centre for sustainable energy

Common concerns about wind power (2nd edn)

Chapter 16
Wind farms and radar

This is one of a series of chapters of evidence-based analysis drawing on peer-reviewed academic research and publicly funded studies.

For other chapters, see **www.cse.org.uk/concerns-wind-power-2017**

Centre for Sustainable Energy, June 2017

Common concerns about wind power (2nd edn)

Chapter 16
Wind farms and radar

The first edition of Common Concerns about Wind Power was published in 2011 to provide factual information about wind energy, in part to counter the many myths and misconceptions surrounding this technology.

Since 2011, much has changed in the legal and economic sphere, and a second edition became necessary. Research has been carried out for this edition since 2014. Therefore, this edition is formatted as a series of individual chapters available for download at www.cse.org.uk/concerns-wind-power-2017

All chapters written and researched by Iain Cox.

Centre for Sustainable Energy, June 2017
Written and researched: 2014

The Centre for Sustainable Energy is a national charity committed to ending the misery of cold homes and fighting climate change.

We share our knowledge and practical experience to empower people to change the way they think and act about energy.

We are based in Bristol although most of our work has relevance and impact across the UK. Our clients and funders include national, regional and local government agencies, energy companies and charitable sources.

centre for sustainable energy

OFFICE 3 St Peter's Court
Bedminster Parade
Bristol BS3 4AQ

PHONE 0117 934 1400

EMAIL info@cse.org.uk
WEB cse.org.uk
TWITTER cse_bristol

CHARITY 298740
COMPANY 2219673
FOUNDED 1979

Chapter 16

Wind farms and radar

Summary

The rapid expansion in the 21st century of onshore and offshore wind farms has led to an increasing number of objections being raised to developments for reasons of aviation safety and military security. The central reason for this is that wind turbines positioned in critical areas can have adverse effects on radar performance. Turbines possess a radar cross-section that is a result of the tower, nacelle and blades all being able to reflect the radio waves used by radar systems, which produces 'clutter' that can obscure a target of interest making it difficult or impossible to track. This can drastically reduce the effectiveness of air defence surveillance and air traffic control radar, especially civil systems used to track incoming aircraft and weather fronts in the vicinity of airports. Interference from wind turbines can therefore present a danger to civilian air passenger safety, and can degrade military capabilities with regards to early warning systems and radar defence. In some cases, the presence of obsolete radar systems is a contributory factor to the problem, but even modern systems may require significant upgrades to ensure interference is effectively mitigated. Ultimately, radar technology has proven very capable of adapting to the problems posed by the increasing deployment of wind farms, but it requires meaningful cooperation between wind farm developers and the civil and military aviation authorities. Several solutions have already been implemented, involving improved software, additional 'infill' radar systems and the replacement of ageing equipment. The UK has taken a leading role in showing how constructive dialogue and a flexible, collaborative approach to mitigation measures can remove planning obstacles resulting from conflicts with radar. In the last decade, a significant amount of UK wind capacity has been 'unlocked' through early stakeholder engagement and the successful implementation of cost-effective solutions.

What is this based on?

The word 'radar' is now used as a common noun in the English language, but it is from the acronym, 'RAdio Detection And Ranging'. This describes the basic operating principle of radar, which is to locate a distant target using radio waves and supply meaningful information regarding its range, altitude, speed and direction of movement. Radar detection relies on objects reflecting and scattering the radio waves that are broadcast by the radar transmitter. When some of those reflected waves are returned in a certain direction they can be picked up by a radar receiver. The power of the returned radio signal and the degree of scattering, combined with knowledge of the location of the radar transmitter and receiver, allows one to calculate the position of the reflecting object.* Note that whilst the transmitter and receiver are usually located close to each other, this is not always the case.

