A WAY FORWARD
WIND FARM – WEATHER RADAR COEXISTENCE

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1. INTRODUCTION

The Nation's weather services and the wind energy industry share common goals of enhancing the Nation's economy and quality of life for its citizens. Unfortunately, we have observed that sometimes the best locations for developing a wind energy project are near established weather radar sites, since both usually desire optimal siting on high, unobstructed terrain. In recent years, NEXRAD system operators and data users have become increasingly aware of the interaction between weather radars and wind farms. When wind farms are developed too close to Doppler weather radars, they can cause radar signal interference. One of the key tools weather forecasters use in preparing forecasts and severe weather warnings is the Nation's network of weather radars known as the Next Generation Weather Radar (NEXRAD) system. Experience has shown that when wind farms are located in a NEXRAD radar beam/radar line of sight (RLOS), the rotating wind turbine blades can adversely impact radar data quality and the performance of the radar's internal weather detection algorithms. Just as the wind energy industry has invested billions of dollars in wind farm development, the federal government has invested over $1.4B in the NEXRAD network, and operates and maintains that network to ensure the best possible protection of life and property.

Wind farm interference with the NEXRAD radar network will increase with the anticipated large growth in wind energy projects. This increased interference will result not only from the growth of the number of wind farms, but also from the increasing size of wind farms and the use of taller turbines (which can impact radars from a greater distance). Figure 1 shows the 50 meter wind resource map with NEXRAD locations overlaid, highlighting the need to collaborate to mitigate potential conflicts.

Though wind farms can impact any Doppler radar system, this paper discusses wind farm interference issues specific to the NEXRAD radar. Information is presented on: the NEXRAD system; how wind farms can impact NEXRAD data and life-saving severe weather warnings; how the NEXRAD Radar Operations Center (ROC) assesses the potential impacts of proposed wind farms on NEXRAD systems; ROC initiatives for research, education, and collaboration with the wind energy industry; and mitigation options. Finally, there are considerations for a way forward that allows both the wind industry and the NEXRAD program to meet their national goals…promoting renewable energy and public safety.

2. NEXRAD Radar Network Overview

To meet the Nation's need for detailed weather radar data, NEXRAD radars were installed at 159 operational locations across the contiguous United States (Fig. 1), Alaska, Hawaii, Puerto Rico, and select overseas sites. (Developers can obtain the location and elevation of individual radars by contacting the NEXRAD Radar Operations Center (http://www.roc.noaa.gov/Feedback/)). The radar is a high-power Doppler system designed to detect weather targets and storm-scale winds at long ranges. In addition, its receiver is sensitive enough to detect clear-air (without the presence of clouds or rain)

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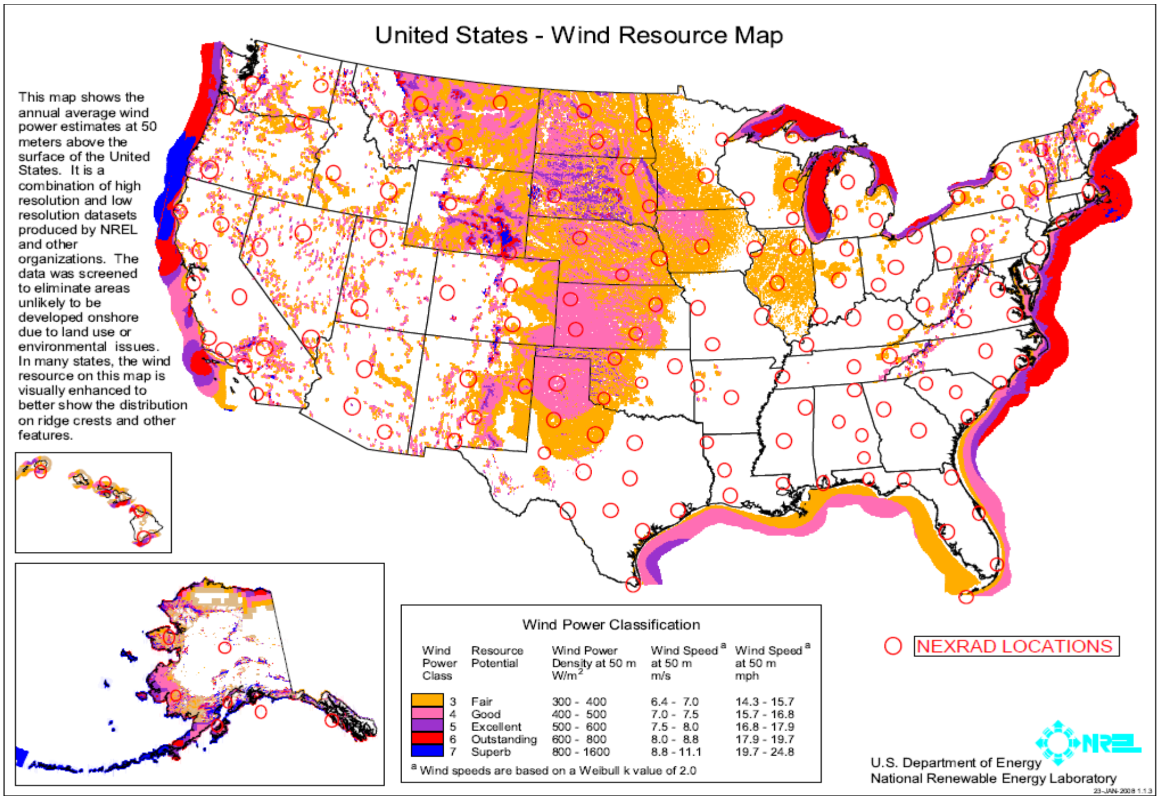

