Title: Options to mitigate utility-scale wind turbine impacts on US defence capability, air supremacy, and missile detection

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ABSTRACT

There is increasing interest in, and concern over, the impact that the growing number of utility-scale wind farms are having on air supremacy and early warning missile detection in relation to radar clutter and shadow, seismic noise, and flight obstructions. This work identifies US defence industry concerns in relation to wind developments and conducts US industry interviews with representatives from the field of radar, the wind development industry, and government defence agencies. The results of the interviews provide detailed insights defining radar and military concerns raised around wind turbines and reveal that the US Department of Defense (DOD) have invested US $3 million to date on developing a suite of solutions to these concerns. This research discusses selected solutions available for the US DOD approval and alternative options that may be introduced to mitigate the impact of utility-scale wind turbines on defence and security. Implementing solutions will require greater cooperation between government agencies and wind developers, dedicated funding, a common research plan, and streamlined processes.

Glossary of acronyms

AEDS	Atomic Energy Detection Systems
ARSR	Air Route Surveillance Radar
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
AWEA	American Wind Energy Association
CFAR	Constant False Alarm Rate
CTBT	Comprehensive Test Ban Treaty
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
EWR	Early Warning Radar
FAA	Federal Aviation Administration
IMS	International Monitoring Systems (Nuclear)
LRR	Long Range Radar
MIT	Massachusetts Institute of Technology

MTI/D	Moving Target Indication/Detection
NERL	National Air Traffic System En-Route Ltd
NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic Atmospheric Administration
PSR	Primary Surveillance Radar
Radar	Radio Detection and Ranging
RAG	Range Azimuth Gating
RAM	Radar Absorbing Material
RCS	Radar Cross Section
SSR	Secondary Surveillance Radar
UK	United Kingdom
US	United States
WSR-88D	Weather Surveillance Radar-1988 Doppler

1. Introduction

Wind turbines affect radar as their echo characteristics often match those of an actual aircraft or storm pattern, which radar seeks to track. Wind turbines cause two main types of interference with radar: direct interference and Doppler interference. Direct interference is caused by the high reflectivity of the turbine components: towers, nacelles, and blades, reducing the sensitivity of the radar via increased background noise, creating false readings and shadowing areas of radar coverage. Doppler interference is caused by the moving blades of a turbine that can generate false targets, false Moving Target Indication/Detection (MTI/D), and impacts both airborne and fixed radar [1]. Existing research investigating wind turbine impact on Air Traffic Control (ATC), Long Range Radar (LRR), Early Warning Radar (EWR), and weather radar are summarised in Table 1.

Table 1. Selected research confirming wind turbine interference.

Organisation	Radar research summary
Network of European Meteorological Services	French radar research into wind farm capacity to block beams, cause clutter, and cause Doppler interference on weather radar showed farms up to 30 km from the radar have a high potential to degrade meteorological data and impact weather readings and forecasts [2].
US Department of Commerce – National Telecommunications	US research into wind turbines higher than 250 feet (76 m), on ATC and Federal Aviation Administration (FAA) radar showing numerous documented 'cases of deleterious effects'

and Information Administration	[3].
UK Royal Air Force	UK tests to determine wind farm effects on ATC primary surveillance radar confirmed shadowing and clutter effects can be ‘highly detrimental to the safe provision of Air Traffic Services’ due to a decrease in ‘probability of detection’ and the inability to differentiate between turbine-induced clutter and actual aircraft [4].
Keele University Applied and Environmental Geophysics Group (UK)	The research demonstrated wind farms in the vicinity of the Eskdalemuir seismic monitoring site in Scotland, generated seismic and infrasound noise that influenced site data. However, the interference influence could be controlled through the allocation of a ‘noise budget’; within which detection capabilities are not compromised [5].

1.1. Shadowing and clutter

Objects including wind turbines can completely and partially block, and diffract electromagnetic waves. The US DOD describes the shadowing effect of wind turbines on radar as: “Objects in the path of an electromagnetic wave affect its propagation characteristics. This includes the actual blockage of wave propagation by large individual objects or interference in wave continuity due to diffraction of the beam by individual or multiple objects” [6]. Clusters of wind turbines typically cause diffraction of radar electromagnetic energy and therefore create ‘shadow zones’ or ‘blind spots’ where radar is less efficient. The amount of shadow incurred is dependent on the size of the wind farm and the topographical features which surround it.

The DOD define radar ‘clutter’ as “any unwanted reflected signal that enters the radar receiver and can interfere with the determination of the desired attributes of the target of interest” [6]. Ian Chatting, Head of Research in Britain for wind turbine manufacturer Vestas explained in a public interview that wind farms can make it difficult to identify if an aircraft flying in and out of the clutter is the same aircraft or an alternative aircraft [7]. The DOD [6] state radar clutter from wind turbines could occur if any portion of the turbine appeared in the radar’s line of sight and its level of electromagnetic energy reflectivity, given by its radar cross-section (RCS), exceeds accepted thresholds. The amount of clutter is in direct proportion to the number of turbines within the line of sight of the radar, and the RCS for some turbines can be greater than that of a long haul aircraft [6, 8]. While a single turbine located at a distance from the radar will have minimal impact, a large number of turbines over a wide sector of the radar's coverage will significantly reduce performance [4].

