponding to a turbine height of 160 meters Above Ground Level. Multiple radar elevation angles are considered for projects close to the radar. The Radar Operations Center then performs a meteorological and engineering analysis using: distance from radar to turbines; maximum height of turbine blade tips; the number of wind turbines; radar azimuths impacted; elevation of the nearby NEXRAD antenna; an average 1 degree beam width spread; and terrain from the geographic information system database. From this data the Radar Operations Center determines if the main radar beam will intersect any tower or turbine blade based on the

Standard Atmosphere's Refractive Index profile. Finally, the Radar Operations Center estimates operational impacts based on amount of turbine blade intrusion into radar line-of-sight, number of radar elevation tilts impacted by turbines, location and size of the wind farm, number of turbines, orientation of the wind farm with respect to the radar (radial vs. azimuthal alignment), and severe weather climatology. The Radar Operations Center also compares the wind farm to other operational wind farms to estimate impacts.

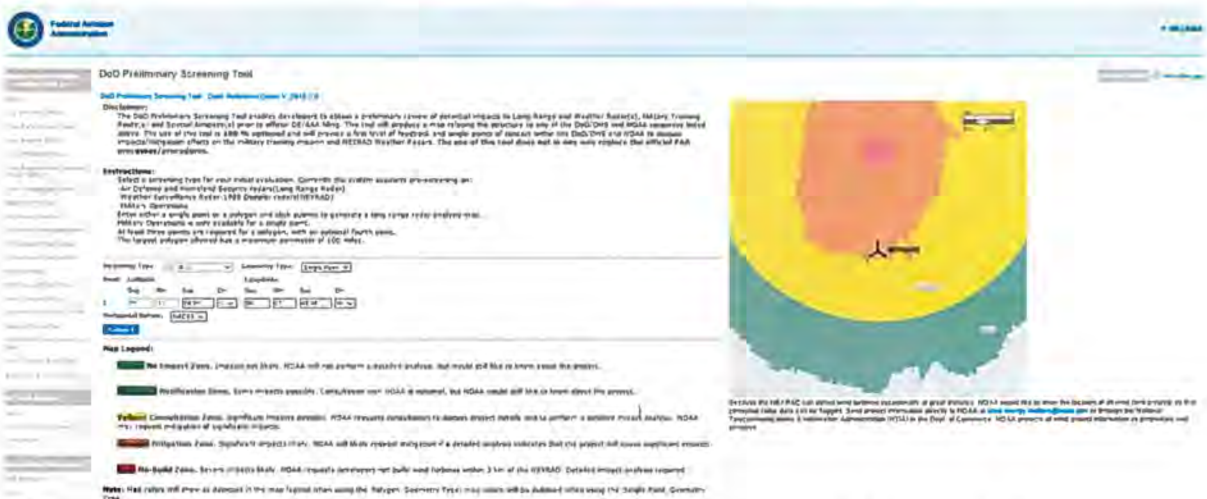

Figure 16. Example Obstruction Evaluation/Airport Airspace Analysis NEXRAD Screening Tool.

In 2017 and 2018, the Department of Defense and National Weather Service worked closely together to address impacts from multiple proposed wind farms near the Fort Drum, NY NEXRAD site. These proposed projects are illustrated in Figure 11. One developer was responsible for three proposed developments. According to the National Oceanic and Atmospheric Administration, "this developer had no interest in working with the National Weather Service to reduce mission impacts, as they cited no legal obligation to do so." However, the developer was willing to work with the Department of Defense at Fort Drum since they raised national security concerns related to mission impacts from the NEXRAD data contamination. Ultimately, the developer worked with Fort Drum on two of the three developments to reduce impacts by lowering turbine heights, eliminating some turbines from the projects, and working with Fort Drum on a legally binding curtailment agreement. The National Oceanic and Atmospheric Administration observed that, on the third project, which had lesser impact to Fort Drum but high impact to the National Weather Service, the developer made no effort to address the concerns raised by the National Weather Service.

In 2018, the Department of Defense and National Weather Service started working together to address impacts from multiple wind projects proposed near the Dyess AFB, TX NEXRAD site. Personnel from Dyess AFB and the National Oceanic and Atmospheric Administration's Radar Operations Center are actively collaborating with the developers to reduce impacts from the projects, such as proposing lower turbine heights, turbine alignment, and a legally binding curtailment agreement. This collaboration is underway.