Fig 1. US Dept of Energy wind resource map showing areas (colored) favorable for wind energy development with NEXRAD locations overlaid.

boundaries such as temperature and humidity discontinuities. The NEXRAD radar transmits a ~10 cm wavelength, 1° beam at a peak power of 750 kW. The system received a state-of-the-art digital signal processor upgrade in 2006. Operationally, the radar automatically scans the atmosphere in pre-defined coverage patterns from 0.5° to 19.5° elevation above the horizon, then processes and distributes reflectivity, mean radial velocity, and spectrum width (a measure of the variability of radial velocities in the resolution volume) data. From this data, computer algorithms generate a suite of meteorological and hydrological products and alerts used for determining short-term forecasts, advisories, and warnings for significant weather events such as tornadoes, large hail, wind shear, downbursts, flash floods, and other weather phenomena. National Weather Service (NWS) and DOD weather forecasters use NEXRAD data to provide life-saving information to the public, to support military operations, and to inform resource protection decision makers. The data are also used for the safe and efficient operation of the National Airspace System - NEXRAD data are displayed on Federal Aviation Administration (FAA) air traffic controllers' screens and sent directly to many airborne aircraft. Additionally, the commercial weather industry has experienced rapid growth the last decade, due in part to the availability of and use of real-time NEXRAD data. Television broadcasters rely on both their own weather surveillance radars and data collected from the NEXRAD network to inform their viewers of evolving weather conditions.

The general public may access the radar data from private meteorology companies and the Internet (e.g., http://radar.weather.gov/). Information about the NEXRAD radars and their operation is available (Federal Meteorological Handbook No. 11, Parts A – D; http://www.roc.noaa.gov/FMH_11/default.asp).

There are important differences between weather surveillance radars, such as NEXRAD, and Air surveillance radars (ASRs), such as those operated by the FAA and DOD. Though they both operate on similar principles, their targets of interest and signal processing are significantly different. Therefore, any ASR-wind turbine clutter mitigation techniques may not be useable in the other type of system. ASRs look for large, hard, point targets (aircraft) and process the data to mitigate weak environmental returns. In contrast, weather surveillance radars are designed to sample small, weak and distributed returns (e.g., water droplets, aerosols, atmospheric particulates) and perform signal processing to remove or mitigate strong, point targets. The identification and removal of wind turbine clutter is likely to be more difficult for weather radars since the signal returned by the many rotating turbine blades of a wind farm is very similar to the signal returned by real weather.