In addition, modern radar systems employ sophisticated processers to analyse the return signals, which helps enhance object tracking by giving information on an object's size and aspect, reducing signal noise and background interference, and filtering out 'clutter' caused by other objects reflecting the radio waves, such as buildings, hills, sea swell and precipitation (weather radar obviously does not filter out the latter).

A further enhancement of radar detection is achieved by exploiting the Doppler effect. You may remember the Doppler effect from learning about soundwaves and how the sound of an approaching or receding object (like a train horn) can change in pitch. If the source of noise continues to move towards you, successive sound waves are bunched closer together and this results in a higher frequency – the sound of the train's horn rises in pitch. Conversely, if the source of noise is moving away, then successive sound waves are spread further apart and you hear a lower frequency sound – the pitch of the train's horn goes down. This phenomenon is associated with any type of wave and, hence, because radar relies on the propagation of radio waves, the Doppler effect can be observed. When sucessive radio waves bounce off of a moving object and are returned to the receiver, the degree to which these waves are bunched together or spread apart over time gives useful information about the speed and direction of the object. This makes radar extremely useful for ranging airborne objects, whether

* Note this is a very simplified description. These calculations also account for factors such as the gain of the transmitter, the area of the receiving dish, the pattern of propagation, the refractive index of the atmosphere and the scattering coefficient of the reflecting object.

tracking civilian aircraft as part of air traffic control or for targeting moving objects that may pose a threat; it also allows useful data to be gathered regarding the movement and precipitation of weather fronts.

Why do wind turbines present a special problem for radar detection? Modern wind turbines are large structures: typical hub heights for the 1.5–3.0 MW designs used onshore range between 70 and 120 m; the hub height for offshore designs is usually in the same range even though the turbines are rated higher (3.0–6.0 MW), because the wind conditions out to sea allow more energy extraction at a given height than occurs on land.[1,2] In addition to being tall structures, wind turbines have moving parts. The rotating face of the blades on a turbine can sweep across a significant area (roughly 5,000 to 7,000 square metres), with each blade in the region of 30 to 50 m in length.[3] Turbines being designed and built for future planned expansion both onshore and offshore will incorporate even higher hub heights and longer blades, with one offshore design already unveiled that uses 75 metre-long blades.[4] Thus, wind turbines can present a large radar cross-section to a radar system operating in the vicinity, which can interfere with detection even over quite large distances if the turbines are clustered in the line of sight of a long-range radar.[5,6] The large steel structure of a wind turbine tower and hub, plus the exposed face of the blades, all contribute to creating false 'echoes' and scattering radar transmissions, which leads to direct interference. This interference can mask a target of interest or overload the receiver with unwanted signals, making it difficult to maintain effective tracking.[5] A group of wind turbines will present a radar cross-section that is significantly larger than a passenger airliner, which can render a surveillance radar system incapable of detecting such aircraft when they fly in the 'shadow' of a wind farm.[7] Indeed, the radar clutter of a wind farm can make it difficult to identify whether an airplane emerging from the shadow is the same one that flew into the shadow or an alternative airplane.[†]

The movement of the blades also causes Doppler interference, as radio waves are reflected at different points and different times across the area of the rotor face.[5] Radar systems have developed to effectively filter out the radar cross-section of background objects and acquire the characteristic signal obtained from large aircraft that typically fly at predicable elevations and are in constant motion.[7] The Doppler effect that results from rotating wind turbines confounds many radar systems, as they cannot distinguish between the two moving radar cross-sections produced by the rotating blades and a moving aircraft.[‡] The blade tip speed on a large wind turbine can be in the region of 180 mph, well within the range of smaller airplanes or low-flying aircraft (such as airliners approaching for a landing), but even if the speed of the rotating blades is less than an aircraft's speed the signal can still confuse the surveillance radar.[3,5,8] As aircraft traverse the area of a wind farm, the radar may even merge the target with the signal from a turbine, especially if the turbine spacing in a wind farm is relatively dense. This can cause the aircraft track to become associated with overlapping signals from the turbines, resulting in loss of target (known as 'target seduction').[9]

