CATAPULT
Offshore Renewable Energy

AN ASSESSMENT OF RADAR MITIGATION TECHNIQUES FOR OFFSHORE WIND

OWIC_SDAW_Programme B Study on Stealth; Layout; Data

ENGINEERING REPORT

In partnership with:

Offshore Wind Industry Council

Lorna Bennet
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Foreword

The ambitious UK Government Goal of 50 gigawatts of offshore wind by 2030 and further expansion for Net Zero by 2050 will be critical to driving the national transition to a green society. As such, large scale deployment of offshore wind is needed to meet these goals.

To do this, offshore wind needs to co-exist and operate side by side with UK Air Defence and Air Traffic Management Surveillance Capabilities. Thus, the need to assess existing and emerging options for the mitigation of the impacts of offshore wind farms on aviation surveillance systems (i.e. radars) was identified by the OWIC Aviation & Radar Workstream.

This Report was commissioned to consider the opportunities and challenges of mitigation options including: windfarm layout optimisation, stealth technology, and data and information exchange, in particular the considerations of such options to offshore wind farms.

While these topics have previously and still remain a consideration for aviation and defence stakeholders, little to date has reviewed and documented these through the lens of the offshore wind sector. For these to have any chance of being successful they need to be plausible and possible for all parties.

The conclusions and recommendations of this Report reinforce the importance of collaboration between all stakeholders and identify key areas where further evidence-gathering and work may be needed.

Hopefully, stakeholders agree that this Report provides a solid, balanced and evidence-based foundation, which will inform prioritisation of next steps and actions as we work towards the co-existence of offshore wind and civil and defence aviation.

We wish to thank Offshore Renewables Energy Catapult Team for their support in completing this study, and all those across the stakeholder group that engaged with the it.

If you have any comments and suggestions on next steps, please do get in touch with Head of Aviation at RenewableUK.

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Nomenclature

2D	Two Dimensional
3D	Three Dimensional
5D	Five Dimensional
AC	Alternating Current
ACCSEAS	Accessibility for Shipping, Efficiency Advantages and Sustainability
AD	Air Defence
ADR	Air Defence Radar
AEP	Annual Energy Production
AI	Artificial Intelligence
ALARP	As Low As Reasonably Practicable
AMB	Aviation Management Board
AMG	Aviation Maintenance Group
ANFIS	Adaptive Neuro Fuzzy Inference Systems
ANN	Artificial Neural Network
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATF	Aviation Task Force
ATS	Air Traffic Services
BEIS	Business, Energy and Industrial Strategy
bn	Billion
BPDN	Basis Pursuit Denoising
CA	Cell Averaging
CAA	Civil Aviation Authority
CAP	Combat Air Patrol

CES	Crown Estate Scotland
CFAR	Constant False Alarm Rate
CIA	Cumulative Impact Assessment
CMS	Condition Monitoring System
CNN	Convolutional Neural Networks
CNS	Communications, Navigation and Surveillance
DAE	Denoising Adversarial Autoencoders
DAERA	Department of Agriculture Environment and Rural Affairs
DAP	Directorate of Airspace Policy
DASA	Defence And Security Accelerator
dB	Decibel, unit for expressing the ratio between two signals
dBsm	Decibel relative to square metres
DCAE	Deep Convolutional Autoencoders
DCCNN	Dual-Channel Convolutional Neural Networks
DECC	Department of Energy and Climate Change
DfT	Department for Transport
DIO	Defence Structure Organisation
DSP	Digital Signal Processing
DT	Decision Tree
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agencies (England and Wales)
FIR	Flight Information Regions
FOW	Floating Offshore Wind
FRAME	Full Radar Absorbing Materials and Equipment
FSS	Frequency Selective Surface
GA	Genetic Algorithms
GAN	Generative Adversarial Network
GHz	Giga Hertz, unit of frequency
GRP	Glass Reinforced Polymer
GW	Giga Watt, unit of power
HM	Her Majesty
H-PMHT	Histogram Probabilistic Multi-Hypothesis Tracker
HVDC	High Voltage Direct Current
Hz	Hertz, unit of frequency
ICAO	International Civil Aviation Organization
IFF	Identification Friend or Foe

IMC	Instrument Meteorological Conditions
km	Kilometre, unit of distance
km^2	Kilometre squared, unit of area
kNN	k-Nearest Neighbours
kV	Kilo Volt, unit of voltage
kW	Kilo Watt, unit of power
LCoE	Levelised Cost of Energy
LOS	Line Of Sight
LPS	Lightening Protection System
m	Metre, unit of distance
m/s	Metres per second, unit of velocity
m^2	Meter squared, unit of area
MASTERI	Multi-Autonomous Sensor Tracking Eliminating Radar
MCA	Maritime and Coastguard Agency
MHz	Mega Hertz, unit of frequency
ML	Machine Learning
MLP	Multiplayer Perceptron
mm	Millimetre, unit of distance
MOD	Ministry of Defence
MRT	Multi Radar Tracking
MSAR	Multistatic Staring Radar
MTD	Moving Target Detection
MTI	Moving Target Indications
MW	Mega Watt, unit of power
MWh	Mega Watt Hour
NAIZ	Non-Auto Initiation Zone
nRAM	nano-scale Radar Absorbing Material
NSIP	Nationally Significant Infrastructure Project
O&M	Operations & Maintenance
OEM	Original Equipment Manufacturer
OREI	Offshore Renewable Energy Installation
OWGP	Offshore Wind Growth Partnership
OWIC	Offshore Wind Industry Council
P_D	Probability of Detection
PRF	Pulse Repetition Frequency
PSR	Primary Surveillance Radar

RADAR	Radio Detection and Ranging
RAF	Royal Air Force
RAM	Radar Absorbing Material
RASOD	Radar-Assisted Shutdown On Demand
R-CNN	Region-Based Convolutional Neural Network
RCS	Radar Cross Section
RF	Radio Frequency
RPM	Rotations Per Minute
s	Seconds, unit of time
SAR	Search and Rescue
SCADA	Supervisory Control and Data Acquisition
Sodar	Sounds Detection And Ranging
SPEA	Scottish Environmental Protection Agencies
SPV	Special Purpose Vehicle
SR	Scoping Report
SSR	Secondary Surveillance Radar
SVM	Support Vector Machine
TBD	Track-Before-Detect
TCE	The Crown Estate
TMZ	Transponder Mandatory Zone
TRL	Technology Readiness Level
UHF	Ultra-High Frequency
UKSRR	United Kingdom Search and Rescue Region
USD	United Sates Dollars
UXO	Unexploded Ordnance
VHF	Very High Frequency
WTG	Wind Turbine Generator
µm	Micro Metre, unit of distance

1 Executive Summary

In order for Net Zero to be achieved by 2050, at least 75 gigawatts (GW) of offshore wind will need to be installed within the UK's Economic Exclusion Zone (EEZ) waters [1]. The clutter and interference that could be caused to aviation radar by offshore wind farms is causing a conflict between the requirement for the UK to produce clean energy, and the safety and security of the country afforded by civilian and military aviation radar. Air Defence (AD) Radar objections could require mitigation from over 20 GW of offshore wind energy installations in the UK (as of January 2022). 92% of the overall wind farm development rejection rate in the UK is due to radar issues [2].

Offshore wind farms are growing - both in seabed area covered, and the number and size of wind turbine generators (WTGs). These factors combined are increasing the potential issues caused to aviation radar. In 2003, a significant offshore wind farm had a capacity of 60 MW, with 30 WTGs covering a seabed area of just under 10 km^2 [3]. Today, a large wind farm may have a capacity of 1,200 MW, with more than 170 WTGs covering a seabed area of over 400 km^2 [4]. WTGs have also grown in capacity and size from 2 MW, with a rotor diameter of 80 m and a tip height of 110 m, to 12 MW, with rotor diameters in excess of 220 m, and tip heights of approximately 250 m [5]. This results in an affected radar horizon of approximately 50 – 80 miles (dependant on antenna height) [6]. The affected radar horizon will also increase further as future WTGs are designed with tip heights over 350 m.

With the size and volume of WTGs and offshore wind farms increasing, along with an increase in the number of air space users, coexistence is key for the UK to remain secure, competitive, and green. If the UK is to achieve Net Zero by 2050, aviation radar must cease to be a barrier to deployment of offshore wind. Offshore wind needs to ensure that the build out to 2050 has the least detrimental impact possible to air space users and does not hinder UK air defence obligations.

This study sought to engage with stakeholders, both from the offshore wind and the aviation communities, to review potential mitigation strategies for offshore wind farms, and provide recommendations for easing and supporting the coexistence of offshore wind, aviation safety, and national security through air defence radar operations. The three areas of mitigation considered within this study are wind farm layout optimisation, stealth technologies on WTGs, and data and information use to improve radar performance.

A comprehensive literature review was conducted by ORE Catapult, and interviews were held with 30 key stakeholders, including six offshore wind farm developers, the Civil Aviation Authority (CAA), the Ministry of Defence (MOD), as well as radar mitigation solution developers and users.

In summary, the two most prominent recommendations are:

- to increase collaboration between MOD, CAA, the wind farm developers, and radar and WTG OEMs to resolve the best cost-benefit solutions, and
- continue to build and share evidence through simulation, development, testing and operations of potential solutions.

Optimised layouts may reduce overall clutter and make more visible "lanes" between rows of WTGs, however the issues of significant blind spots, tracking in clutter and false alarms will remain. Therefore, regarding any layout optimisation, significant benefit might only be achieved if the capabilities of surveillance systems are also upgraded. Applying layout mitigation strategies with legacy radar systems still in place is expected to provide limited benefit, and may potentially cause unplanned complications if those legacy systems are subsequently replaced or supplemented.

While the different layout methodologies will have varying impacts and will depend on the specifics of the wind farm site in question and the position of the primary surveillance site, the most pragmatic layout mitigation approach for initial consideration is a standard grid layout aligned with rows adjacent to a single radar LOS and with a reasonably large space (> 1km) between each row.

The ultimate recommendation is that these layout considerations can be modelled during planning, but must be balanced against the impact on overall project viability – only being adopted if the layout impacts can be managed within the viability profile of the wind farm, and where the specific benefits outweigh the costs.

The use of radar stealth technologies and techniques for WTGs present some interesting potential outcomes to the mitigation problem for future builds, however they will only reduce (not eliminate) the RCS and will not completely solve the issues.

The biggest issue currently with stealth based strategies is that insufficient information exists in the public domain to determine exactly what components need to have stealth technology applied on the WTGs and how effective the respective stealth technologies will actually be in improving the radar picture. This means significant joint analysis between MOD, CAA, radar providers and the offshore wind industry is needed if stealth is to be seriously considered.