3. IMPACTS OF WIND FARMS ON THE NEXRAD RADAR

Wind farms impact NEXRAD radars in three ways whenever the turbine blades are moving and they protrude into the radar's line of sight (RLOS). First, if turbines are within a few kilometers of the radar, they can block a significant percentage of the radar beam and attenuate the radar signal down range of the wind farm. Second, they can reflect energy back to the radar system and appear as clutter on the radar image, contaminating the reflectivity data. In addition to the visual clutter, the radar algorithms may generate false rainfall estimates and other false storm characteristics based on this contaminated reflectivity data. Third, they can impact the velocity and spectrum width data, which are also used by radar operators and by a variety of algorithms in the radar's data processors to detect certain storm characteristics, such as rotation (tornadoes), storm motion, turbulence, etc.

Wind farm returns during precipitation events can have serious operational impacts. Weak rain showers can be mistakenly identified as strong thunderstorms and large regions of velocity data can be disturbed and erroneously displayed over areas much larger than the wind farm itself. Both conditions can distract users or reduce their situational awareness particularly during hazardous/severe weather events and potentially lead to incorrect decision making. Misidentification of rain showers as strong thunderstorms by FAA controllers and pilots can lead to needless and expensive rerouting of aircraft to avoid the implied thunderstorms. The worst operational impacts occur during life-threatening events, such as severe thunderstorms and heavy rainfall. Weather forecasters rely on correctly displayed radar data and algorithm output to make quick warning decisions during rapidly evolving severe weather events. Both missed events and generation of false-alarm warnings are taken very seriously because of the negative impact they have on the entire warning system (emergency managers, the television and radio media, and all users of the warnings, including commercial weather vendors and the general public).

The NEXRAD has a sophisticated clutter removal scheme. Since weather is always in motion and most clutter targets (i.e. terrain, buildings, towers, etc.) are stationary, the clutter removal scheme filters targets that essentially have no or very little motion. Unfortunately, the radar sees rotating wind turbine blades as moving targets and does not filter signal returns from the blades.

Figure 2 depicts the relative notional impact of wind farms on NEXRAD radars as a function of distance if wind turbines are in the RLOS. Impacts increase exponentially as wind farms are sited closer

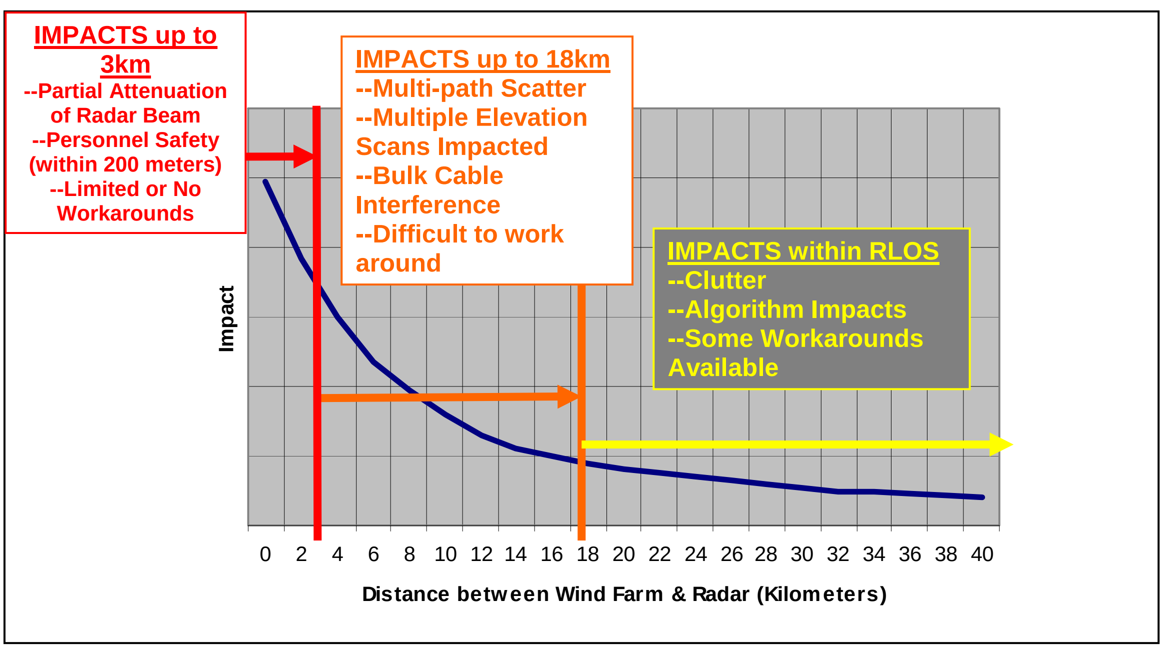

Fig 2. Notional impact of wind farms on NEXRAD radars relative to the separation distance.