An important role for radar is that of weather prediction, which is essential for monitoring severe weather in real time; Doppler weather radar can also be used to provide estimates of wind speed.[10] Wind turbine clutter appears very similar to typical radar signatures produced by weather phenomena, particularly fronts containing precipitation.[11] Similar to target tracking for aviation radar, weather radar can typically filter out clutter from stationary objects, even structures like the turbine tower itself. However, most algorithms that do this cannot distinguish the Doppler shift caused by the rotating blades, especially as the returns from these moving components can result in quite complex signatures.[12] The short time window of dynamic weather features, including hazardous phenomena, means radar is the only effective way to monitor these events. Aggregated wind turbines in a poorly sited wind farm can significantly degrade radar performance for weather prediction.[13]

What is the evidence?

Hardware considerations

As wind farm development began to accelerate in the early 2000s, military and civil aviation authorities, meteorological organisations and seismic monitoring stations all realised the potential impact.[14] Measurements across several sites in Europe have shown that existing wind farms can have a significant impact on weather radar performance, sometimes over distances of 60 km (37 miles) or more.[13] There are also several examples of wind farms, large and small, affecting nearby weather radar systems at critical points across England, Wales and Scotland.[9] In one instance, a three-turbine development in Wales was still capable of casting a significant radar shadow.

Studies by the Royal Air Force (RAF) and US military have also demonstrated the deleterious effects wind farms

† Ian Chatting interviewed in: Reuters, '"Stealth" wind turbine blade may end radar problem,' CNET, 27 Jan, 2010, www.cnet.com/news/stealth-wind-turbine-blade-may-end-radar-problem.

‡ A key feature of the filtering carried out by radar systems is the ability to suppress signals from stationary objects, but the changing echoes from rotating blades means this cannot be applied to wind turbines without unreasonably lowering the detection threshold of the whole system.

can have on radar systems, and this has led to many projects being blocked by defence departments due to concerns over the surveillance capabilities being compromised.[6,7] The blocking effect caused by wind farm clutter observed on RAF surveillance radars led to the recommendation that any proposed wind turbine installation situated in direct line of sight must undergo consultation with the Ministry of Defence regardless of distance (the limit had previously been set at 74 km).[6]

High frequency radar is also used for monitoring conditions at sea and for seagoing vessels to forewarn themselves of nearby objects. The increasing number of offshore wind farms around UK coastal areas have been seen to interfere with these radar systems, reducing their effectiveness with regards to marine navigation, wave measurements, and search and rescue capabilities.[15–18] Those involved with marine spatial planning must ensure that owners of UK offshore wind projects are fully cognisant of the constraints that come from developing in areas that include some of the busiest waterways in the world.[19]

Despite these issues, there are a number of solutions that have been proven to mitigate the impact of wind turbines on nearby radar installations, or show a great deal of promise for future implementation.[20] These vary in cost and are most effectively applied in combination with non-technical solutions, such as clear zoning policies and better stakeholder collaboration.[14] Technical solutions incorporate various computational advances (i.e. improved software applied to existing systems), upgrades to obsolete equipment, and also the placement of infill (or gap fill) radar systems. The latter approach is particularly attractive, since it employs existing 'off-the-shelf' equipment,[9] is relatively cost-effective (at least for large developments) and is readily applicable to existing developments that are stuck in the planning stage.[14]

The principle of infill radar is simple – a new surveillance source is created to help 'fill in' the gaps on a surveillance display that are due to the presence of wind turbines.[20] The infill approach uses a secondary radar that is either strategically positioned so that it cannot see the turbines but still illuminates aircraft of interest, or a specially designed system that is optimised to distinguish the Doppler shift produced by a spinning turbine from a moving target. Systems that use X band radar, which uses a narrow beam radar signal and a higher frequency band of radio waves, have been shown to be capable of providing effective infill coverage. Trials of radar systems in the UK, and elsewhere in Europe and the USA, have successfully passed the requirements necessary to mitigate wind turbine interference, making it possible to 'unlock' considerable levels of renewable generating capacity.[9,14,21] Recent trials conducted in 2014 under the auspice of the UK's national air traffic control service (NATS) have shown that infill radar using off-the-shelf systems can be used by airports to reliably detect aircraft moving through wind farms, even up to 40 nautical miles.