Additionally, the amount of stealth required to provide the necessary benefit against the lifecycle costs (i.e. determining the best bang-for-buck) is not yet being thoroughly investigated. Little has been actively field tested in offshore wind. As such, at the present time, and despite possible benefits, stealth technology in offshore wind raises more questions than it answers, meaning that it has higher risks and potentially longer deployment timelines.

The use of data and information likely presents the highest potential for mitigation. Ordinary data processing techniques such as the use of Constant False Alarm Rate (CFAR) algorithms are unsuited for the task of handling the effects of WTGs. However, machine learning algorithms have become increasingly useful in identifying and classifying WTG returns, “training” radars to accurately discriminate between WTGs and targets. Other solutions such as Clutter Cell Blanking and Non-Auto Initiation Zones (NAIZ) may not be able to provide effective levels of mitigation by themselves, but are cost-efficient measures that could form a component of future solutions.

Despite recent questions over the efficacy of some radar models, using next generation radars as replacements, as well as infill and gap-filler radars has so far shown the most potential overall. While further investment into the development and installation of these radars is likely to deliver the most effective future WTG mitigation, it is unlikely that a one-size-fits-all solution exists for all mitigation and coexistence scenarios. As such, stakeholders need to increase efforts to jointly explore all option-sets - potentially adopting multiple cost-effective technologies to ensure an enduring solution.

2 Recommendations

Following a comprehensive literature review and interviews with key stakeholders from across the offshore wind industry, CAA, MOD and radar mitigation solution developers and users, the following recommendations have been drawn:

2.1 General

- The offshore wind industry, MOD, the CAA and radar OEMs should increase collaboration efforts towards more open communication and a more standardised approach to mitigation – as a minimum, working to create a unified database which lists both radar sites (ADR and ATC) and wind farms (onshore and offshore), alongside any potential future sites.
- Ahead of expensive field tests and to reduce the uncertainty of effectiveness among the discussed mitigation techniques, the wind and radar industries should work together to develop high fidelity simulations of wind farms and radars to examine the strengths and weaknesses of all possible scenarios in detail.
- Many of the analysed mitigation techniques in this report have not themselves been thoroughly developed or tested in the field – however there is much opinion and many anecdotal reports. To that end, significant engineering analysis, cost build up and impact modelling must be carried out before key investment decisions are made on any of the discussed mitigation techniques.
- More evidence of radar picture when WTGs are stationary on non-windy or arranged service days should be assessed, to reduce the current gap in knowledge of the different impacts between rotating and stationary WTGs. This could be performed using correlation of stoppages against legacy radar tapes, or recording changes to picture during future WTG stoppages.
- Based on existing open-source document review and stakeholder interviews, the best cost-benefit ratio and lowest risk option to study in detail first is: Improving existing surveillance system coverage and processing, whilst noting that until a fully proven mitigation solution is available no other options discussed herein should be entirely discounted.

2.2 Layout

- It is expected that layout optimisation may provide some limited benefit with legacy surveillance systems. Significant benefit would likely only be obtained through parallel upgrade/ replacement of the ADR (and where required, ATC) surveillance systems.
- Layout considerations can be modelled during wind farm planning on a case-by-case basis, but must be balanced against the impact on overall project viability – only being adopted if acceptable radar mitigation cannot be achieved in any other way, and the layout impacts can be managed within the viability profile of the wind farm, and where the specific benefits outweigh the costs.

- Generally speaking, the more distance between WTGs the better for radar, and the pragmatic “radar friendly” layout for initial consideration would be to have the WTGs aligned in rows at a tangent to the primary mitigated radar with a reasonable distance between rows.
- As there is insufficient evidence shared as to the overall impact of layout mitigation strategies on legacy radar systems, it is recommended that MOD, DSTL and the offshore wind sector work together on a review of existing radar tapes. Reviewing data for any wind farm that is closely aligned to a radar axis, or is believed to have minimal impact on the radar picture as a result of layout would help provide additional evidence.
- To better understand the impact of layout on developing radar technology and processing techniques, detailed modelling and further research into the impacts of layout techniques on radar false alarms and false tracks should be carried out. Accurate synthetic data could be modelled between radar OEMs and the offshore wind sector.

2.3 Stealth

- The benefits of incorporating stealth technology into wind farms, especially with developing radar technology, are largely theoretical at present and will very likely be costly and time consuming to develop, implement and maintain. That said however, due to major gaps in evidence for existing practical progression, further joint investigation into stealth technology for offshore wind is recommended to fully understand the realistic option set. The specific areas where greater understanding is required are covered below.
- Further assessment, testing and data collection of the specific radar impacts from different components of a WTG is required to determine which parts cause the greatest problems for ADR and where to focus improvements and stealth technologies. The RCS differences between the tower, nacelle and stationary blades versus rotating blades need to be properly established and evidenced.
- It should be determined how much RCS reduction is actually required (although this may vary from site to site) for both the current radars in the UK inventory and likely near future candidates. Once understood, further research is required to determine the optimal ratio between RCS reduction, cost, and compatibility with current and future WTG infrastructure.
- Seek to understand whether it is more feasible and cost effective to lift wind farm objections through a 99+% reduction or whether there should instead be less RCS reduction with an aim towards complementing data solutions.
- If stealth treatments are to be considered, further research and trials into the application of broadband RAMs to the blades must be carried out. Consideration should also be given to leaving an untreated area surrounding the LPS as well as providing coverage over at least 3 bands. Partial treatment to the tower could further reduce RCS, but risks becoming economically unfeasible.
- Shaping of the towers and the nacelles could be investigated after the RAM coatings.

- In the future, field trials of metasurfaces, with an aim towards applying them as a radar energy absorber for WTG components could be investigated. These technologies have a low TRL, but modelling suggests they should be capable of significant RCS reductions.
- Additionally, further research and development into active cloaking could be investigated in order to determine their potential for RCS reduction. Although theoretical, the application of these antennas could dampen or significantly reduce radar returns.
- Verify to what extent radars are capable of processing stealth WTGs. Anecdotal evidence raises concerns over how well they fit into a holistic solution or whether they are counterproductive. Relevant stakeholders may still have an interest in being able to detect WTGs. It is also necessary to collect data regarding whether stealth WTGs are more challenging to remove wholly from the radar picture.

2.4 Data and Information

- Continue investment into machine learning and deep learning techniques – training radar processors to correctly identify WTGs to reduce false alarms and improve target detection and tracking. Further trials are required to specifically measure efficacy against WTG clutter for aviation radars.
- Where possible, real wind farm data should be used for radar modelling and mitigation strategies. Current modelling generally uses an individual WTG, duplicated across the field to represent the wind farm. This is considered to produce higher levels of inaccuracies and interference when compared to live field trials, as WTGs in the real world rotate at different speeds and different angles which are easier to account for and mitigate against.
- It is necessary to create large datasets for ML training purposes, as existing “training” datasets are limited in size.
- Continue to develop options for the use of infill radars to provide a complete air picture. They have proven to be one of the most effective solutions and are suitable for offshore wind platforms too. However, widespread adoption may be hindered by the numbers and costs.
- Pursue further trials and validation of newer radar models such as holographic radars. Despite their potential, there is scarce data on how well they perform at mitigating WTG clutter compared to traditional scanning radars. More results could encourage greater investment.
- Highlight to stakeholder groups the valuable outputs from the MOD Concept Demonstrations and the DASA 2 programme – especially if they identify technologies or systems with very strong potential for mitigation.
- Consider future research and development into cognitive radars. Although currently theoretical, they represent the next step forward in radar technology and have the potential to spontaneously react to WTG clutter as it appears. Successful development could provide superior mitigation to existing radar models.

3 Introduction

Offshore wind farms can cause clutter and interference to aviation radar signals creating conflict between the requirement for the UK to produce clean energy, and the safeguarding of UK airspace. An MOD trial in 2005 found that clutter on a radar display, caused by wind farms, was highly detrimental to the safe provision of Air Traffic Services (ATS) [7]. The trial found that an Air Traffic Control (ATC) operator would be unable to differentiate between radar returns from a rotating WTG blade and those from a moving aircraft, resulting in the operator being obliged to treat WTG blade induced radar returns as though they were unidentified aircraft.

The aim of this study is to review the current and emerging techniques and methodologies that could contribute towards mitigating the impact of wind farms on aviation radar, including the AD picture, from an offshore wind perspective. Military and civilian stakeholders use radar as a means of surveillance, identifying and tracking known and unknown aircraft and vessels. The MOD provides the AD picture for the UK and is expected to be able to identify a potential enemy target as small as one square metre within 200 nautical miles of the UK coastline. To achieve this there are seven fixed radar stations and approximately 90 civilian and military radar systems providing ATS around the UK [6], [8]. WTGs can lead to false alarms, hinder the ability of a radar operator to identify a potential enemy target flying close to the WTG, or cause a certain amount of airspace around the WTG to be inadmissible to aircraft due an inability to certify that the airspace is clear and safe to fly in.

Developers are therefore required to complete their own pre-planning assessment of any issues that may affect civil and defence aviation, although they may also take advantage of pre-planning services offered by consultees such as MOD and NATS . The onus is also on the developer to consult with the relevant aviation stakeholder to determine whether mitigation is feasible. It is expected that the developer and Air Navigation Service Provider (ANSP) will cooperate to find an effective solution [9].

At present the UK's baseline policy and guidance for WTGs and aviation is in the CAA's CAP764 (and surveillance technical aspects covered in CAP670), however, the CAA does not comment on any issues affecting military aviation unless requested by the MOD. Any development that does cause such an issue must therefore seek separate consultation with the MOD via the Defence Infrastructure Organisation (DIO) [9]. In September 2021, HMG did issue the first issue of the Air Defence & Offshore Wind Strategy & Implementation Plan. Previously, MOD's DE&S have provided the wind industry with their Front Door Wind Farms Mitigation Process Guidance for AD and ATC radars [10].

A collaborative approach between the ANSP and the wind farm developer is required to ensure an appropriate (i.e. reasonable, achievable, and timely) mitigation is identified [11]. This study aims to bring together stakeholders from aviation and offshore wind, to provide mitigation recommendations from an offshore wind industry perspective, in order for aviation and offshore wind to coexist in a future Net Zero UK.

The cost of electricity generation from offshore wind is expected to fall by over 65% from £120 per MWh in 2015 to £40 per MWh in 2023 and the industry is set to play a major role in the decarbonization of the UK and achieving Net Zero goals by 2050 [12]. For Net Zero to be achieved, the UK's offshore wind installed capacity is required to nearly quadruple from 10.4 GW in 2020 to 40 GW by 2030, as set out in the government's ten-point plan for a green industrial revolution [13].