1.2. Military concerns

Beyond radar interference, Dougherty [9] identifies obstruction and safety as additional concerns the DOD have related to wind turbines, and Möller *et al* [10] notes, the expansion of wind farms into new locations requires an unprecedented level of planning to cater for the growing scale and range of technological and institutional considerations. Like conventional energy systems, long term policies are a fundamental requirement for sound renewable energy investments that integrate well with existing infrastructure and regulations [11-16], and as wind power capacity is rapidly expanding it is fast approaching technical and institutional impediments [10, 17]. For example, dense development of wind turbines near airspace, test ranges, and training ranges used by the US military can occupy the same altitude as aircraft. Seismic and infrasound noise is another publicly stated area of concern for military operations. The seismic and infrasound noise produced by wind turbines may affect sensitive military monitoring operations. Studies by Styles *et al.* [5] confirm that sophisticated equipment such as seismic arrays can detect seismic noise caused by wind turbines.

1.3. DOD existing approved solutions

The utility-scale wind industry acknowledges there is no single solution to radar and military site concerns due to variables such as: location, radar type, mission type, and terrain type in each proposal [18]. In contrast, the DOD in *'Effect of Windmills on*

Military Readiness' [6] concluded non-technical solutions are the only proven mitigation means to avoid the degradation of radar capability and interference with military training due to wind turbines. Non-technical solutions involve avoiding placing wind turbines in the line of sight of radar via zoning, terrain masking or terrain relief.

1.3.1. Zoning

Zoning refers to placing turbines a predetermined distance from a radar to avoid interference. The DOD report [6] recommends a distance of 30 nautical miles (nmi) for turbines with blade tips that protrude over 300 ft (91 m) above the local terrain. Zoning is a common mitigation measure supported by policies pertaining to wind turbine siting in many European countries. In Austria, wind farms greater than 10 km from an air defence radar will receive no objections. In the Netherlands, only wind farms within 15 nmi (approximately 24 km) from a military radar require review. In Germany, policy enforces a protection zone of 10 km around all ATC radars, with an area of interest up to 18 km from ATC radars. These zoning policies address both military and civilian concerns over radar shadowing (for Germany and the Netherlands), and electromagnetic interference and obstacles to low flying routes (in Austria) [6]. Zoning is also a mitigation measure used in UK Civil Aviation Authority policy as a means to manage shadowing and false plots on secondary surveillance radar (SSR). Turbines placed over 24 km from an SSR are not thought to impose an issue [19]. However, primary surveillance radar (PSR) zoning policy in the UK still requires wind farm developers that have proposed installation of wind turbines in the line of sight of the radar to undergo consultation with the UK Ministry of Defence, regardless of distance [6]. Zoning is also a technique that has been used to overcome seismic noise interference for nuclear explosion monitoring in the UK. Studies in Eskdalemuir in the UK, site of the longest operating seismometer array and a very good wind development area, found that turbines within 10 km of nuclear monitoring sites should be prohibited [5]. Research by Styles *et al*. [5] concluded that wind turbines between 10 and 50 km from nuclear monitoring sites should not exceed a predetermined ‘noise budget’, and turbines over 50 km from the radar should have no restrictions applied pertaining to this monitoring type.

1.3.2. Terrain masking and relief

Under the UK, US, and European policies mentioned in the previous section, turbines may be placed closer to the radar if further analysis determines there are no effects or the effects can be suitably mitigated. Non-technical solutions to facilitate this include ensuring there is elevated terrain between the radar and the turbine (terrain masking) or ensuring the elevation of the radar is above that of the turbine (terrain relief) [6]. Kelly [19] also identified terrain masking as the “simplest method of mitigation”. Analysis using wind farm models and terrain databases is required to determine whether this mitigation is suitable for a particular wind farm. The DOD [6] advocate that while the analysis is not complicated it can be time-consuming.

1.3.3. Alternative and evolving perspectives

The practicality of using zoning alone can be limited due to the vast distribution of US radar. Seifert [1] highlighted recommended turbine siting areas based on radar location and by introducing a 20 nmi buffer zone. While this map implies substantial unaffected areas for wind development, Bill Troia, International Business Developer for LRRs at Lockheed Martin, identified a key reason for competing land use between wind farm and radar and military training sites; noting that flat, open areas with good visibility to the horizon are desired for both uses, cited in [18]. In addition, Ed Ciardi from the National Oceanic Atmospheric Administration (NOAA) acknowledged that altering the position or orientation of turbines could represent a loss in energy productivity or efficiency for wind developers, cited in [20]; representing an opportunity cost that could be considerable. Alternatively, Kalinowski [21] suggested that moving the radars to facilitate zoning is an impractical option. Additional radars may be added, but existing coverage cannot be lost, and the FAA did not have a 'stock of spare radars', with new radars requiring changes in national airspace system reporting points and airspace 'fixes'.