An obvious alternative is relocating existing radar stations. This solution may involve turning one station into two, hence, the new sites provide equivalent coverage to the old one.[22] In fact, developers of Europe's second largest wind farm, Whitelee Wind Farm in central Scotland, have employed both strategies: a Met Office radar at nearby Corse Hill was replaced with two new installations at Holehead and Munduff Hill, with great success;[22] in addition, following consulation between the developer and the air navigation service provider for Glasgow airport, a new infill radar was installed at Kincardine to provide an unaffected radar feed that removed the surveillance clutter produced by the Whitelee site.[21,23] Both strategies were hallmarked by a consultative process that was instigated early on in the planning process by the wind farm developer to research options in collaboration with the relevant authorities. It is acknowledged that the UK has been one of the leading nations in championing this approach, with demonstrable success.[14] However, one aspect of the Whitelee development that should not be overlooked is the cost. The wind farm developer funded most of the additional cost of implementing both solutions, although, since costs involve proprietary company information, the exact details are not publically available.[22,23] Estimates vary, with a figure of £250,000 quoted for the installation of the infill radar system and a £3,000,000–£5,000,000 final cost for the integration of the Kincardine radar data with air traffic control.[14,23] This level of cost might be considered the equivalent of two or three additional turbines. For large sites this represents a few percent of total construction costs for the wind farm itself, but it may not be a viable solution for a small, community-led development.

Software consideration

Radar systems can also receive software upgrades, which may involve digitising older radar sets. This is an alternative to upgrading the radar hardware itself, which can be an expensive option.[14] Software upgrades can improve long-range radar performance, since known wind turbine positions can be integrated into the radar signal processor data to help suppress unwanted returns by applying a 'constant false alarm rate' (CFAR) algorithm for areas that have constant high background levels. This can markedly improve detection of aircraft passing over these areas, i.e. airplanes traversing a wind farm. Using this processing technique may not be effective if a slow-moving aircraft stays in the area for several sweeps of the radar transmitter, or if the strength of the return signal is not very strong (the radar cross-section of wind turbines can often be greater than even large aircraft).[20]

Using CFAR algorithms is not always effective in situations where turbines are placed relatively close together, as might occur in regions where space is constrained (for example, the Swedish Lillgrund offshore wind farm, which lies in a constrained area close to an approach corridor for Copenhagen airport).[9] Densely packed turbines result in high background levels across all 'cells' scanned by a radar, and CFAR thresholds cannot be usefully applied.[14] Overlapping signals from adjacent turbines can even coalesce, preventing radar from accurately mapping the turbines' position and increasing the risk of target seduction when an aircraft passes through the affected cells. Video processing techniques to 'mask' the returns generated by the turbines can significantly reduce this artefact, allowing moving aircraft to once again be successfully tracked whilst entering, traversing and leaving the wind farm area.[9]

Other software enhancements enable long-range surveillance radar to 'look over' turbines by raising the antenna tilt and altering the transition of the transmitter beam, but this can reduce the radar's low-level coverage.[14,20] More sophisticated signal processing software can also be taught to maintain tracking of identified targets using a range of probabilistic techniques (such as predicting the forward track of an aircraft), and by rejecting new target tracks that arise in a cell where there is a wind turbine, but retaining pre-existing tracks that enter the same cell from elsewhere.[20] Other research has focused on developing high-resolution 'clutter maps' for stationary background objects. By integrating these maps into the memory circuits of the radar the unwanted returns can be filtered out from the background more effectively on each sweep.[20] However, this requires processing large volumes of data across a wide bandwidth, and many radar sets are also limited by the maximum number of cells they can analyse in each sweep. Thus, it may not be possible for the radar system to accommodate a clutter map of sufficient complexity to account for a wind farm, and essential components of older radar sets may require a complete redesign if they are to use clutter maps effectively.[14,20]