To date, a main method to remove the clutter caused by offshore wind farms is to essentially 'blank out' the affected area around a wind farm, so that the clutter would not show on the radar operator's screen. With the expected growth and build out projections of offshore wind, this mitigation will no longer be feasible. By 2050 the UK is projected to have over 75 GW of installed offshore wind capacity [1]. The area affected by these wind farms will be immense. Blanking those areas out will no longer be an option, both in terms of national security and aviation safety. Additionally, individual WTGs have more than quadrupled in size over the last 30 years, shown in Figure 3-1. This results in an increased cross-section presented to radar systems, compounding the potential negative impact a WTG can have.

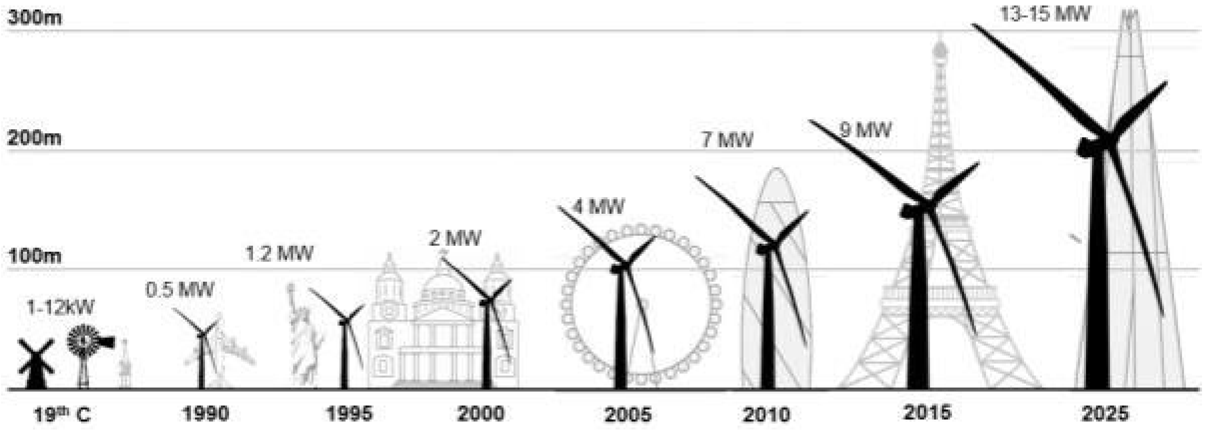


Figure 3-1 Offshore WTG size increase from 1991 – 2021 [14]

This study investigates three areas of mitigation and identifies the opportunities and challenges that may be faced by offshore wind farm developers. The areas of mitigation being considered are;

- **Layout optimisation of wind farms.** It has been suggested by aviation stakeholders that wind farm layouts could be optimised to reduce and minimise the interference caused to aviation radar. This study will review the current layout optimisation process that developers conduct, including current constraints to layout, in order to assess whether this area can realistically present a mitigation solution for future offshore wind farm developments.

- **Stealth Technologies on WTGs.** Techniques used to mask objects from radar detection have been considered for adaptation by the wind industry in recent years. The study will evaluate various techniques that can be used to reduce the Radar Cross Section (RCS) of offshore WTGs, thereby reducing radar interference created by the WTG. This study will consider how this may or may not be complimentary to future WTG (and radar) technological developments.

- **Data and information exchange to improve radar performance.** The adoption of increasingly advanced radars and data processing algorithms has been suggested as a way to reduce the impact of WTG clutter. This study will look at the feasibility of upgrading and installing new radars, algorithms, and the use of other solutions deriving from data and information available from wind farms.

3.1 Aviation Radar

3.1.1 UK Aviation

UK airspace is divided up into three Flight Information Regions (FIR). These are:

- London FIR, covers England and Wales
- Scottish FIR, covers Scotland and Northern Ireland
- Shanwick Oceanic FIR, covers over 700,000 square miles over the north east Atlantic

The UK airspace FIR's are shown in Figure 3-2. However, UK airspace is further split into 17 smaller sectors as shown in Figure 3-3.

Figure 3-2 Map showing the FIR's that make up UK airspace [15]

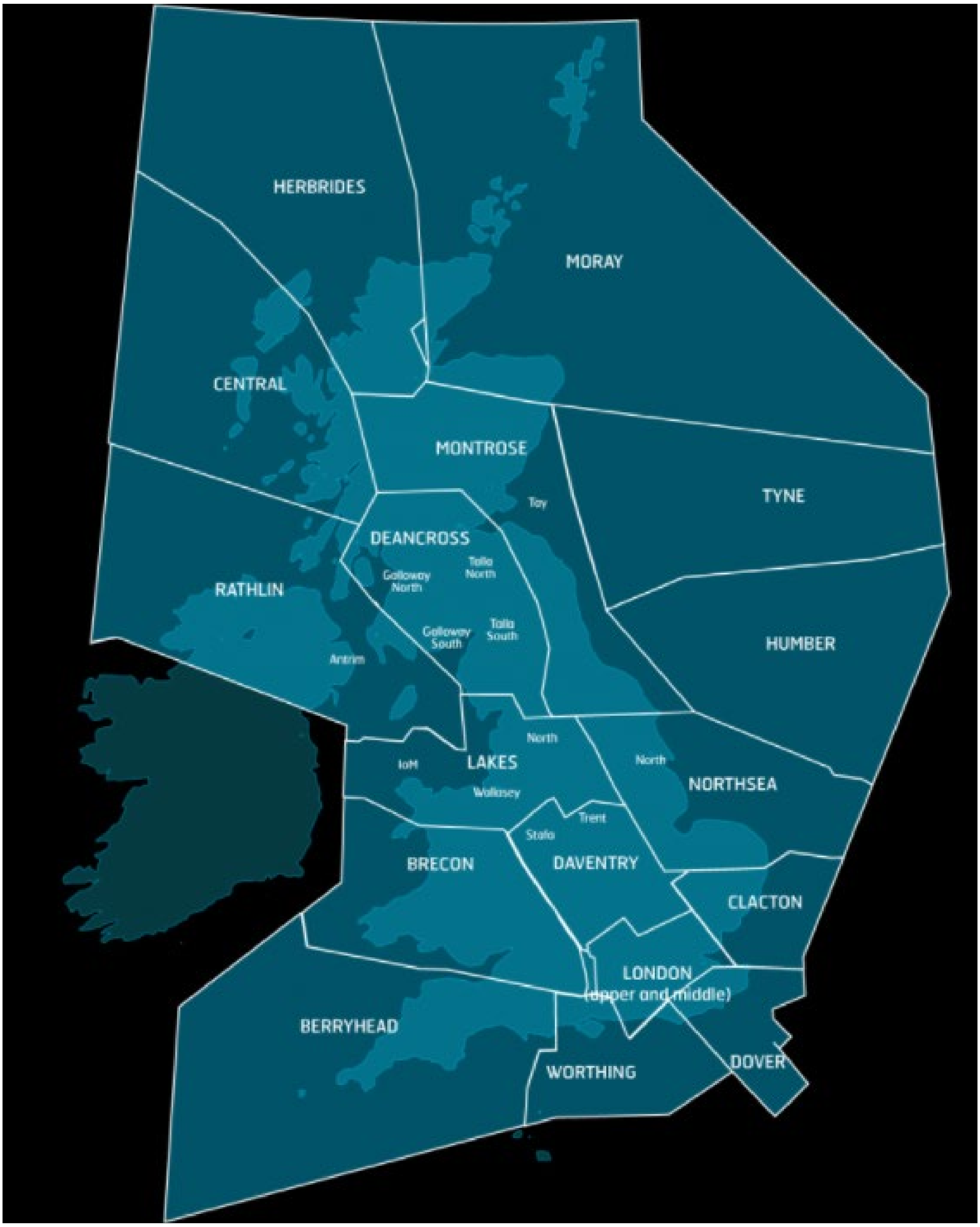


Figure 3-3 Map showing the sectors that make up UK airspace [15]

UK airspace is further categorized into five classes, following International Civil Aviation Organization (ICAO) standard airspace definitions. The class determines the rules that must be followed by aircraft utilising the space, and the air traffic services that must be provided. These can be controlled airspace (A, C, D & E), or uncontrolled airspace (G). In controlled airspace, aircraft must follow instructions from air traffic controllers who direct them within defined areas. In uncontrolled airspace, aircraft do not need to talk to air traffic controllers and can navigate independently. Controlled airspaces are also divided into four classes as shown in Figure 3-4.

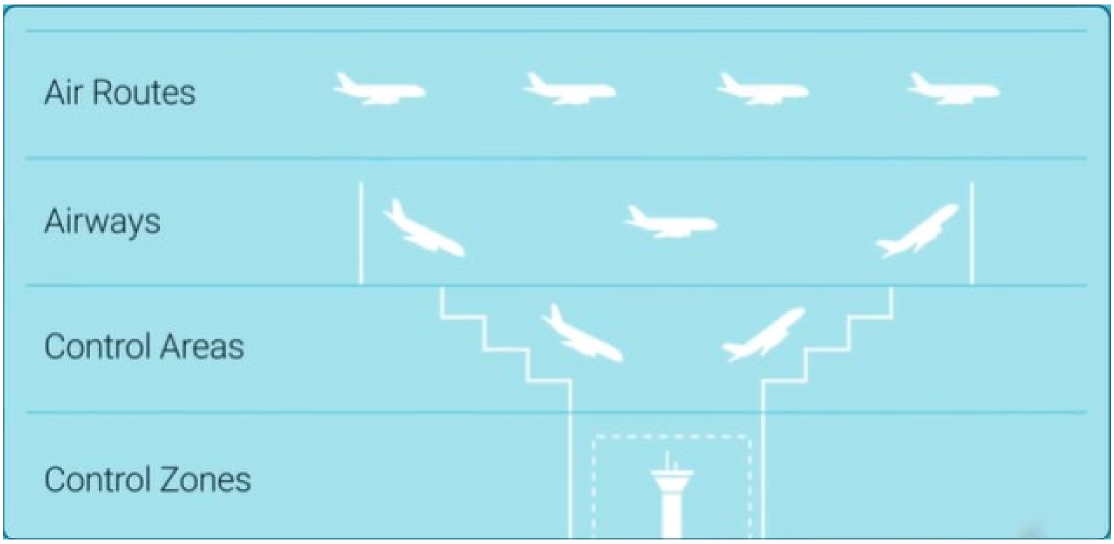


Figure 3-4 Area types within a controlled airspace [15]

3.1.2 Airspace Responsibilities

The Department for Transport (DfT) is the UK government department with responsibility for aviation, setting the national standards for aviation safety and security. The CAA is the UK's independent aviation regulator and is responsible for safety regulation of civil aviation under the Civil Aviation Act 1982 [16]. The CAA established the Safety and Airspace Regulation Group to carry out the planning and regulation of all UK airspace, including CNS (Communications, Navigation and Surveillance) infrastructure, to support safe and efficient operations by the appropriate aviation stakeholder [11]. Furthermore, the responsibility for the provision of safe services lies with the ATS provider or ANSP.