to the radar, especially within 18 km, and radar operator workarounds become more difficult. When turbines are sited within 200m of a radar, there is potential for damage to both radar and turbine electrical components, and construction or maintenance personnel may be exposed to microwave energy exceeding OSHA (Occupational Safety and Health Administration) thresholds. Turbines sited within 1km of the radar will prevent proper radar beam forming, causing significant radar errors down range from turbines. Within 18km, multiple radar elevation scans can be contaminated, further limiting the data available for forecasters interrogate storms. Determination of RLOS and impact distance are highly dependent on local terrain, requiring site-by-site analyses.

Examples of how wind farms appear on operational NEXRADs are shown in Figures 3 & 4. These and other examples are available at: http://www.roc.noaa.gov/windfarm/windfarm_impacts.asp

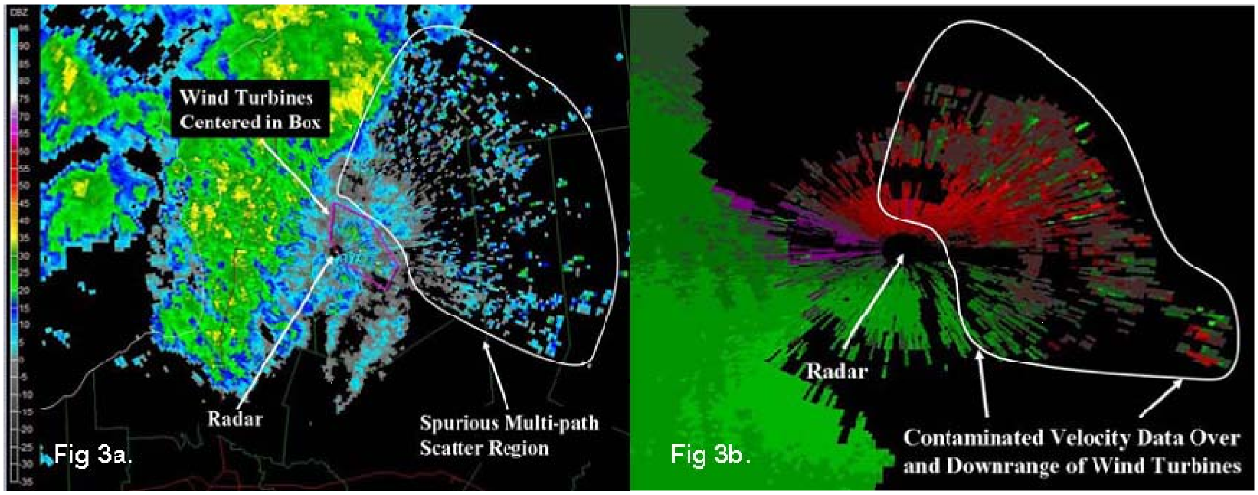

Fig 3a. A 0.5 degree scan Reflectivity product from the Fort Drum, NY WSR-88D (KTYX) on December 15, 2008 at 1307 GMT. A wind farm is approximately 6 - 14 km north - southeast of the radar (see annotations). The blue and green pixels that extend down-radial of the wind farm are due to multi-path and inter-turbine scattering of the radar beam. The echoes west of the radar are from an approaching area of rain. **Fig 3b**. A zoomed 1.5 degree scan Mean Radial Velocity product from the same radar on March 10, 2007 at 1234 GMT. Red colors indicate outbound velocities and green colors indicate inbound velocities. The imagery shows contaminated velocity data due to the rotating turbine blades in the vicinity of and down range of the wind farm. Note the anomalous “chaotic” wind velocities down range of the wind farm in comparison with the velocities in the “real weather” west of the radar. These echoes could confuse data users and contaminate radar algorithms particularly since they are occurring in multiple elevation tilts.