The aim of this research is to gain further insight into the radar- and military-related concerns raised around wind turbines, and to discuss alternative options that may be introduced to mitigate the impact of utility-scale wind turbines on defence and security. The research objectives are to answer: How significant are the wind turbine-related radar and military site concerns that have been raised by the DOD?; How viable are the proposed solutions to these concerns?; What is required (e.g. governance and resources) to implement the most viable solutions?

2. Method

The research methodology uses a synthesis of literature analysis and industry interviews. Eight selected representatives from the field of radar, the wind development industry, and government defence agencies were invited to participate in an interview on radar and military concerns associated with wind turbines. Ethics approval was obtained from the Murdoch University Human Research Ethics Committee (ethics permit number 2011/043). There was a 50% response rate to the invitation and the individuals interviewed were David Belote (Executive Director of the US DOD Energy Siting Clearing House, under the guidance of a DOD media advisor); Tom Vinson (American Wind Energy Association's, AWEA's, Senior Director, Federal Regulatory Affairs); a "Military Pilot" (who declined to be identified, yet who had military experience in the US), and; a "Wind and Radar Expert" (who also declined to be identified, although was affiliated with a US Federal Government Agency). The phone interviews were semi-structured with a transcript of the interview being scribed throughout, and responses to both scripted questions and conversational leads were recorded. Only non-classified information was sought, and included subsequent detailed questioning depending on the preferences and expertise of each participant.

3. Results and discussion

3.1. Effects of wind turbines on military sites and operations

When asked about efforts to improve the range of technical mitigations available to overcome wind/radar issues, the Wind and Radar Expert interviewed by the author explained, “There is military concern around the use of wind farms (clutter and shadow zones) by unfriendly aircraft to transition below the radar level of detection.” The Expert also mentioned, however, that acceptable levels of interference for radar can vary. “Just because a radar can see a turbine, that doesn’t mean the radar cannot do its job. The aviation industry is of the view that a little bit of sparkle is manageable, while the military are concerned with any loss of coverage…The metrics you use to determine what is allowable are very specific to the site.”

The interview with the Military Pilot confirmed that wind turbines may obstruct aircraft. Wind turbines can be over 400 ft tall (122 m) [22], and military flight training missions can be as low at 10 ft (3 m); meaning wind turbines can physically obstruct low flying missions or aircraft during take-off and landing. A representative of Dyess Air Force Base in Abilene in central Texas, where more than 2,000 turbines have been built within a 100 mile radius, advocated that wind turbines could pose hazards for B-1 bombers and C-130 transports used in the area. Base officials also found wind farms in West Texas interfered with low attitude training missions that can extend up to 120 miles from the base [23]. The DOD [6] highlights that a single turbine poses the same aviation obstruction as radio antennas and cell phone towers, and as such could be mitigated through the same process; however the number and proximity of turbines being installed makes them harder to mitigate with traditional measures.

Overhead transmission lines associated with wind farms also provide a flying hazard for aircraft, which poses a safety risk to flight and weapons training operations [6]. From the interview conducted by the author with the Military Pilot, it was confirmed that: “Both the poles and the lines provide obstacles to aircraft. The lines are particularly hard to see while using night vision equipment”, adding “…there have been many aircraft accidents due to wire strike. They’re definitely a concern for pilots on low flying missions”. Flight training and testing concerns however, are likely to be restricted to only particular areas of the US. Tom Vinson, from AWEA, noted there are only a relatively small number of flight training areas, primarily in Nevada, California, and Texas. David Belote from the US DOD explained that some stealth and radar training and testing facilities require “an electromagnetic pristine environment” for testing new technologies aimed at covert security operations, confirming that electromagnetic interference by wind turbines is also a fundamental concern to the DOD [24].

3.1.1. Seismic and infrasound noise

Wind turbines produce seismic and infrasound noise that could “contaminate monitoring stations providing data to support the Comprehensive Test Ban Treaty (CTBT) and US nuclear explosion monitoring effort” [6]. The Wind and Radar Expert interviewed by the author said, “A wind turbine changes the environment meaning there isn’t the same baseline for testing from one day to the next.” This comment is supported by the seismic noise tests conducted in the UK at Eskdalemuir; however the tests in Scotland also pointed out that only the most sophisticated monitoring equipment would be affected [5].