It should be noted that the CAA does not have regulatory powers to approve or reject wind farm planning applications. The CAA was previously formally involved in wind farm preplanning consultation process, however this ceased in 2010 [17]. Developers are now required to undertake their own preplanning assessment of potential civil aviation related issues themselves, however the CAA do provide regulatory guidance to local planning authorities on request where there are issues over aviation objections.

The CAA highlights the potential for aviation to be impacted by WTGs in the CAA Policy and Guidelines on Wind Farms (CAP 764), which outlines how the development of WTG sites has the potential to cause a variety of negative effects on aviation including [11]:

- Physical obstructions to both aircraft and surveillance systems.
- The generation of unwanted return signals on Primary Surveillance Radar (PSR).
- Adverse effects on the overall performance of CNS equipment.
- Turbulence, caused by the wake of a WTG.

The cumulative effects of WTGs on aviation need to be assessed if developments proliferate in specific areas. When assessing the potential effects, a worst-case scenario should be adopted when planning mitigation for wind farms.

While developments with small numbers of WTGs can have an adverse effect on aviation operations, it is the proliferation of developments, and the resulting cumulative effect, that is of far more significant concern. It may be possible to successfully mitigate the effects of a single WTG or small development; however, the combined effect of numerous individual WTGs or multiple wind farm developments can be more challenging.

The CAA is proactive with appropriate Government departments in respect of wind energy related issues. The CAA is a member of, and provides expert input to, numerous organisations and boards that address issues involving wind energy and aviation, mainly the:

- BEIS led Aviation Management Board (AMB) and related groups including those with the Offshore Wind Industry Council's (OWIC) Offshore Wind Sector Deal Aviation Workstream.
- Defence Airspace and Air Traffic Management (DAATM) organisation, focussed on bringing together the MOD and CAA in a coordinated approach to legislative and requirements developments.

3.1.3 Air Traffic Control Radar (ATC)

ATC radar is an umbrella term used to refer to a myriad of different systems which provide air traffic management to both civil and military air traffic. Terminal radars and surveillance systems are designed to assist positive aircraft deconfliction for both approaches and departures, and are utilised to confirm an aircraft's position at altitudes of below 25,000 feet and distances of 50-70 miles from an airport. En-Route radars are responsible for monitoring air traffic outside of the airport. They measure an aircraft's position, course and speed and can detect at distances of up to 300 miles at higher altitudes. ATC radars are generally 2D as they expect to receive transponder signals from co-operative aircraft providing an accurate height. While ATC radars can be affected by offshore wind farms, depending on their location, they are more often primarily concerned with onshore wind farms.

This report primarily focuses on the impact faced by Air Defence Radars.

3.1.4 Air Defence Radar (ADR)

The safety of aircraft in UK airspace is often dependent on ground-based navigation and radio aids [11]. There is a requirement for uninterrupted views of the airspace surrounding the UK coastline. The Royal Air Force (RAF) is responsible for protecting UK airspace and uses long range (LR) radar as a backbone of its ability to provide an AD picture, identifying and tracking unrecognised or non-cooperative aircraft. LR ADR is designed to be able to detect and identify the position, speed, and course of an aircraft. Their range can exceed distances of 300 miles and they have 360-degree coverage, which satisfies the necessary requirements. This allows them to identify approaching enemy aircraft or missiles. LR ADR is used as an early warning device and to guide Combat Air Patrol (CAP) aircraft. LR ADR are generally 3D – providing range, bearing and height information.

Figure 3-5 shows the permanent, stationary LR ADRs currently utilised by the RAF. The four LR ADR systems located on the east coast mainland at Buchan, Brizlee Wood, Staxton Wold and Trimmingham have been replaced since 2011 using wind farm industry funding. The previous systems were replaced with three Lockheed Martin TPS-77S units and T92 upgrade units. These were thought to offer superior capability to the extant radars, and the "best available mitigation" for wind farm effects [18]. The devices are flat-plane 'washboard' arrays, which rotate mechanically in the horizontal plane and project multiple electronically scanning beams in the vertical plane. However, after extensive trials and in-service evaluation, the long term efficacy of the TPS-77 is in question by the RAF when considering the pace and scale of offshore wind growth in the UK EEZ [19].

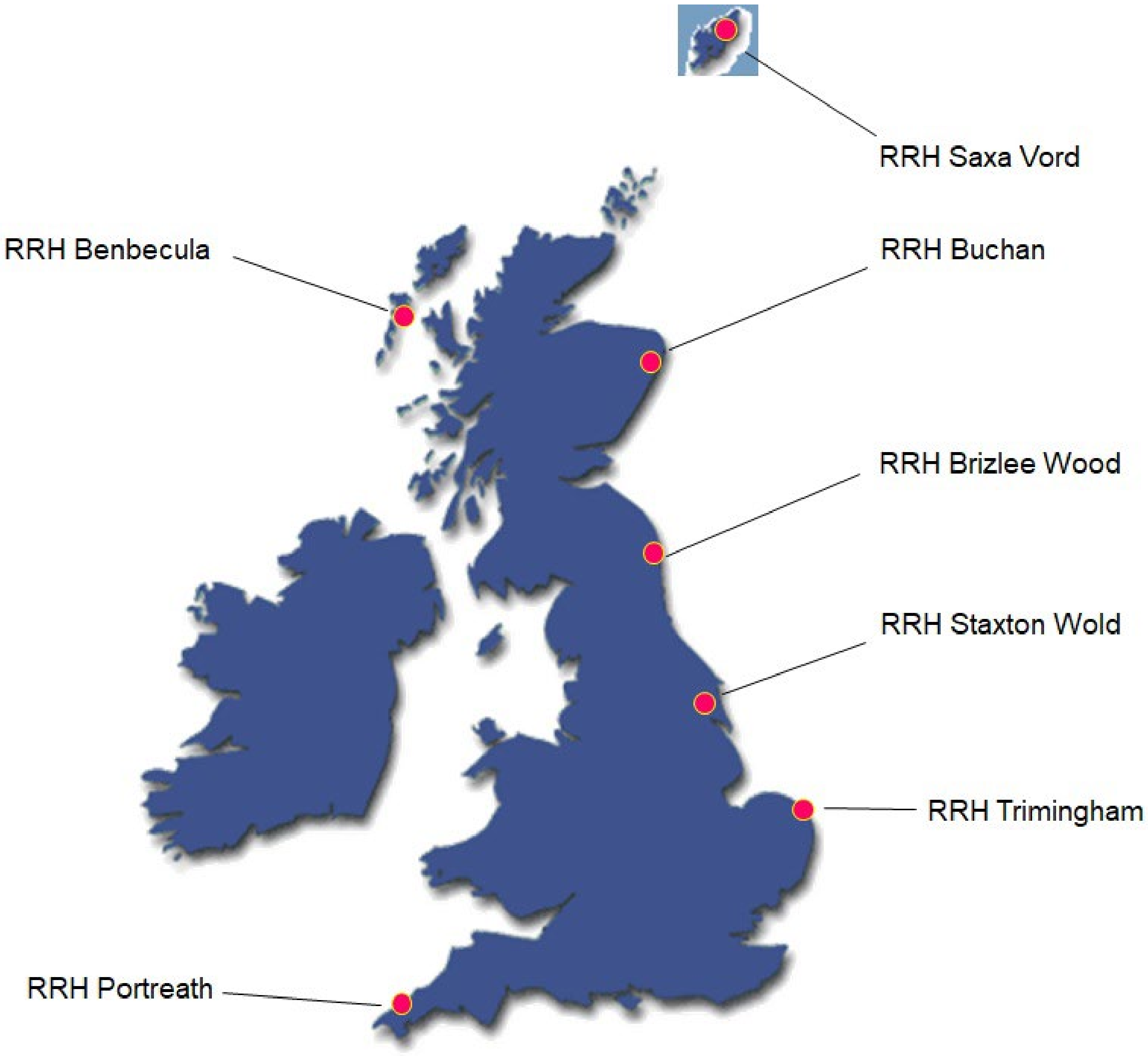


Figure 3-5 Position of MOD stationary ADR in the UK [20]

3.1.5 Radio Detecting and Ranging (RADAR)

A primary radar transmits a short radio pulse with very high pulse power. This pulse is focused by the directivity of the antenna and propagates with the speed of light. If there is an obstacle or 'target' in this direction, then a part of the energy of the pulse is scattered in all directions. A very small portion is also reflected back to the radar, as an echo or return signal. The radar antenna captures this energy and sends it to the receiver, enabling the radar to evaluate and process the information contained, to produce an image on the radar screen.

The probability of detection (P_D) is the ratio of detected targets to the number of all possible 'blips' on a radar screen. The P_D is given by:

$$P_D = \frac{Detected\ Targets}{sum\ of\ all\ blips} \times 100\%$$

Typically an ATC radar system must be able to detect a one metre squared target with a 90% P_D at a defined range. ADR requirements may vary to these.

3.1.6 Primary Surveillance Radar (PSR)

PSRs to date are a keystone element of AD and ATC radars in the UK. A PSR will emit microwaves with frequencies ranging between 1 and 12 GHz. In military applications, the frequencies are grouped into following bands [21]:

L-band: 1-2 GHz

S-band: 2-4 GHz

C-band: 4-8 GHz

X-band: 8-12 GHz

At present, X-band radars have cornered the market for shorter range terminal radars which are commonly used for onshore wind farms, but L-band and S-band radars are also useful for wind mitigation. L-band radars are best suited towards long-range surveillance owing to their range of over 250 nautical miles. Owing to this, stakeholders such as NERL and the MOD use them for both ATC and ADR purposes. S-band radars have a shorter range of approximately 50-60 nautical miles, but are commonly used by airports for ATC too, with many modern radars undergoing trials being S-band.

Emitted radar waves will interact with the surface of any object in the beam path and reflected signals will be picked up by the PSR's receiver. In monostatic PSR systems (the standard for military ADR), the transmitter and receiver antennae are in the same location, whereas multistatic PSRs have receiver antennae at different locations. Monostatic radars are used as they are more cost-efficient and practical. They can cycle the duty times of the transmitter and the receiver, ensuring that the high-intensity waves generated by the transmitter do not interfere with the receiver's components. However, some evidence suggests that multistatic radar systems have greater potential at mitigating WTG clutter, especially when two or more are deployed to cover the same wind farm, owing to their ability to overlap resolution cells and take advantage of a high pulse repetition frequency (PRF) [105].