By analysing the predominant Doppler shift within a scanned cell it is also possible to filter out the erroneous background targets that are created by the rotating blades of a turbine, so getting around the problem of wind turbine clutter (this is 'adaptive moving target indication').[20] This type of detailed analysis of the spectral characteristics of wind turbine clutter can also be used to create algorithms that are able to filter out the Doppler shift for weather radar systems, resulting in weather maps that are free from contaminating signals from a nearby wind turbine.[12] These filtering algorithms can even be applied to groups of turbines together, so providing mitigation for wind farms, not just single turbines.[24]

Collaborative considerations

Replacing ageing equipment with more modern radars can markedly improve aircraft detection in the presence of wind turbines.[14] In particular, the Lockheed Martin TPS-77 radar system has been trialled in the UK, and has enabled the MoD to remove its objections to several significant wind farm projects totalling more than 3 GW in capacity.[21] Modern systems such as the TPS-77 can significantly reduce the size of areas that are shadowed by wind farms, and are far more amenable to the kind of software upgrades discussed above. The cost of these new systems are likely to be the limiting factor, since only large developments or projects involving multiple developers can absorb the multi-million pound price tag.[14] Nonetheless, service improvements remain a core part of military preparedness, and as ageing and obsolete systems are naturally replaced it is probable that the newer equipment can cope much better with wind farm interference.

Finally, for wind farm developments still at the planning stage, there remains the option of tailoring wind turbine placement and aspect to mitigate some of the projected problems.[20] There has also been research into improving the characteristics of the turbines themselves, through the use of radar-absorbing material (RAM) being applied to the turbine structures that minimises the reflection and scattering of radar transmissions. This so-called 'stealth' turbine technology has met with limited success, and is unlikely to be a solution that will be viable in the near future.[14] Aerodynamic losses from coating the blades with RAM and the added weight are not considered to be worth the reduction in radar cross-section that can be achieved. Currently, materials are also expensive and bandwidth-specific, so the solution is costly but may not even resolve all the issues.[5,14] Attempts to model the shape of turbine face and tower to reduce its radar cross-section would require knowledge of the radar system in question, and may inadvertently cause an increase in radar cross-section from a different angle.[5]

Zoning policies have existed for a long time in the UK, and many sites selected for a wind farm must undergo mandatory consultation insisted on by the Civil Aviation Authority (CAA), the MoD or the Met Office, to safeguard surveillance capability.[14,20,22] It is noteworthy that the UK, unlike other jurisdictions, has explicitly chosen a collaborative approach between the renewable energy industry and concerned stakeholders, culminating in a Memorandum of Understanding in 2008 between RenewablesUK and the relevant government agencies concerned with energy, defence and air traffic safety.[**] At its heart, this memorandum lays out the responsibility of each side to engage with one another to find effective solutions:

'The wind industry recognises that it is the responsibility of the wind farm developer to achieve an acceptable aviation mitigation solution when required in cooperation with the aviation industry. The aviation industry recognises that it is the responsibility of the aviation stakeholder to engage with the developer in a manner that will allow for reasonable, consistent and timely advice on the identification of mitigation solutions.' (MoU, 2010 update, p.3, para 15.)