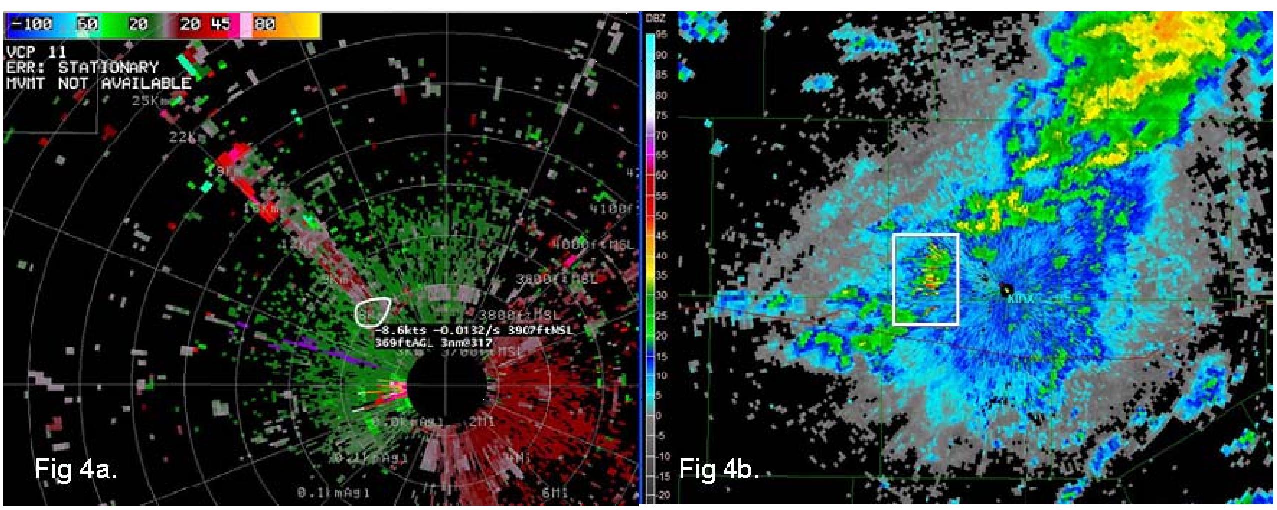

Fig 4a. This Velocity image (0.5 degree scan) from the Great Falls, MT WSR-88D (KTFX) on February 9, 2006 at 1859 GMT shows how only a few turbines very close to the radar can cause a relatively large impact. The 6 turbines are approximately 6 km from the WSR-88D and in the RLOS. The velocity data is contaminated in azimuth for 9

degrees and out beyond 20 km due to multi-path and inter-turbine scattering. **Fig 4b.** This Reflectivity image (0.5 degree scan) from the Dyess AFB, TX WSR-88D (KDYX) on September 9, 2008 at 1044 GMT shows how a large area of wind turbines (west of radar) can look similar to weather returns. Note that weather returns down range of the wind farm do not appear to be affected by attenuation due to the wind farm. Potential blockage/attenuation of radar signals by wind farms must be analyzed on a case-by-case basis.

Wind turbine clutter has not had a major negative impact on forecast or warning operations, yet. However, with more and larger wind turbines coming on line, experience gained to date strongly suggests that negative impacts should be anticipated -- some sufficient to compromise the ability of radar data users to perform their missions.

4. HOW THE RADAR OPERATIONS CENTER (ROC) ASSESSES THE IMPACTS OF WIND FARM PROPOSALS

The ROC learns of wind farm developments through both formal and informal methods. Formally, the Department of Commerce’s National Telecommunications and Information Administration (NTIA) acts as a clearinghouse for developers to voluntarily submit wind farm proposals for review by several Federal agencies, including NOAA. This formal process is in the American Wind Energy Association’s (AWEA) Wind Siting Handbook (AWEA 2008). Informally, the ROC learns of wind farm projects from local weather forecast offices, through local news articles or web links to news stories referencing planned wind farms. The ROC tries to proactively contact the developers if the project appears to have potential impacts to the nearby NEXRAD.

Based on the wind farm proposal, the ROC provides a case-by-case analysis of potential wind farm impacts on NEXRAD data and forecast/warning operations. In the last 3 years, the ROC has provided over 400 analyses. The ROC uses a geographic information system (GIS) database that utilizes data from the Space Shuttle Radar Topography Mission to create a RLOS map specific to the proposal area or turbines under study.

The ROC then performs a meteorological and engineering analysis using: distance from radar to turbines; maximum height of turbine blade tips; the number of wind turbines; elevation of the nearby NEXRAD antenna; an average 1.0 degree beam width spread; and terrain (GIS database). From this data, the ROC determines if the main radar beam will intersect any tower or turbine blade based on the Standard Atmosphere’s refractive index profile.