Traditionally, mechanical radars had to physically move their antennas. Beginning in the 1960s, development in solid-state devices led to the development of the passive electronically scanned array (PESA). By using an array of smaller antennas, they could electronically steer their radio waves to different directions, allowing the radar to scan its environment far quicker than a mechanical system. However, PESA radars were held back as they could send out a single beam at a frequency.

By the 1980s, improvements in radar technology resulted in the development of the active electronically scanned array (AESA). In contrast to the PESA, these could transmit multiple and simultaneous beams over a wide range of frequencies. This allowed AESA radars to scan at a longer range and detect smaller targets more easily. AESA radars also possess multi-mode capabilities, allowing different beams to undertake different tasks at the same time, from ground moving target tracking to air-to-air searching and tracking.

Though reflected radio waves can be returned from any non-reflective material, PSR systems will employ doppler filtering techniques such that only high-speed objects will be identified as ‘targets’. Objects of non-interest are designated as ‘clutter’. Once a track is formed on a target, it is then possible for the radar to develop high-resolution data covering its range, azimuth, elevation, and Doppler. In an ideal situation, multiple radar systems would work in unison, but this is not always practical owing to limitations on power and space.

LR PSRs provide a fast and responsive form of AD coverage as radar waves are transmitted at the speed of light, enabling aircraft to be identified from hundreds of kilometres away. For example, the Lockheed Martin TPS-77 radar has a detection range of up to 470km [22]. Targets that are not transmitting appropriate transponder codes can be immediately flagged as potentially hostile and dangerous. To provide comprehensive coverage of UK airspace, PSRs are designed to rotate between 30 – 120 RPM (Rotations Per Minute), however the trade off from this rotation is that the PSR has a limited timeframe to monitor each target [21].

The construction of offshore WTGs provides an additional factor of complexity to legacy PSRs, as the high-speed rotation of the WTG blades gives reflective radar behaviour similar to the reflection of a moving aircraft. This can cause PSR systems to flag WTGs as targets, thereby inducing unwanted clutter into PSR monitoring systems. Increasing the sensitivity to high-speed targets, though viable for filtering out offshore WTGs, is a brute force solution that leaves AD systems vulnerable to stealth aircraft moving at lower speeds and altitudes.

Standard ATC PSR configurations are 2D, meaning that the radar data only gives information on a target’s range and azimuth. However, there is now an increasing range of 3D ATC PSRs coming onto the market from manufacturers such as Indra and Hensoldt. 3D PSR’s take into account the target’s elevation. This can be achieved through radar beaming, of which there are two common beaming mechanisms: steered beams change the PSR’s transmitter antennae angle such that it can scan the airspace for numerous elevations, while a stacked beamed antennae emits a vertical stack of transmitter beams simultaneously. Though this process may help to filter out WTGs which will typically be at a much lower elevation than any aircraft, it is not a perfect solution. The height of the average offshore WTG trends towards an increase, meaning any elevation thresholds employed will need repeated readjustments [23]. Likewise, aircraft flying at low altitude may become undetectable. From an economic perspective, 3D PSR equipment is more expensive than 2D PSR (and so it may be uneconomic to implement across the whole of the UK).

Conflicts between the offshore wind industry and the aviation industry have arisen due to the adverse impacts offshore WTGs can cause for the PSR systems used in the industry. The areas identified include how they can impact air safety, airspace capacity and efficiency; ADR surveillance capability and weather radar operation [24]. This report will discuss the different methods and state-of-the-art radar mitigation techniques that could be applied to address these impacts.

3.1.7 Secondary Surveillance Radar and Identification of Friend or Foe

In PSRs, the aircraft acts as a passive element and directly reflects electromagnetic signals back to the primary radar. In contrast, Secondary Surveillance Radar (SSR) communication requires the aircraft to be equipped with a transponder to provide a 'response' to the radar surveillance. The secondary radar acts as an interrogator and transmits an interrogation signal to all incoming transponders at 1030MHz [21]. Assuming that the aircraft is friendly, the aircraft's transponder will provide a reply to the interrogation signal at 1090MHz, the 'reply' will contain relevant information needed for the SSR to identify the aircraft such as its altitude and Identification (ID) code.

The military equivalent of an SSR is the Identification Friend or Foe (IFF) system. The key operating quality of the IFF system is that interrogation signals are encrypted using cryptographic computers such that only friendly aircraft can appropriately reply to the interrogation and allows the identification process of friendly and non-friendly aircraft to occur much faster than in standard SSR systems. To travel in international airspace, IFF communications must follow standards such as the NATO STANAG 4193 or the ICAO Annex 10.

3.2 Offshore Wind

The UK government released a ten-point plan in November 2020 which included the ambition to have 40 GW of installed offshore wind capacity by 2030, recognising the critical role offshore wind has as a source of renewable energy [13]. Electricity generation from wind power in the UK has increased by 715% from 2009 to 2020, with the current installed capacity approximately 10.4 GW [25], [26]. Combined with projects either in planning, consented and under construction, the UK will soon have 34 GW of offshore wind capacity. The Crown Estate (TCE) leasing Round 4 will open up potential for an additional 8 GW of capacity, contributing towards the 40 GW target for 2030 [27]. Furthermore, Crown Estate Scotland's ScotWind Leasing Round has to date identified over 25GW of options for lease areas for 17 projects during its initial leasing stages. The Committee for Climate Change has proposed a target for offshore wind to generate up to 80% of the UK's electricity demand by 2050 [1], [28].

The UK's first offshore WTGs were installed at the Northumberland Demonstration wind farm in December 2000. The project consisted of two 2 MW Vestas WTGs, with 66m rotor diameters, located 2km from shore. The UK's largest WTGs are currently being installed at the Seagreen Wind Farm in Scotland, with first power transmission expected to the national grid in early 2022. This project will comprise of 114 x 10 MW WTGs with rotor diameters of 164 m, while the next generation WTGs currently in development are up to 12 MW, with rotor diameters of over 220 m. It is envisaged that into the 2030s, offshore WTGs will be able to provide up to 20 MW with rotor diameters reaching over 300 m [29].

3.2.1 Offshore Wind Industry Council (OWIC)

Established in 2013, OWIC is a senior Government and industry forum whose aim is to drive the development of the offshore wind sector in the UK. The forum consists of members from Original Equipment Manufacturers (OEMs), developers and leading UK and global firms from the offshore wind industry active in the UK, the two Crown Estates as well as ORE Catapult and RenewableUK. OWIC members include:

ABP ASSOCIATED BRITISH PORTS
bp
Crown Estate Scotland Oighreachd a' Chrùin Alba
EDF
equinor
GE
MACQUARIE Green Investment Group
JDR TFKable Group
CATAPULT Offshore Renewable Energy
OFFSHORE WIND LTD
Ørsted
OW OCEAN WINDS
SDIC Red Rock Power Limited
renewableUK
RWE
SCOTTISHPOWER
SIEMENS Gamesa RENEWABLE ENERGY
sse Renewables
Tekmar Energy
THE CROWN ESTATE
VATTENFALL
Vestas

OWIC is tasked with driving the implementation of the Offshore Wind Sector Deal, an agreed industrial strategy signed in 2019, for offshore wind to become the backbone of UK power generation. The sector deal set the following targets for the industry by 2030 (some of which have been superseded) [30]:

- 30 GW of installed offshore wind capacity (increased to 40 GW by the ten-point-plan).
- £40 billion investment in infrastructure.
- 27,000 people employed.
- 60% UK content in UK offshore wind farms.
- Five-fold increase in exports, estimated to be worth £2.6 billion annually.
- £250 million industry investment to develop UK supply chain.
- £100 million in grants from OWIC through the Offshore Wind Growth Partnership (OWGP) to help companies grow in the offshore wind market.

Each OWIC workstream drives key deliverables under the Sector Deal. The aviation and radar workstream consists of [31]:

- Programme A – Air Defence: investigating potential mitigation methods to reduce the negative impact WTGs can have on ADR. This led to the development of the MOD Defence And Security Accelerator (DASA) innovation challenge to develop new technology solutions, and a number of concept demonstrations of high level TRL mitigation solutions run by the MOD.

- Programme B – Surveillance and Airspace: focused on civil aviation and includes elements addressed by this study. Investigating how wind farm layout, stealth technologies and data processing could be utilised to greatest effect, reducing the potential negative impacts of WTGs on CNS. It will also consider wider co-existence between offshore aviation airspace and offshore wind.

3.3 DASA Competition

DASA is a branch of the UK's MOD that specialises in funding projects that enhance the national security of the UK. Established in 2016, the DASA has already rewarded 983 contracts worth a total of £166.8 million for various projects relating to territorial defence [32]. As introduced in Section 2, offshore wind farms can present a serious threat to current radar systems deployed by the MOD in terms of their level of interference with radar tracking. In order to maintain a collaborative partnership between BEIS, the MOD and the offshore wind industry, and to help the UK reach its Net Zero carbon emissions target by 2050, BEIS funded the DASA competition in March 2020 specifically aimed at funding projects to mitigate offshore wind farm radar interference [33]. The competition is currently split into three phases:

3.3.1 Phase 1

The first phase, was themed on assessing the feasibility of ideas presented to DASA, was carried out between March 2020 and March 2021. Initial applications could be presented up to mid-April 2020, after which eligible projects were funded and assessed for their feasibility between July 2020 and March 2021. The first phase was an open competition in which any company could apply for a DASA grant, provided that they could propose a creative and demonstratable solution to one or more of the following challenges:

1. **Alternatives to radar.** Any technology that provided sensory detection of objects that could mitigate the presence of offshore wind farms.
2. **Technologies applied to WTG**. Any technology that could be applied to the WTG metasurface or design to reduce its radar interference.
3. **Technologies applied to the radar**. Any technology that can be applied to the initial transmitted or returned radar signal.
4. **Any mitigation technology that meets the scope of the project,** not specifically covered by challenges 1 to 3**.**

A total of £2 million in funding was granted to six projects led by five companies: Thales, QinetiQ, SAAB, TWI and Plextek DTS [34]. TWI and QinetiQ approached challenge #2 by developing conductive coating for WTG blades and developing radar-absorbing materials for WTGs to absorb radar waves respectively. SAAB and Plextek DTS tackled challenge #3 by developing techniques to mitigate offshore wind through doppler filtering and artificial intelligence. Thales tackled challenge #1 though developing surveillance systems that attempt to eliminate wind farm clutter.

3.3.2 Phase 2

The second and current phase, which commenced in October 2021, and is projected to finish by February 2023, is focused on de-risking some of the projects from Phase 1 that were awarded for further funding, as well as additional projects exclusively introduced for Phase 2. The overarching challenge of this phase is to maintain effective surveillance of airspace in the presence of larger offshore wind farms. The projects will also aim to advance the technologies presented in this phase to a Technological Readiness Level (TRL) of four and beyond, meaning that at minimum the technology should have TRL3 verified performance under laboratory/controlled conditions.