3.2. Safety and security impacts of shadow and clutter

Shadowing and clutter also affect weather radar. The Fort Worth Star [23] reported that clusters of turbines near Albany in Texas produce radar shadows to the north and west of the Dyess Air Force Base. These shadows are of concern as they could potentially hide the appearance of severe weather approaching a base. Butcher [25] describes how a wind turbine at the Jimney Peak ski resort in Hancock, Massachusetts produces a signature resembling a thunderstorm, which cannot be distinguished from heavy rainfall. Kalinowski [21] explains how the false appearance of storm activity on Next Generation Weather Radar (NEXRAD), caused by wind farms, makes it hard to provide accurate weather information to pilots; therefore decreasing the accuracy and safety of weather forecasts. Clutter and shadow zones from wind farms may also allow unfriendly aircraft to conduct missions undetected. The Wind and Radar Expert further explained illicit drug trafficking was an area of DOD concern for such a manoeuvre. Magnuson [18] suggests this concern also pertains to pilots who have hijacked a plane. Schleck Associates [26] suggest clutter and shadow zones could make it hard to maintain security for potential terrorist targets. The DOD [6] highlight that areas with high radar shadow and clutter interference may decrease the time that security forces have to react to potential threats. The interview with the Military Pilot confirmed that it is possible for drug traffickers to have the appropriate flight equipment to fly below the radar (e.g. helicopters or jets). When asked about the feasibility of terrorists or drug traffickers having access to such assets the Military Pilot said, “It’s absolutely plausible. Drug traffickers looking to move product across US borders have been known to use submarines. Having access to a jet is definitely not out of the question.” In considering this option the Military Pilot added “An important consideration is the distance between the take-off point, the wind farm, and potential targets” pointing out that different aircraft types would have different refuelling requirements and therefore different capacities to complete such a mission. The inability of a radar operator to track an aircraft for a short period over and near utility-scale wind farms are thus a real concern for security agencies, and It is likely that proposed wind energy sites near potential terrorist targets or near potential trafficking entry routes would have lower acceptance for loss of radar coverage. However, the US Department of Energy (DOE) [27] website points out, “Wind developers have successfully installed over 21,000 MW of wind power capacity across the US and 93,000 MW across the world in the past 20 years without one documented case of enabling an attack on any nation.” This leaves the question open as to how significant this theoretical threat is to security in terms of terrorist attacks, as opposed to the trafficking of illicit drugs.

4. Proposed technical mitigations

Kelly [19] suggests, where non-technical mitigations such as terrain shielding are not possible, there are three means to limit the impacts of wind turbines on radar:

- Improving radar design of to enable them to distinguish between wind turbines and actual targets e.g. radar upgrades, gap fill radar.
- Reduce the reflectivity of the turbine e.g. via stealth technology to reduce the turbine's RCS.
- Remove the clutter from the radar's vision, e.g. blanking or suppressing of radar cells where turbines are known to be.

4.1. Radar upgrades

Radar upgrades are pertinent to the US due to the aging nature of the US radar fleet. Ken Kingsmore from the DOD, cited in [20], explains that prior to September 11, 2001 the Joint Radar Planning Group in the US who manage long range radar assets, focused primarily on maintaining border sites such as Hawaii, Alaska, and Guam, leaving internal radars to remain untouched. After 2001 the group became more inwardly focused adding 170 additional radar sites covering mainland US. Kalinowski [21] highlights that, due to their age, many current FAA radars have limited capability to filter out clutter. In addition, making adjustments to older radars, e.g. reducing their sensitivity to eliminate clutter, can cause actual targets to be missed.

Gary Seifert, an expert in radar and wind at the Idaho National Laboratory, claims that modern radars are better equipped to deal with turbine impact issues than older radars, cited in [20]. Modern radars are typically digital and have a greater band width than older analogue models, which Webster [28] argues can improve the radar's resolution and ability to track targets between turbines. New radars also include digital processing capabilities such as multidimensional detection, and pulse shapes that can help differentiate between aircraft and wind farms [29]. Brenner *et al* [29] point out that computing power has increased 600-fold since the 1990s, making telemetry transmission where real-time data on the position, speed, pitch and yaw of rotor blades is continuously transmitted back to the radar, an inexpensive option for reducing clutter [30]. The radar software can then predict the RCS of the wind farm and suppress the cells where the turbines are known to be. On the other hand older systems are often hard-wired and unable to be changed, limiting their flexibility.

Modern radars that have been shown to improve aircraft detection and/or reduce the visibility of wind farms include the Raytheon ASR-11 (produced in Canada) and the UK equivalent, the Lockheed Martin TPS-77, which has enabled the UK Ministry of Defence to lift objections to over 3,000 MW of offshore wind projects [28]. (Table 2). The Wind and Radar Expert interviewed by the authors advocated “the Lockheed TPS 77 is a fabulous radar that is designed to provide advanced targeting and coverage for the military”, adding “published limits (for the radar) indicate it can provide coverage as close as 500 m to the edge of the wind farm.” Tom Vinson has stated that the DOD replaced an old ASR-8 with an ASR-11 at the Travis Air Force Base, yet the DOD will not go so far as to outwardly validate the efficacy of these mitigations, and are also testing the TPS-77 radar which has been demonstrated in other countries to also improve coverage around wind farms [24]. NOAA’s NEXRAD radar is also a favourable mitigation option for turbine interference, with its superior processing capability for weather forecasting [29]. For secondary radar systems, Mode Select (Mode-S) radars have the ability to selectively interrogate aircraft and request specific information; however for Mode-S SSR to be effective, all aircraft should be equipped with Mode-S compliant transponders [19].