This collaborative approach has been a key factor in the success of several wind farm developments, which has allowed many gigawatts of clean energy to be deployed by resolving radar issues and opening up wind resources. It has enabled both wind farm developers and air safety service providers to accrue a substantial body of knowledge, with the issues and their potential mitigation solutions being assessed and resolved with increasing effectiveness.20 The UK's success in this regard has led to calls for a similar framework to be adopted in the USA.14

Conclusion

Wind farms can have a marked impact on radar systems in general, leading to reductions in radar performance. This raises legitimate concerns over safety from the standpoint of national security, air traffic safety and meteorological forecasting. Whilst a single wind turbine may be accommodated by nearby radar stations, even a small number grouped together can have a notable effect – larger groupings that are typically found in major wind farm developments only exacerbate the impact. The high radar reflectance of turbines creates large shadows in coverage and excessive signal clutter that masks or drowns out genuine targets of interest. Moreover, although wind turbines are ostensibly stationary objects, their large rotating blades produce a particular effect on signals (a Doppler effect) that is frequently interpreted by radar systems as being a moving target or particular weather pattern. Thus, many surveillance systems cannot effectively track moving aircraft through or beyond a wind farm, and weather radars are unable to correctly assess the level and type of precipitation across a wide geographical area.

Despite the detrimental effects on radar performance caused by wind farms, there are numerous solutions that have been proven to effectively mitigate these problems. There are several advanced signal processing algorithms that can correctly identify wind turbine signatures and filter them out, many of which can be applied to existing radar systems via software upgrades, although older and non-digitised radar sets may not suitable. Another effective solution is the use of infill radar that employs a secondary radar source to provide coverage of the area affected by the wind farm shadow. A substantial body of knowledge has built up in the UK over the last decade thanks to successful collaborative efforts between the wind industry and government agencies, which has resulted in productive stakeholder engagement and discourse to deliver workable solutions in situations where wind developments conflict with radar systems. In addition to the solutions mentioned, the better understanding of the issues involved means risk assessments are more accurate and mitigation solutions can be discussed early during planning and development.

Inevitably, there will be some instances where the physical constraints of a site will mean development cannot go ahead. It should not be forgotten that many of the options employed currently may be too costly for a small project to absorb, and such schemes may require extra support to be able to implement an effective solution. Nonetheless, recent progress has shown that there is little reason to believe radar interference will continue to be the insurmountable hurdle it once was. Both the wind industry and those working with radar technology have demonstrated the flexibility and capability necessary to adapt, thus ensuring low-carbon energy can be delivered without compromising the safety and security that radar systems provide.

** 'Wind turbines and aviation radar mitigation issues: memorandum of understanding, 2010 update,' available from: www.gov.uk/government/publications/wind-turbines-and-aviation-radar-mitigation-issues-memorandum-of-understanding-2011-update (shortened URL: www.bit.ly/1DAghBr)