A total of £3.8 million pounds in funding have been given to seven radar mitigation projects led by six companies [35]. A brief overview of the seven projects are listed in Table 3-1. It is believed that the wind industry are supporting some of these projects, including OWIC members of ORE Catapult, SSE-Renewables and Vattenfall Wind Power.

Table 3-1 Overview of projects funded for the second phase DASA wind farm mitigation competition

Project	Company	Funding (£)	Summary
nRAM: An Integrated, Multi-Function Low-Cost Radar Absorbing Material (RAM) Solution for WTGs	Advanced Material Development	392,605	To introduce advanced nano-scale Radar Absorbing Material (nRAM) at the manufacturing stage of WTGs, ensuring Radio frequency (RF) absorption is integrated into the base materials
Mitigation of radar conflicts due to wind farm placements utilizing wideband RAM	Trelleborg Applied Technologies	600,000	To deliver Full Radar Absorbing Materials and Equipment (FRAME™) to mitigate WTG radar interference
Manufacturing of Metasurfaces Phase 2	TWI Limited	600,000	A solution to develop a novel metasurface manufacturing method for the mitigation of radar clutter caused by wind farms
Multistatic Staring Radar (MSAR) for Wind Farm Mitigation - Synchronisation	Thales & Aveillant	599,970	To develop a solution to synchronize two remote holographic radars with which Thales will demonstrate synchronized MSAR
System Design for Wind farm Mitigation Using Multistatic Staring Radar (MSAR)	Thales	481,019	To design and demonstrate MSAR systems using a validated synthetic environment, to provide continuous all-weather air surveillance in and around wind farms.
Wind Farm Radar mitigation through AI and advanced Doppler filtering – Phase 2	SAAB Technologies UK Ltd.	599,692	To incorporate machine learning and artificial intelligence techniques into ADR, providing a trusted air surveillance picture in noisy and cluttered environments.
Multi-Autonomous Sensor Tracking Eliminating Radar Interference (MASTERI)	Livelink Aerospace	505,938	Multiple low-cost sensors on the nacelles of WTGs that can transform the WTGs from being a radar disrupter, to becoming the eyes and ears of an advanced AD.

3.3.3 Phase 3

The third phase of the DASA competition, is expected to be themed around demonstration of the ideas presented in Phase 1 and 2, is targeting commencement by April 2023 for approximately two years. No further publishable details can be given on the third phase at this time.

4 Offshore Wind Development Overview

4.1 Introduction

The process for developing an offshore wind farm is long and drawn-out, involving many distinct phases. The process from site identification to commissioning can take upwards of 10 years, during which time numerous events can occur resulting in the project becoming unviable. A schematic showing the phases and the length of time (in years) of a wind farm lifecycle is given in Figure 4-1.

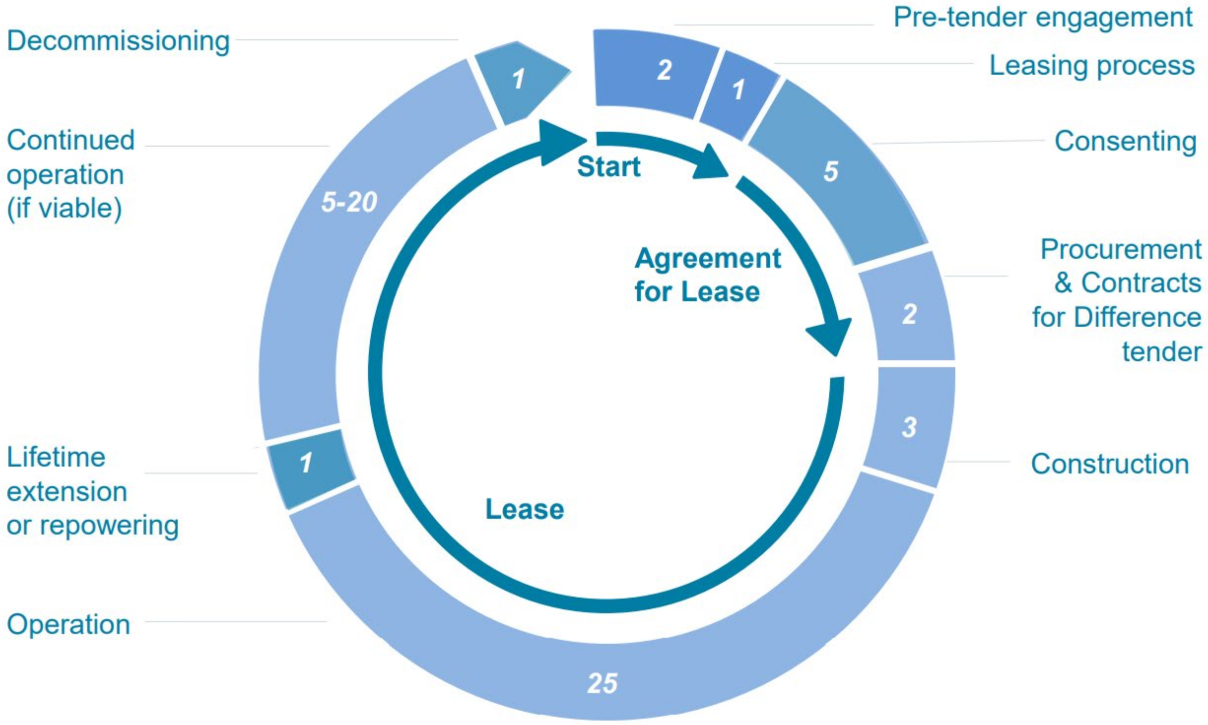


Figure 4-1 Lifecycle of an Offshore Wind Farm [36]

4.2 The Leasing Process

The process by which a developer gains the right to lease and develop, build and operate a wind farm on an area of seabed varies depending on location. This section gives an overview of the process in the UK. TCE manages leasing of seabed areas for England, Wales and Northern Ireland, while the Crown Estate Scotland (CES) deals with seabed leasing areas for Scotland. The leasing process differs between the two organisations as summarised below.

4.2.1 The Crown Estate (TCE)

TCE and the CES manage the leasing of seabed areas off the coast of the UK. TCE has undertaken detailed analysis of the seabed to identify and promote areas offering favourable development resource, as the waters around the UK vary greatly in water depth, sea-state and seabed geology [37]. These factors determine where construction of offshore wind farms may be feasible. These areas are released to be bid upon in 'leasing rounds'.

Leasing Round 1 was held in 2001 and 18 sites were awarded with a combined capacity of 1 GW. This round was for small scale projects up to a maximum of 30 WTGs per project. The last of Round 1 projects were installed in 2013. The UK's first commercial wind farm, North Hoyle, was commissioned in 2003 and consists of 30 x 2 MW Vestas WTGs, installed 8km off the north coast of Wales, in water depths of up to 12 m.

Burbo Bank, off the coast near Liverpool, was the first wind farm to feature WTGs with over 100 m rotor diameters. The wind farm consists of 25 x 3.6 MW WTGs. The aim of the Round 1 leasing was to provide prospective developers the opportunity to gain technological, economic and environmental expertise in offshore wind farm development [38].

In 2002 the government issued the report 'Future Offshore' in which three strategic areas were identified for development [39]. These were The Greater Wash, The Thames Estuary, and Liverpool Bay, and a Strategic Environmental Assessment was carried out for these areas [40].

Leasing Round 2 was held in 2003 and over 7 GW of capacity was awarded with the first 100 MW+ projects emerging. Lynn and Inner Dowsing were twin projects, commissioned in 2008, with an installed capacity of 194 MW. The Moray Firth project in Scotland had WTGs with a rotor diameter over 120 m. The first project consisting of 100 WTGs also came out of leasing Round 2, with Thanet wind farm commissioned in 2010. The 3 MW WTGs are located 12 km from shore in average water depths of 23 m. The Greater Gabbard project was awarded under leasing Round 2 and was the largest wind farm under development in the world, before it was commissioned in 2012. The project has a capacity of 504 MW from 140 x 3.6 MW WTGs.

In 2008, nine development companies were awarded leases to develop in Scottish territorial waters. These developments are now managed under the CES, which was established in 2017.

Leasing Round 3 awarded the rights to over 18 GW of capacity in 2010. The round allowed projects of up to 10 GW capacity in nine development zones, where multiple projects could be developed in each zone. This round produced numerous GW+ projects, with Rampion as the first project to become operational in 2017. Both the Dogger Bank and Hornsea zones were leased during Round 3. Dogger Bank zone is the largest of the nine zones, and following various changes to plans, will now consist of four wind farms, each with a capacity of 1.2 – 1.4 GW. The Hornsea 1 zone is being developed under four sub zones with a combined capacity of 6 GW. Hornsea 1 was completed in January 2021 and has a capacity of 1.2 GW.

Leasing Rounds 1, 2 and 3 gave the UK a pipeline of projects of over 30 GW total capacity. In 2017 TCE launched an opportunity for existing projects to apply for project extensions. Following extensive assessment to extension plans, seven projects were approved for extension in 2019. These extensions represent an additional 2.65 GW to the UK's offshore capacity.

Table 4-1 outlines some of the key offshore wind projects to emerge from TCE leasing Rounds 1 – 3. Distance from shore, number of WTGs, and rotor diameter are the key factors that can have an effect on a wind farms capability to interfere with aviation radar. As can be seen offshore wind farms are increasing in size, and number of WTGs, as the leasing rounds progress, and WTG technology advances.

Table 4-1 Growth of Offshore Wind in the UK

Wind Farm	# of WTGs	WTG Capacity (MW)	Rotor Diameter (m)	Farm Capacity (MW)	Distance to Shore (km)	Leasing Round	Status
Northumberland Demo	2	2	66	4	2	-	Decommissioned 2019
North Hoyle	30	2	80	60	8	1	Operating
Burbo Bank	25	3.6	107	90	7	1	Commissioned 2007, Extended 2017
Lynn and Inner Dowsing	54	3.6	107	194	5.2	2	Commissioned 2009
Thanet	100	3	90	300	12	2	Commissioned 2010
Greater Gabbard	140	3.6	107	504	23	2	Commissioned 2012, Extended 2018
Moray East	100	9.5	164	950	22	3	Under Construction
Hornsea 1	174	7	171	1218	120	3	Commissioned 2020
Dogger Bank A	95	13	220	1235	196	3	Under Construction

Leasing Round 4 was opened in 2019, for projects of 400 MW – 1.2 GW capacity, with the intent that Round 4 was designed at a repeatable scale and focused on water depths up to 60 m. Bidding areas for Round 4 were selected based on extensive analysis of the technical resources and constraints on the seabed around England, Wales and Northern Ireland, to identify the best resources for offshore wind development. Six projects were awarded leases, with a total capacity of 8 GW of potential new OSW. Developers were able to propose their project sites within the bidding areas offered by TCE. The four bidding areas that are thought to present the strongest opportunities for new offshore wind developments are shown in Figure 4-2.