Finally, the ROC estimates operational impacts based on amount of turbine blade intrusion into RLOS, 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), severe weather climatology, and operational experience. The ROC also compares the wind farm to other operational wind farms to estimate impacts.

The ROC established the RLOS as a benchmark for seeking further discussions with developers to determine if alternative siting strategies (e.g., relocation, terrain masking, and/or a more optimum deployment pattern) or operational curtailment (covered in section 6) could reduce the potential impact of wind turbines on radar performance. About 20% of analyzed wind farm proposals have been projected to be in the RLOS of a NEXRAD and 9% have been projected to be within 10 miles (18 km) of a NEXRAD. As a result of these analyses, the ROC conferred individually with over 25 developers to discuss possible mitigation strategies for the wind farms. Some developers stated they will re-site planned turbines to more favorable locations with respect to the NEXRAD, or consider operational curtailment to mitigate impacts during significant weather events.

5. ROC INITIATIVES

Weather radar operators began reporting radar – wind farm interactions early in this decade. In 2006, the NOAA/NWS and the ROC, on behalf of the NEXRAD Program, began systematic efforts to investigate radar – wind farm interactions. These efforts included creating awareness of the issue within the wind energy industry and the meteorological community, collaborating with other impacted Federal agencies, and exploring potential radar-based solutions.

On behalf of the NEXRAD Program, we have worked diligently to create awareness of the potential impacts of wind farms on NEXRAD radar, while promoting a collaborative, low-impact coexistence with the wind industry. We plan to continue to expand contacts with the wind energy industry in 2009 and beyond to promote earlier and more frequent sharing of information and collaboration. To help developers submit wind project plans to the NTIA, the ROC has developed a template that will be available soon on the ROC web site. The ROC will continue its interaction with other Federal agencies to leverage off of their progress and work with AWEA to develop a memorandum of agreement template for brief operational curtailment of turbines in critical weather situations. We will continue our collaboration with DHS to develop a quantitative "Radar - Wind Turbine Interaction Model" that will accurately determine the interaction between radars and wind turbines (current and proposed).

The ROC is supporting research studies to explore potential radar-based mitigation strategies. Current studies include potential signal-processing techniques developed by the Atmospheric Radar Research Center (ARRC http://arrc.ou.edu) at the University of Oklahoma (e.g., Isom et al 2009). A goal of these sophisticated signal processing methods is to automatically identify and flag turbine-corrupted radar data. In addition to detection, signal processing methods based on real-time, telemetry-based algorithms are being explored by the ARRC. These knowledge-based techniques would exploit wind turbine data of blade rotation rate, orientation, etc., and are a good example of the benefits of collaboration with wind farm operations. An initial phase is currently being conducted in a controlled laboratory environment using scaled models and scattering experiments (Fig 5).

Fig 5. Model wind turbine in the ARRC Lab at the University of Oklahoma

6. POSSIBLE MITIGATION ACTIONS

a. For Developers

Early in the wind farm planning process, developers can do a quick, anonymous analysis of their project's potential impact on the NEXRAD radar network by using the new NEXRAD Tool on the FAA's Obstruction Evaluation (OE/AAA) web site (https://oeaaa.faa.gov/ oeaaa/external/portal.jsp). The ROC plans to upgrade the site to include selectable turbine heights (200m, 160m, 130m) for developers to perform a more accurate prescreening. An example of the tool's analysis screen is seen in Figure 6. The tool uses input coordinates to determine if the project is in a NEXRAD's RLOS (200m AGL) and displays a color-coded map to indicate the level of impact (Green = no impact, Yellow = minor to moderate impact, Red = significant impact). If the tool indicates potential impacts, the developer should contact the ROC for a more thorough analysis and learn about possible mitigation options.

The best mitigation technique is to avoid locating wind turbines in the RLOS of a NEXRAD. This strategy may be achieved by distance or terrain masking. Mitigation of impacts, if turbines are in the RLOS, can be achieved by reducing the number of turbines in the RLOS, the amount of blade penetration into the RLOS, greater separation from the radar, or through selective turbine siting (e.g., to reduce the azimuthal extent of the turbines with respect to the radar). Each situation requires case-by-case analysis.