Although each of these modern systems has a greater ability to manage the effects of wind turbines, at present no radar is capable of distinguishing a wind turbine echo from a valid aeroplane target echo, and therefore no system can consistently provide un-degraded coverage in the area of wind farms [19]. This view was supported by the Wind and Radar Expert interviewed by the author who said: “You cannot completely eliminate clutter. New software allows you to track… right up to the edge of a turbine and then pick it up right after the turbine, therefore reducing the size of areas without coverage… Raytheon’s ASR-11 is very effective at reducing zones with poor visibility to one or two (radar) cells either side of a turbine.” Geoff Blackman, a consultant on wind radar issues for Westslope Consulting, recommends older US ATC radars such as the ASR-8 (38 in US) and ASR-9 (135 in US) radars should be considered for replacement with ASR-11 radars, cited in [20], due to their improved clutter processing capability. Blackman added that some of the newer radars already installed might cope with wind farm interference through additional software upgrades. Tom Vinson, said “The only issue (for radar upgrades) is cost. A Lockheed radar is in the vicinity of [US]$15 - $20 million and is not going to be viable everywhere; particularly for single developer projects. Only areas with multiple developer interests will, most likely, be able to afford such a cost.”

Table 2. Selected radar technology, capability, and descriptions.

ARSR-1 / ARSR-2 / FPS-20	1950’s model, 2D, L-band frequency long range radars with a maximum range of 200 miles (320 km), which is being replaced with the ARSR-4 [31].
ARSR-4	The most modern 3D long range surveillance radar, providing improved reliability, ability to track small objects, and coverage up to 250 nautical miles (460 km) [32].
ASR-8	Analogue Air Surveillance Radar with limited processing capability when compared to modern radar types. ASR-8’s are being replaced by ASR-11 radars [33].
ASR-10	Flexible, modern radar that meets the requirements of the US FAA/DOD [34].
ASR-11	Digital Air Surveillance Radar providing PSR coverage of 60 miles and SSR coverage of 120 miles (100 km) and SSR coverage of 120 nautical miles (200 km) [34]. The radar provides digital processing, improved reliability and performance unavailable in earlier models e.g. ASR-8 radar [33].
NEXRAD / WSR-88D	Weather radar using Doppler maps to detect rain, hail, and snowfall [6], with an approximate short range of 230 km, and a long range of 460 km [35].

TPS-77	The Lockheed Martin TPS-77 is a 3D long range air surveillance radar, with an operational range of up to 250 nmi (460 km). The missile tracking, special processing, and short range surveillance beams (using MTI and Doppler processing) provides improved radar coverage as close as 500 m to the edge of wind farms.

At the time of writing, a number of new radar systems are being trialled in the region of the Indian Mesa Wind Farm in West Texas, in the US IFT& E3 program coordinated by the US FAA, DOD, DOE along with Department of Homeland Security (DHS). The Massachusetts Institute of Technology (MIT) will independently assess and report on the results of the testing. The Lockheed Martin TPS-77 and the Raytheon ASP-11 radar technologies are being tested along with a novel short range holographic 3D radar system, from UK company Aveillant, that claims to identify between aircraft and wind turbine signatures [36].

4.2. Software upgrades

Various ‘software upgrades’ can be added to modern radars or digitised older radars to improve their coverage of areas with wind turbines. Concurrent beam processing involves two radar beams, one high and one low, which are obtained and processed simultaneously. This helps identify wind farm clutter from actual aircraft [28]. Lok and Drake [37] established that tests in Stockholm in 2005, the FAA Technical Center in 2007, and Travis Air Force Base in 2008 have shown the advantages of concurrent beam processing over standard switched beam configuration. Tests at Altamont Pass Wind Farm showed ~20% improvement in probability of detection. Geoff Blackman, from Westslope Consulting, recommends this upgrade would be beneficial to Long Range US radars such as FPS-20 series and ARSR 1/2s, and for ATC ASR-11 radars [20], to help them cope with wind turbine interference. Furthermore, Constant False Alarm Rate (CFAR) processing can suppress data in radar cells that have high level signals from turbines, which contribute to the average background level. Suppressing the high return cells reduces the average background level and detection threshold, which improves the radar's ability to detect aircraft over wind turbines [28]. CFAR processing can be implemented manually using a map of known turbine positions or automatically using turbine positions from the radar's track extractor. Butler and Johnson [38] state the manual method is the least demanding as it only affects the radar signal processor. However, CFAR processing would be considered ineffective if the turbines are so dense they raise the background level in all cells. 'Enhanced tracking techniques' are another software-based proposed mitigation that is in the process of implementation and evaluated on ASR-11 radar systems [37]. Lok and Drake [37] showed that enhancements can aim to 'look over' rather than 'through' the turbines by increasing the antenna tilt and altering the radar's beam transition, and can improve the probability of detection at selected affected sites in tests from 67.53% to 92.72%. Webster [28] also supports the exploration of enhanced tracking techniques, arguing increasing the height of radar installation, or using increased antenna elevation angle, has been shown to eliminate a significant portion of radar performance concerns. A further software-based alternative is 'high resolution clutter mapping' which store information about the average background clutter for successive radar cells. Clutter maps can be incorporated into MTI/D configurations, and decreasing the size of clutter map cells will increase the number of cells between turbines, and in turn the probability of detecting aircraft between cells [38]. The implementation of clutter mapping mitigation requires a wide instantaneous band width transmitter and receiver, and a signal processor and plot and track extractor that can cope with high data rates and volumes. Geoff Blackman from Westslope Consulting, suggests that enhanced clutter map processing is useful on ARSR-4 long range radars to help see through clutter, but notes that it requires a redesign of many of the radars essential components, cited in [20].