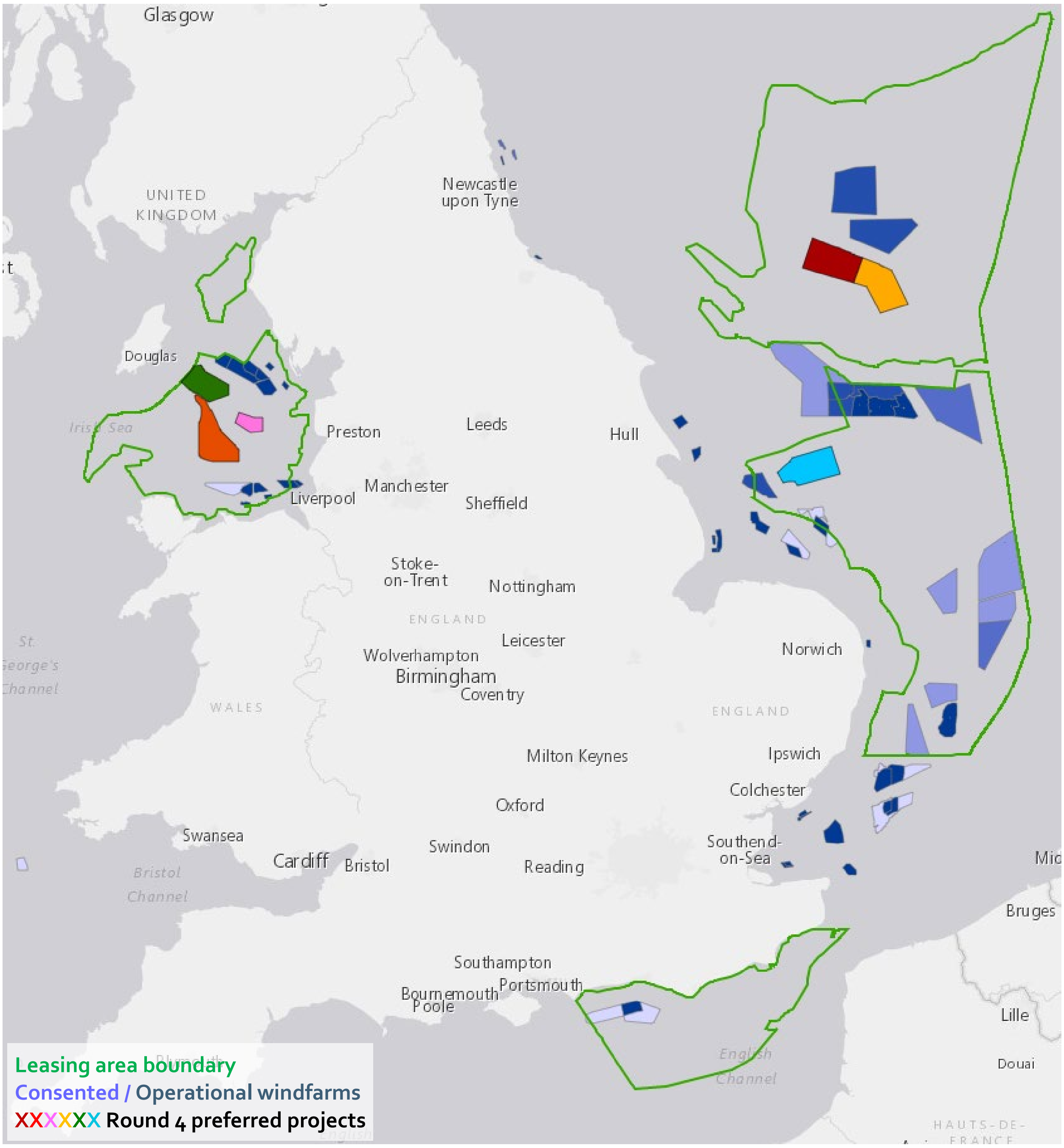


Figure 4-2 TCE leasing areas and agreed wind farm seabed lease sites [41]

4.2.2 Crown Estate Scotland (CES)

Scotland aims to generate at least 50% of total energy consumption from renewables by 2030. It has already achieved over 97% of electricity demand being met by renewables in 2020, however there is a long path to forge to decarbonise the energy demands of heating (currently only 6.4% renewable) and transport [42]. The country has committed to Net Zero by 2045, five years earlier than the UK's current ambition [43].

The Scotland Act 2016 allowed for the management of Crown assets to be devolved to the Scottish Parliament [44]. CES was established in 2017 as an independent board, responsible for managing Crown assets including the rights and access to the seabed up to 12 nautical miles from the Scottish coast. The revenue profits generated by CES are passed to the Scottish Government to invest in public spending [45].

As of April 2021, there are 17 offshore wind projects registered under CES, six of which are operational with a combined capacity of 896 MW and three are currently under construction with a future capacity of 1,447 MW. The final eight are in the planning and consenting process, which hope to add several thousands of MW to the Scottish offshore wind portfolio.

ScotWind was launched in June 2020 and is the most recent round of seabed leasing for offshore wind in Scottish waters, in which the application window closed in July 2021. In January 2022, 17 projects were selected for the development of up to 25 GW of new offshore wind capacity across a seabed area of 7,000 km^2. As part of the leasing process CES awarded Option Agreements which will set out the terms on which CES will grant such a lease in the event that the developer succeeds in obtaining all other necessary consents. A lease provides a developer with the rights to construct and operate an offshore wind farm on the seabed but is only one step in the consenting and development process [46].

Marine Scotland is the department of Scottish Government that leads in the identification of potential areas suitable for commercial scale offshore wind development. These areas are known as Plan Option areas. Marine Scotland produced a report for a Sectoral Marine Plan for Offshore Wind Energy in October 2020 [47]. ScotWind will limit the total area of all option agreements in the first cycle to 8,600km^2 or less, offering 8 – 10 GW of capacity, across 15 sites, in 4 different regions (North, North East, North West and West), as outlined in Figure 4-3.

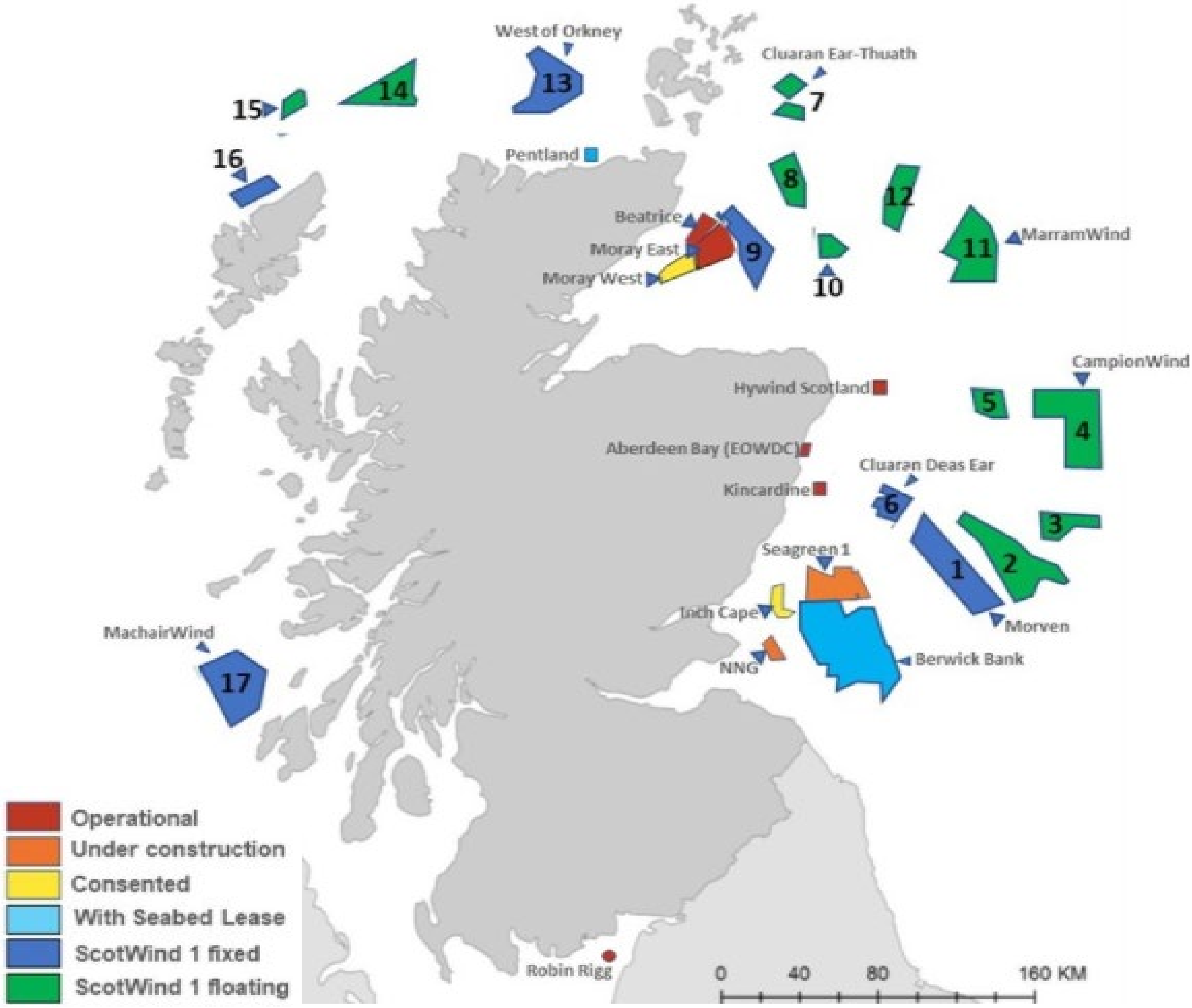


Figure 4-3: Map of Current Offshore Wind Activity in Scotland noting the 17 ScotWind projects [48]

4.2.3 Floating Offshore Wind in Scotland

There are currently more than 50 Floating Offshore Wind (FOW) projects at various stages of development worldwide, 75 % of which are based in Europe [49]. FOW is allowing developers to set their sights on areas of seabed further offshore and in greater water depths, enabling WTGs to be sited in previously inaccessible locations where water depths exceed 40 m and wind resources are superior [50]. The reduced need for heavy lift operations offshore during deployment and commissioning phases of a wind farm mean that FOW has the potential to offer increased economic efficiency over fixed bottom offshore WTGs, offering a reduction in LCoE to the customer.