The NEXRAD Program is looking into another promising option for developers. This involves entering into discussions with the local Weather Forecast Office (WFO) or military Base Weather Station to define significant weather scenarios or criteria under which the wind farm operators would briefly curtail turbine operations to allow the forecasters to receive uncluttered radar data from the wind farm area. Stopping the turbines eliminates wind turbine clutter (WTC), except when turbines in the RLOS are very close to the radar. The wind farm operator and WFO could establish a memorandum of agreement detailing the weather scenarios or criteria, points-of-contact on each side, and the agreed-to operating procedures.

Wind Farm developers or operators might also consider sharing wind farm meteorological tower weather data with the local forecast office to compensate for the contaminated radar data over the wind farm area. Additional surface weather observations would provide "ground truth" information for radar operators and could include precipitation amounts, temperature, dew point, pressure, and winds at 10-meters AGL. Developers would not need to share the critical and proprietary wind data near turbine hub height.

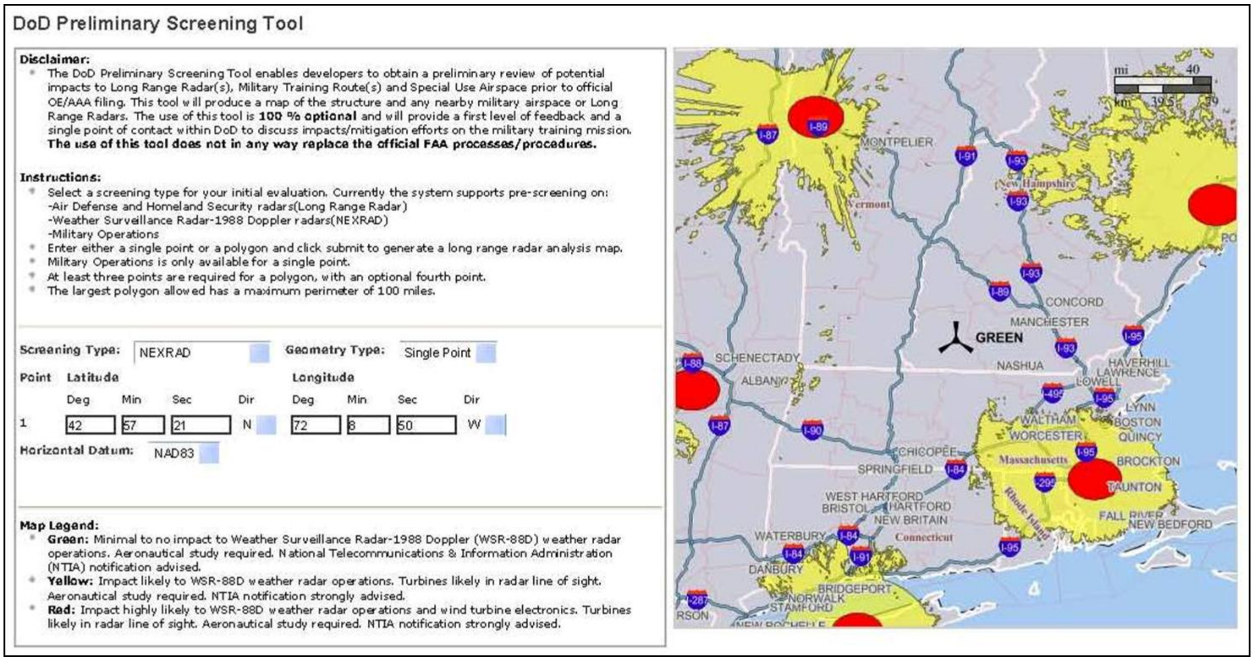

Fig 6. Example of NEXRAD Tool on FAA's OE/AAA web site—to be updated/revised in June 2009.

b. For Radar Operators

Wind farm interference on radars is a relative term, but the bottom-line metric is the impact the interference has on the operational mission. Experienced weather forecasters can often distinguish WTC from weather signals. However, a major concern is the effect of WTC on the radar's automated detection algorithms, and on inexperienced users. Weather forecasters can learn to recognize wind farm weather radar signatures, reduce impacts through proper radar configuration, and accommodate or "work around" the wind farm impacts in their decision process (Burgess et al 2008). However, all "work arounds" compromise data quality and coverage to some degree. Work arounds include simple awareness of wind farm locations, establishing exclusion zones to limit precipitation overestimation or false accumulations, looking at higher elevations to "see over" wind farms, looking at adjacent radars, and knowledge of how WTC impacts radar data and products.