4.3. Gap filler radars

Gap filler radars, are secondary radars which are strategically placed to cover an area obscured by a wind farm [28]. Brenner *et al.* [29] describes how a second view of the obscured area, provided by the gap filler radar, makes it possible to process the effect of wind farms out through data fusion. Levitan [39] supports this theory explaining that shortwave radars placed within or adjacent to the wind farm can work in tandem to provide the extra coverage required. Existing 'X-band' panel and gap filler radars have been identified as possible solutions that have been trialled on NEXRAD weather radars. Raytheon have conducted tests using X-band gap filler and panel radars to cover targets above the wind farm, noting that the narrow pencil beam is able to avoid interference as opposed to the wide beam radars already in place. Studies for application on long range primary radar are also being conducted [37]. Lok and Drake [37] identified gap filler radar mitigation as suitable for ATC radars, such as ASR–10, ASR-11, and ASR- 23, as well as LRR. Testing of this mitigation has been carried out on an ASR-11 radar at Travis Air Force Base and further testing on an ASR-10 radar in the Netherlands, cited in [20]. From interviews with the Wind and Radar Expert it was highlighted that, "X-band radar is very effective at picking up aeroplanes in between turbines. Data gathered in Oregon showed it could track private aircraft without transponder before, after, and over a wind farm; while long range could only see before and after a wind farm". Lok and Drake [37] do however note complications with the implementation of X-band panels due to the growing height of turbines and the requirement for panels to be positioned higher than the turbines.

Kelly [19] states that gap filler radar plays an important role in the UK in enabling 'blanking' of main radars. National Air Traffic System En-Route Ltd (NERL) policy requires a minimum of three radars to cover a wind farm area before one can be blanked. Gap fill radars help provide the additional views required. Webster [28] points out that a gap filling radar by Pager Power, at the low cost of US$250,000, allowed the implementation of multiple MW of wind power in Scotland, with no reduction of the level of detection in the radar. Brenner *et al.* [29] recommends developers should have the option to help fund gap-filler radars, or long distance radars. Brenner *et al.* [29] further suggests the contribution would equal a few percent of the turbine farm construction costs; estimating the cost of a single radar as between US$3-8 million, relatively small when compared to the US$2-4 million cost of a single turbine.

4.4. Stealth turbines

Stealth turbines are focused on lowering the RCS of wind turbines by altering the shape of turbine components and using radar absorbing material (RAM) on the turbines [40]. This can reduce the clutter effects of the wind farm by either altering the Doppler return of the turbines, so it falls outside the detectable range of the radar, or by making the turbine's Doppler return uniquely identifiable and able to be rejected by the radar [34]. RAM can be either active or passive. Passive RAM works by phase cancellation or absorbing and converting electromagnetic energy to heat. Active RAM, also known as phase-switched screens, delivers low reflectivity by redistributing the electromagnetic energy incident over a wider bandwidth [40]. The Wind and Radar Expert interviewed by the author thought positively of stealth turbines, advocating "It can reduce the distance at which turbines interfere with radar by around 30%, allowing you to site turbines closer to radar without interfering with it."

Stealth mitigation options are still in the testing phase with turbine manufacturers such as Vestas and QinetiQ leading research and design. Studies by Bryanton *et al.* [40] identified the main sources of scattering on turbines, and delivered prototype RAM components for the Vestas V82 turbine, revealing the main areas of mono scattering were caused by the tower (75%) and the turbine blades (20%). The required RCS reduction for each turbine component was calculated to be: tower 20 dBms, blade 10 dBms, and nacelle 15dBms. RAM design was delivered via a polycarbonate skin with a foam core, which was considered low maintenance, light weight and fire retardant. Results of the study indicated the RCS of the tower and the nacelle can be reduced significantly with shaping alone. RAM components for the turbine blades further reduced the RCS [40]. QinetiQ has tested its prototypes on shorter-wavelength radars, which they claim also significantly reduce the RCS.Brenner *et al.* [29] state that the impacts of the RAM layer on aerodynamics and turbine longevity is currently unknown, and Jenn and Ton [41] go further and state that the relatively small reduction in RCS would not be worth the degradation in aerodynamic performance, increased weight and cost associated with using RAM. QintetiQ alternatively suggests modifications to the inside of the blade, using layers of circuits and reflectors, which they hope would be effective on L-band radar used by US air-defence. In the future stealth technology which is limited to only reducing a turbine's RCS, may make way for technologies that can eliminate the RCS altogether. Recent advances in the development of metamaterials that make electromagnetic waves either appear to bend around objects or cancel each other out upon reflection could potentially act as 'invisibility cloaks' for wind turbines [42].