References

1. Wiser R, Yang Z, Hand M, et al. Wind energy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.* Cambridge, UK and New York, USA: Cambridge University Press; 2011. 535–607.
2. Raadal HL, Vold BI, Myhr A, Nygaard TA. GHG emissions and energy performance of offshore wind power. Renew Energy. 2014; 66:314–24.
3. Kulpa JS, Baczyk MK, Kurowska A, Rzewuski S. Wind farm interferences in Passive Coherent Location. *RADAR Proceedings.* IEEE International Conference on Radar, September 9–12, 2013, Adelaide. 64–68.
4. REN21. *Renewables 2013 Global Status Report.* Paris: REN21 Secretariat; 2013. 51–52.
5. Jenn D, Ton C. Wind turbine radar cross section. Int J Antennas Propag. 2012; Article ID 252689:1–14.
6. RAF Air Warfare Centre. *Further evidence of the effects of wind turbine farms on AD radar.* London: Ministry of Defence; Aug 2005. 56 p.
7. Auld T, McHenry MP, Whale J. US military, airspace, and meteorological radar system impacts from utility class wind turbines: Implications for renewable energy targets and the wind industry. Renew Energy. 2013; 55:24–30.
8. NATS Safeguarding Office. *Options for mitigating the impact of wind turbines on NERL's primary radar infrastructure.* Doc. ref. SUR/RPT/02. Whiteley, Hants: NATS Ltd; 18 Dec 2006. 11 p.
9. Hansen K, Thomsen ACK, Riis MA, Marqversen O, Pedersen MØ, Nielsen E. Detection and tracking of aircraft over wind farms using SCANTER 4002 with Embedded Tracker 2. IET International Conference on Radar Systems, 22–25 October, 2012, Glasgow. 1–6.
10. Met Office. *Safeguarding our observations. Met Office guidelines for wind farm developers: meteorological radar and other technical sites used for meteorology.* Exeter: Met Office; Apr 2012. 28 p.
11. Isom BM, Palmer RD, Secrest GS, et al. Detailed observations of wind turbine clutter with scanning weather radars. J Atmos Oceanic Technol. 2009; 26(5):894–910.
12. Hood K, Torres S, Palmer R. Automatic detection of wind turbine clutter for weather radars. J Atmos Oceanic Technol. 2010; 27(11):1868–1880.
13. Chèze J-L, Haase G. *Radar site selection and protection.* OPERA deliverable: OPERA_2010_04. Brussels: EUMETNET; 2010. 17 p.
14. Auld T, McHenry MP, Whale J. Options to mitigate utility-scale wind turbine impacts on defence capability, air supremacy, and missile detection. Renew Energy. 2014; 63:255–262.
15. Brown C, Howard M. *Results of the electromagnetic investigations and assessments of marine radar, communications and positioning systems undertaken at the North Hoyle wind farm by QinetiQ and the Maritime and Coastguard Agency.* MNA 53/10/366. Maritime and Coastguard Agency; 15 Nov 2004.
16. MARICO Marine. *Investigation of technical and operational effects on marine radar close to Kentish Flats offshore wind farm.* London: BWEA; Apr 2007. 52 p.
17. Wyatt LR, Robinson AM, Howarth MJ. Wind farm impacts on HF radar current and wave measurements in Liverpool Bay. Proceedings of Oceans, 6–9 June, 2011, Santandar, Spain. IEEE; 2011. 1–3.
18. Stanley JM. *Offshore wind farm helicopter search and rescue trials: 8. Report of the Officer Commanding C Flight, 22 Squadron.* Maritime and Coastguard Agency; 5 Apr 2005.
19. Toke D. The UK offshore wind power programme: A sea-change in UK energy policy? Energy Policy. 2011; 39(2):526–534.
20. CAA. *CAA policy and guidelines on wind turbines.* CAP 764. London: Published by TSO (The Stationery Office) on behalf of the UK Civil Aviation Authority; Jun 2013. 91 p.
21. See: 'MOD paves way for new wind-farm-friendly radars,' *gov.uk,* 12 January 2012, www.gov.uk/government/news/mod-paves-way-for-new-wind-farm-friendly-radars (last accessed 7 Aug, 2014); and 'ScottishPower Renewables offers radar solution to help unblock major wind power projects in central Scotland,' *ScottishPower Renewables,* 12 July 2012, www.scottishpowerrenewables.com/news/pages/scottishpower_renewables_offers_radar_solution_to_help_unblock_major_wind_power_projects_in_central_scotland.asp (last accessed 11 Aug 2014).
22. Hutchingson G, Miles R. The protection of weather radar networks. The UK experience. Proceedings of Fifth European Conference on Radar in Meteorology and Hydrology, Helsinki (ERAD 2008). 1–5.
23. Pager Power. *Whitelee case study – The largest onshore wind farm in Europe: Executive Summary.* Sudbury, Suffolk: Pager Power; May 2010. 2 p. Available from: http://www.pagerpower.com/media/Case-Studies/Whitelee-Radar-Infill-Case-Study.pdf (last accessed 11 Aug 2014).
24. Naqvi A, Ling H. Signal filtering technique to remove Doppler clutter caused by wind turbines. Microwave Opt Technol Lett. 2012; 54(6):1455–60.