In March 2018, National Oceanic and Atmospheric Administration's Radar Operations Center hosted a weather radar and wind turbine impacts workshop in Norman, OK. The purpose of the meeting was to discuss the growing impacts to NEXRADs in Oklahoma and north Texas from an increase in wind turbine development and affecting the National Weather Service's ability to assess severe weather and issue timely weather notifications. The National Oceanic and Atmospheric Administration's Radar Operations Center educated Department of Defense personnel on the analysis process, impacts, and mitigation strategies. Sheppard AFB, TX also provided the group information on how wind turbines affect military training routes across the region. The workshop was a resounding success to increase communication and awareness between the National Oceanic and Atmospheric Administration's and Department of Defense on wind turbine NEXRAD issues. Routine communication between National Oceanic and Atmospheric Administration's Radar Operations Center and Vance AFB, OK; Altus AFB, OK; Dyess AFB, TX; and Fort Drum, NY continue presently due to ongoing wind turbine proposals affecting those NEXRAD systems.

The Office of the Secretary of Defense Siting Clearinghouse serves as the Defense Department's interface with industry in seeking solutions to mitigate wind turbine weather radar impacts. This is normally conducted through the Siting Clearinghouse attendance at industry day events, for example, those hosted by the American Wind and Energy Association. To date, the Department of Defense has received various mitigation proposals from industry during MRT's, however, the Siting Clearinghouse representatives who attend industry day events and are the face for DoD has not directly received proposals from industry.

(8) Mitigation Options, including Software and Hardware Upgrades, which the National Oceanic and Atmospheric Administration and the National Weather Service have Researched and Analyzed, and the Results of such Research and Analysis.

In 2010 the National Weather Service entered an agreement with two University of Oklahoma entities, Cooperative Institute for Mesoscale Meteorology Studies (CIMMS) and Atmospheric Radar Research Center (ARRC), to investigate automatic wind turbine detection. The technique was not sufficiently effective in detecting the wind farms and the study did not address mitigating the wind farm effects. Follow-on studies by the National Weather Service attempted to mitigate the effects of the wind farms through smoothing, averaging, or manipulating the data that forecasters use to issue severe storm warnings. However, National Weather Service staff objected to this proposal because it was insufficient in reducing the radar data clutter.

In 2010 and 2011, CIMMS/ARRC at the University of Oklahoma investigated mitigation of wind turbine clutter via image processing of the range-time Doppler spectrum. The evaluation showed that missed detections were rare; essentially the program did very well in this area. However, the algorithm had problems with false alarms, which is, contaminating good data when wind turbine clutter was not present. Contamination of good data diminishes a forecaster's confidence in the algorithm, particularly if the contamination is in close proximity to a wind farm during situations where severe weather is possible. Results of this research proved to be impractical in mitigating wind farm clutter so that forecasters could use the algorithm operationally to issue severe storm warnings.

(9) A Review of Mitigation Research Performed (to date) by the Government and/or Academia

A number of studies have been performed to explore the impact wind turbines can have on the performance of ground-based weather radars located within the radar's line-of-sight. The bibliography provides a few references for some studies that have been performed in Europe and the United States on this topic.

The following review of mitigation research performed to date discusses several sources that typically report research efforts in radar meteorology. These include journals published by the American Meteorological Society and the Institute of Electrical and Electronics Engineers.

There are also two international conferences that focus on radar meteorology and these have provided a platform for presentations on the wind turbine clutter problem. The American Meteorological Society organizes a conference on radar meteorology every two years that is well attended by the international radar community.

Also held every two years, the European Conference on Radar in Meteorology and Hydrology focuses on research in Europe, but with significant world-wide participation. Wind turbine clutter mitigation is a major topic of interest in Europe due to the significance of green energy initiatives. This is especially true in Germany, where use of wind energy is a priority of the government.

This review identified fifteen papers and conference presentations covering a period from 2009 to 2018. Most of them report on efforts regarding data collection and analysis aimed at characterizing the clutter contamination signal and impacts on radar data quality. Mitigation efforts are limited to identifying the contamination and employing work-arounds that reduce the operational impacts. However, development of methods that remove the clutter directly from either the time signals or frequency spectrum have not been forthcoming. Since the contamination spreads over the full width of the Nyquist co-interval (the maximum time interval between equally spaced samples of a signal that will enable the signal waveform to be completely determined), and the signatures are quite variable, efforts in developing signal processing methods for delivering a clean data stream meeting functional requirements have largely failed. One proposed approach requires significant increases in resolution through the use of short duration pulses resulting in greatly increased system bandwidth (Norin, 2017). Another recent approach uses advanced signal separation algorithms that are computationally complex, do not work at low signal to noise ratios, and require a large number of samples (Uysal, 2016). Unfortunately, neither of these recent methods are likely to be practical for operational radar network applications.