Solutions to reduce interference of wind turbines on radar and military operations and sites seem plentiful, although the viability of each can be restricted by cost, development phase, and approval by the DOD. The Wind and Radar Expert interviewed by the author stated, "Integrating infill or gap fill radars will be the most promising mitigation in the short term. That would be followed by improved software mitigation techniques. In the longer term, stealth technology, replacing old radars with newer radars, and integrating advanced signal processing algorithms are promising solutions."

5. Proposed non-technical mitigations

Brenner *et al.* [29] argues non-technical solutions alone are narrow-sighted, stating the 2006 DOD report favoured to "block the installation of offending turbines, rather than to attempt to find technical means of ameliorating the turbine impact". In the interview, Tom Vinson indicated the non-technical solutions for turbine impacts on testing and training routes are “not as technical” and “more operational”, for example “curtailing a wind farm during a military testing period” or “altered training routes”. Other non-technical mitigations that have been proposed for radar that encompass operational solutions include:

- Upgrades to navigational aids, published data or Notices to Airmen, and procedural changes where new wind farms have been implemented [21].
- Policy changes for ATC radars (already adopted in the UK) that dictate that all readings, including false returns from wind farms, must be treated as real aircraft; meaning a minimum lateral separation of 5nmi should be maintained where critical air surveillance operations take place [6].
- Additional training of ATC staff to help them discriminate between wind farm clutter and aircraft [28]. Butcher [25] however suggests for weather radar that a single turbine can be accommodated by meteorologists, but an entire farm is difficult to mentally account for.
- Mandating that aircraft near and above wind farms have secondary radars in use [29].

Tom Vinson, said in the interview that to date the wind industry had come up with a “radar-by-radar mitigation plan”, and Vinson advocated the best value would be in mitigations that could “clear the most projects”. The practicality of such a plan will be dependent on funding and cooperation between government agencies and wind developers. Vinson added “...now the debate is around how we validate solutions, which ones do we validate, and who is going to pay for that. Once a solution has been validated there will also be debate around who pays for its deployment.” The Wind and Radar Expert also supported the need for a research agenda, “The most important thing to do now is push the research agenda, the military will like options such as TPS 77, but these incur a significant investment.” The Wind and Radar Expert suggested instead that research into synchronising “multiple radars looking at the same area” while avoiding “issues with accuracy” would be beneficial to gap filler solutions. Vinson noted if agencies want developers to engage 12-18 months prior to construction, “There needs to be agreement about what can be discussed at that stage and what information developers need to have. Micro-siting of the turbines for example doesn’t happen until fairly late.” The structured ‘early engagement’ of stakeholders was also noted by the Wind and Radar Expert, suggesting that improvements to the current technology validation process is required, “Radars are much more capable than you’d expect, it’s the processes that we approve them under that is concerning. Certification can take 2-3 years… The time it takes to certify and accept new technologies is a major issue.” Independently, David Belote from the DOD focused on the need for collaboration when asked about the next steps required to help resolve wind/radar concerns, “…we need to sit down with major developers and those affected, as there needs to be a cost sharing, and negotiate a public private partnership… It won’t be easy but it has to be a team effort”.

5.1. Stakeholder cooperation

Numerous efforts have been made by industry groups and government organisations to bring together the wind energy developers, radar experts, and government defence agencies to help resolve wind/radar concerns. Despite extensive consultation [28], US progress to resolve wind/radar concerns appears slow. Tom Vinson shared the following view on collaboration to date, “I would say there is agreement that there are challenges and alignment as to what those challenges are. There is also broad agreement there are technological solutions that are available, or could be available.”

Nonetheless, a major proposal that has failed to gain traction for some years is to follow the UK model for resolution. Tom Vinson advocated the approach of the British wind energy association –RenewablesUK– who were able to negotiate with the