7. POSSIBLE NEW NATIONAL DIRECTION

Our current strategy is two fold. First, to educate the wind energy industry and radar users on the potential impacts of wind farms on NEXRAD weather radars. Second, to reach out to individual developers as we learn about planned wind farm developments, evaluate potential impacts, and work with developers to mitigate significant impacts. This is a labor-intensive process that only increases as more developers seek to place wind farms on land with the best wind resource, which is often near weather radars. A more effective approach will be needed to ensure this critical, national radar asset is not significantly degraded. In cooperation with the wind industry and other federal agencies, the ROC is exploring two possible areas: national guidelines for the wind industry, and new funding to find technical solutions to the interference problem.

a. National guidelines might include one or more of the following:

(1) A Memorandum of Understanding (MOU) between the wind energy industry and federal agencies, similar to an existing British MOU, with agreement on consultation zones near and no-build zones very near radars, notification of federal agencies with Doppler radar assets, consultation to mitigate impacts, and wind farm operational curtailment during significant weather events.

(2) A national "clearing house" for developers to submit wind farm proposals to all federal agencies with radar assets – e.g. DHS, DOD, FAA, and NOAA. This clearinghouse would function similar to the FAA's Obstruction Evaluation Office for determining obstructions in navigable airspace.

(3) Federal statutory authority for mandatory developer notification of projects and government evaluation of potential wind farm impacts (similar to FAA Regulation Part 77), and consultation zones near and no-build zones very near radars.

b. New funding might be used to help develop radar-based and/or wind-turbine based solutions:

(1) Radar-based mitigation funding to develop modeling software that produces estimated radar impacts, develop signal processing technology that eliminates wind turbine clutter (a difficult technical challenge for which there may not be a solution) and build additional gap-filler radars for impacted areas.

(2) Wind turbine-based mitigation funding to develop radar-friendly "stealthy" wind turbine blades and towers, provide supplemental surface weather data (precipitation, temperature, dew point, pressure, 10-meter wind speed and direction) transmitted automatically from the wind farm to the National Weather Service (NWS) to compensate for the wind-farm-contaminated radar data.

8. SUMMARY

NOAA's NWS supports responsible wind energy development and wants to work with the wind energy industry to avoid potential impacts to the NEXRAD radar network and to find technical solutions to the radar interference issue. NEXRAD is a key tool of the NWS warning and forecast system and provides critical life-saving data to multiple federal agencies and the public. Experience with established wind farms located in NEXRAD RLOS has shown that wind turbine clutter impacts the radar reflectivity, velocity, and spectrum width data as well as internal algorithms that generate alerts and derived weather products, such as precipitation estimates. The severity of the impacts depends on many factors. In general, wind farm impacts to the NEXRAD radar exponentially increase as the separation distance between them decreases, especially within 18 kilometers. The ROC is funding studies on radar-based signal processing solutions to initially identify and flag wind farm contaminated data, and eventually filter them from the real weather data. Awareness and early consultation with the NEXRAD Program is essential to minimizing wind farm project risk and operational conflicts with the Nation's weather radar network. The ROC, on behalf of the NEXRAD Program, is fully committed to open and transparent collaboration with developers and the wind industry to arrive at mutually beneficial siting and/or operational decisions. We can coexist through cooperation. Please visit our wind farm web site at http://www.roc.noaa.gov/windfarm/windfarm_index.asp to learn more.

9. RELATED URLs

Federal Aviation Administration Obstruction Evaluation / Airport Airspace Analysis (OE/AAA): https://www.oeaaa.faa.gov/oeaaa/external/portal.jsp

National Telecommunications and Information Administration (NTIA) Interdepartmental Radio Advisory Committee (IRAC): http://www.ntia.doc.gov/osmhome/irac.html

University of Oklahoma Atmospheric Radar Research Center: http://arrc.ou.edu/

WSR-88D Radar Operations Center Wind Farm-Radar Interaction Page: http://www.roc.noaa.gov/windfarm/windfarm_index.asp

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