Members of the German Weather Service provided a comprehensive survey of the problem at the 38th American Meteorological Society conference on radar in Chicago (Seltmann, 2017). This paper is the most complete discussion of the problem to date and the authors included a section on current and potential mitigation techniques. They concluded that no operational algorithms suitable for "Quantitative Wind Turbine correction" were available.

This review did not identify any potential direct signal processing methods that may be suitable for use in the NEXRAD.

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(10) Identification of Future Research Opportunities, Requirements, and Recommendations for the SENSR Program to Mitigate Energy Development

The NEXRAD tri-agencies (National Oceanic and Atmospheric Administration, Department of Defense, and Department of Transportation) will pursue, given available funding, viable future research opportunities to remove wind turbine clutter from the weather signal without negatively impacting both weak and strong weather returns. Participation by the tri-agencies in the multi-agency Wind Turbine Mitigation Working Group and the tri-agency Radar Operations Center's interaction with international radar partners will aid in the identification and funding of viable research activities.

Last fall, the National Oceanic and Atmospheric Administration removed their weather requirements from the SENSR program due to the inability of industry to meet current National Oceanic and Atmospheric Administration's weather requirements such as dual-polarization (enhancements to the NEXRAD system that provides the ability to collect data on the horizontal and vertical properties of weather (e.g., rain, hail) and non-weather (e.g., insect, ground clutter) targets). This decision enabled the other participating agencies, to include the Department of Defense, to pursue SENSR for air traffic and weather radar requirements without having to meet National Oceanic and Atmospheric Administration's weather requirements. Meanwhile, the National Oceanic and Atmospheric Administration continues to research the use of phased array technology as a potential replacement for the NEXRAD.

Future opportunities, requirements, and recommendations for the SENSR Program to mitigate energy development are currently being explored. During the most recent Request for Information (RFI) to industry, respondents were asked to provide an approach to meeting SENSR performance and requirements. One of the identified factors (clutter environment) did include wind farm impacts. Specifically, industry was required to take into account the clutter environments in certain locations introduced by sea, terrain, urban environment, and wind turbine farms.

Regardless of the type of system that will eventually replace the NEXRAD, it is important that National Oceanic and Atmospheric Administration and the Department of Defense harness research efforts on developing strategies to remove wind turbine clutter from the weather signal. The next generation weather radar should anticipate an increase in turbine height (greater than 200 meters) within a close proximity,10 miles (16 kilometers)of the radar when establishing requirements. Several wind energy developers are even investigating the use of off-shore wind turbines on land, which could potentially reach land heights of 400 meters. This evolution in the wind industry should be closely monitored by the National Oceanic and Atmospheric Administration and Department of Defense and reflected requirements for a future radar system.

Conclusion

Communication and early engagement with wind energy developers serves as one of the most vital first steps toward developing cooperative wind energy development-NEXRAD solutions, and engagement of the National Oceanic and Atmospheric Administration by the developers is critical. Solutions include, but are not limited to: eliminating turbines from the project that are in close proximity to the NEXRAD or very tall, causing clutter in multiple radar elevation scans; lowering turbine heights; moving turbines farther away from the NEXRAD system; aligning turbines along NEXRAD, radials such that the east/west or north/south spread of clutter is reduced; and/or developing a binding curtailment agreement, in which the developer legally agrees to cease operation of the turbines during specific weather conditions set forth by the NEXRAD tri-agencies including weather events such as severe thunderstorms, tornadoes, lake effect snow, etc.

Tri-agencies must continue to engage with industry and academia on determining weather radar wind turbine mitigation solutions. A multi-agency workgroup envisioned in the process of preparing this report would address technical questions and afford a communication forum. Lastly, efforts considered with respect to the NEXRAD system may prove beneficial to any follow-on weather radar solution considered by the National Oceanic and Atmospheric Administration, Federal Aviation Administration, and Department of Defense.

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