Ministry of Defence and Civil Aviation Authority to bring about early agency engagement, clear timeframes for resolving conflict, and provide a research and development agenda, cited in [18]. Warwick [22] states that RenewablesUK and the UK government have formed a consortium to fund mitigation research that allocates funding on the likelihood of success and wind capacity at stake. The UK aviation plan recognises "There is no universal solution to mitigate the effects of wind turbines on radar" hence have made it their mission to "develop a suite of mitigation solutions endorsed by aviation stakeholders" that facilitates "constructive dialogue" between wind developers and aviation stakeholders [20]. In 2009 Blackman cited in [20] noted that the UK plan by 2008 was focused on gap filler radars, mandatory transponder zones, studies into SPE-3000, Raytheon radars, stealth technology, and web based screening tools. Commenting on the split between the number of DOD concerns related to radar versus military sites, David Belote said he believed, "Most of the pure radar concerns could go away in the next 3-5 years. Scientists understand it, industry wants to solve it, and government wants to solve it. People will develop techniques to overcome the clutter rejection issues we see." When asked which proposed technologies are most viable in delivering a wind/radar solution, Belote described the DOD as "technology agnostic" suggesting "there is not enough data to say one technology is better than another." Belote added the DOD is currently testing a number of technology solutions. Stealth turbines however, will not be in the testing mix, "From my experience I know it's difficult to keep stealth 'stealthy'. Stealth works in a given frequency band…its expensive… we aim to deliver solutions to the problem more cheaply and quickly", Belote said.

5.2. Research and funding

Seifert [43] points out that only experts from the DOD, FAA and DHS can determine whether a mitigation is acceptable. Therefore further research from these bodies is required to expand the range of viable mitigations. Tom Vinson, said the DOD is working on collaborative research with the DOE, DHS and MIT Lincoln Laboratory which involves “field testing the Lockheed TPS 77” and “looking at testing ‘off the shelf’ infill and gap fill radars that have had limited field trials”. The Wind and Radar Expert added, “I believe they’re looking at what changes can be made to the dynamic mapping e.g. RAG (Range Azimuth Gating) mapping and clutter mapping. They’re also using clutter mapping and combining that with new post processing systems and improved filtering mechanisms.” Vinson however, questioned whether these research areas were at the “top of the list” in terms of “what would clear the most projects”. In reference to research being conducted to expand available solutions, David Belote confirmed that the DOD have paired up with the DOE and MIT Lincoln Laboratory to conduct “Interagency Field Test and Evaluation” studies, referring to the aforementioned US IFT& E3 Program, designed to compare available solutions. Belote said “They’re taking a look at adaptive clutter mapping, in-fill radar, gap fill radar (to see behind turbines), Raytheon concurrent beam process (to track objects over and behind turbines), and Lockheed Martin pencil beam radar.” The research interviews revealed that the DOD has invested over US$3 million so far to develop a menu of DOD endorsed solutions. Brenner *et al.* [29] argues there is significant potential for mitigations, however, neither wind farm manufacturers nor the government support significant research to test proposed mitigations in the practical environment, and advocate that parties on both sides should provide funding [29]. NOAA has a well-established research plan but no source of sufficient funding to execute it. Dougherty [9] proposed US$30 million in congressional appropriations for a 5 year effort with a split of the costs:

- US$10 million to federal agencies to develop wind-radar impacts projects.
- US$10 million to a public-private partnership to test existing and emerging technology fixes.
- US$5 million to develop and maintain a ‘wind-radar impacts toolkit’ focused on pre-screening capabilities and viable mitigation options.

- US$5 million to an overseeing organisation to manage projects.

The interview results expanded on the perspective of funding of potential solutions. When asked about previous and future cost allocation for wind/radar mitigations, David Belote explained that historically “There’s really only one example and that’s at Travis Air Force Base. Thus far developers have borne the entire cost of optimisation and changes to display.” Looking forward, Belote affirmed that the DOD would be interested in promoting solutions that suit developer finances, “Speaking to industry, 1% of the cost of project seems to be a magic number. If the industry can create solutions such as in-fill and gap fill at 1% cost then I think we’ll have solutions developers are interested in”.

6. Conclusion

The research found that genuine concerns have been raised in the US around the impact of wind turbines on radar and military sites. The concerns are varied, however, this research clarifies that each concern is theoretically plausible. Additional clutter, shadow, seismic noise, and flight obstruction are the main concerns the DOD have raised, and a particular concern is the use of radar clutter and shadow zones by unfriendly aircraft to move below the radar, enabling them to potentially conduct missions undetected. A representative from the DOD was optimistic that most of the concerns over radar could be eradicated within the next five years and confirmed that the DOD have invested over $3 million to date to develop a suite of solutions.

The proposed solutions available to help resolve wind turbine interference with radar and military concerns are numerous, with gap fill radar, software upgrades, radar upgrades, and stealth technology as favoured solutions. Initial research between government agencies and academia will focus on the viability of adaptive clutter mapping, in-fill radar, gap fill radar, concurrent beam radar and pencil beam radar to provide mitigation solutions. The interviews suggest that stealth turbines are unlikely to be endorsed by the DOD as a viable technology solution.

Interviewees listed cooperation between government agencies and wind developers, dedicated funding, a common research plan, and streamlining certification procedures as necessities for implementing and expanding the range of approved mitigation solutions available to address the impact of wind farms on radar and military operations. It is clear from the literature and the interviews that wind industry stakeholders seek 'early engagement' from authorities with distinct requirements such as the DOD, DHS, FAA, and NOAA, to ensure wind turbine projects are not unduly delayed or prevented, and that US defence capability, air supremacy, and missile detection is not compromised [24].

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