The world's first FOW demonstrator was a small scale, 80 kW WTG installed in 2008, 21 km off the coast of Italy [51]. Soon after, the first commercial scale, 2.3 MW, FOW demonstrator was commissioned 10 km offshore in Norway, at Hywind 1 in 2009 [52]. The world's first commercial FOW farm was Hywind Scotland, with five 6 MW WTGs commissioned in October 2017 [53].

The ORE Catapult FOW Centre of Excellence forecasts up to 50GW of floating wind power to be installed by 2050. ScotWind comprises of 15 areas of seabed available for development, which received

74 applications for leasing. 17 projects were awarded lease agreements in January 2022, with a combined capacity of up to 25 GW, with almost 60% of the projects planned to be FOW developments (14.57 GW) [54]. Following that, developers will be required to obtain all necessary consents and planning permissions before being granted full seabed leases from CES. Table 4-2 shows details of the ScotWind leasing areas, 11 of the 15 areas are marked for FOW, with water depths up to 148m.

Table 4-2 ScotWind Seabed Leasing Areas

Leasing Area	Seabed area (km^2)	Distance from shore (km)	Water Depth (m)	Capacity (MW)	Foundation type
N1	1161.43	41.5	44-99	2,000	Bottom fixed
N2	560.17	40.4	72-113	2,000	Floating
N3	1106.04	44.3	33-140	2,000	Floating
N4	200.08	8.5	34-59	1,000	Bottom fixed
NE1	750.96	48.7	100-132	2,000	Floating
NE2	344.94	29.1	59-85	1,000	Floating
NE3	264.31	51.2	69-90	1,000	Floating
NE4	439.99	41.4	43-82	1,000	Bottom fixed
NE5	Cancelled due to fishing impacts				
NE6	698.18	45.3	58-125	2,000	Floating
NE7	683.77	94.3	91-119	3,000	Floating
NE8	338.32	91.4	74-102	1,000	Floating
E1	3743.22	109.2	62-148	3,000	Floating
E2	1291.36	102.4	63-93	2,000	Floating
E3	474.06	37.7	54-125	1,000	Floating
W1	753.54	23.1	0-71	2,000	Bottom fixed
SW1	Cancelled due to negative visual-economic impacts				

In addition to the ScotWind announcement, CES has recently announced plans for the Innovation and Targeted Oil and Gas (INTOG) leasing round. INTOG will be an opportunity for developers to apply for the rights to build individual OSW projects of less than 100 MW, specifically designed to decarbonise operational oil and gas installations by providing low carbon electricity directly to them. Figure 4-4 shows the locations of the ScotWind and proposed INTOG seabed leasing areas in relation to existing wind farms and ongoing developments.

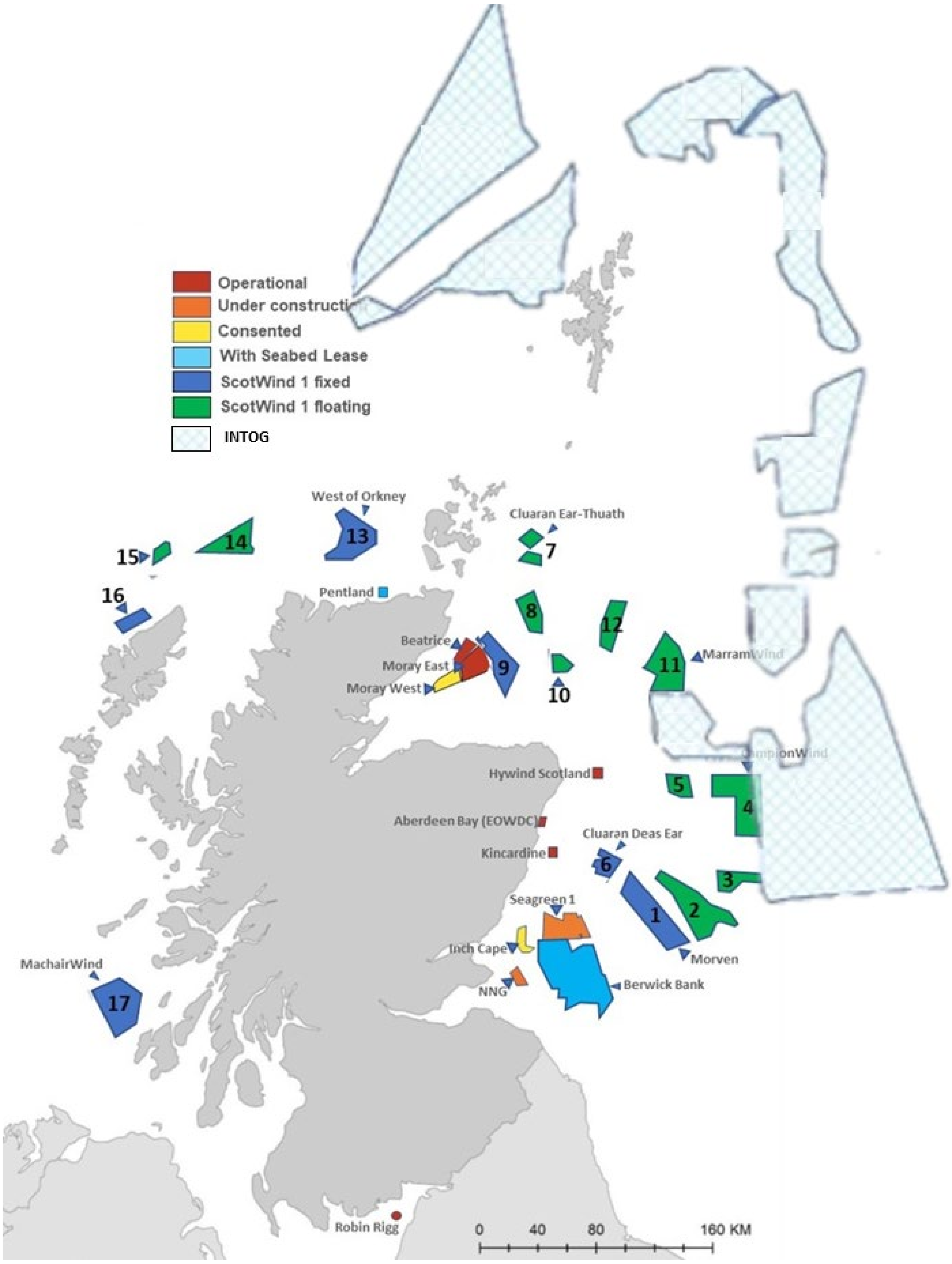


Figure 4-4 Existing, ScotWind and Intog seabed lease areas

4.3 Consenting

Upon successfully gaining leasing rights the developer has a long way to go before construction of the offshore wind farm can begin. The developer is responsible for securing planning consents which, for any offshore wind projects over 100 MW, is examined by the planning inspectorate and is designated a Nationally Significant Infrastructure Project (NSIP). The Secretary of State for the Department for Business, Energy and Industrial Strategy (BEIS) ultimately grants or refuses consent to a developer having considered the findings of the relevant planning inspectorate. Table 4-3 outlines the relevant authorities and acts that assess a planning application for the development of an offshore wind farm.

Table 4-3 Consenting bodies/acts for offshore wind development in the UK

Country	Body/Act under which consent is granted
England	The Planning Act 2008
Northern Ireland	The Marine Strategy and Licensing Department within The Department of Agriculture Environment and Rural Affairs (DAERA)
Scotland	Marine Scotland Act 2010 (up to 12 nautical miles from the coast) Marine Coastal Access Act 2009 (out to 200 nautical miles from the coast of Scotland)
Wales	Natural Resources Wales

Throughout the development process, up to consenting, developers are obliged to engage with numerous statutory consultees. Those with aviation interests include:

- Ministry of Defence (MOD)
- NATS
- Civil Aviation Authority (CAA)
- Maritime and Coastguard Agency (MCA)

There are numerous surveys and reports that must be undertaken prior to consent being authorised. A developer will have a specialist team in place called a Special Purpose Vehicle (SPV), which is a legal entity to control and subcontract the work required. The SPV also provides a structure to enable external investment on a project.

An early step in the consenting process is the Scoping Report (SR) which is required to define and determine the level of impact the project could have on various receptors. This also helps guide the direction and focus of the Environmental Impact Assessment (EIA). The relevant planning authorities are engaged at this stage and the development activity becomes more defined and focussed.

4.3.1 Environmental Impact Assessment (EIA)

The EIA provides a detailed description of the potential impacts a development could have on a wide range of environmental factors. Impacts on the physical, biological and human environments are assessed for each stage and lifecycle of an offshore wind farm and involves a full suite of environmental surveys. After impacts have been assessed mitigation measures are defined. The EIA informs the Environmental Statement which is submitted by the developer to support the consent application. The EIA can take up to 3 years to complete and can cost up to £8 million for a proposed 1 GW development site, as they can require specialist vessels and equipment, with an ornithological survey alone costing up to £1 million [55]. Examples of necessary surveys include, but are not limited to:

- Birds, fish and marine mammals
- Benthic
- Marine navigation

- Socio economic
- Noise assessment
- Visual assessment
- Archaeological
- Commercial fishing
- Landscape
- Aviation impact
- Onshore environmental (for cable laying activities)

As part of an EIA, a cumulative impact assessment (CIA) must also be undertaken. This involves the developer taking into account not only the potential environmental impact of their own development, but also assessing the impact their development will have combined with surrounding existing and future developments.

4.3.2 Metocean Assessments

Metocean assessments provide atmospheric and oceanographic datasets to inform the engineering design of a wind farm, the potential future energy production, and the full description of the likely operating conditions at the proposed wind farm location [55]. This stage of a development for a proposed 1 GW wind farm can cost upwards of £4 million and involves various pieces of specialist equipment and vessels to capture data that will dictate the design of a wind farm and calculate the AEP for the proposed development.

4.3.3 Seabed Surveys

A developer must investigate the seabed conditions for both the proposed wind farm site and the export cable route. Geophysical, geotechnical, and hydrographical surveys provide information that allows for detailed wind farm layout design to be conducted. Costs for seabed surveys for a 1 GW proposed wind farm can run up to £8 million.

Geophysical surveys can be obtained using seismic methods, echo sounding and magnetometry to assess the water depth, seabed bathymetry; soil stratigraphy and possible unexploded ordnance (UXO) identification.

Geotechnical surveys allow for engineering properties of specific seabed features to be assessed and analysed, which can impact the type of foundation considered, in addition to the construction methods, due to the variability in the seabed characteristics.

Hydrographic surveys are used to examine the impact of a development on local sedimentation and erosion. These help to assess the scour characteristics of a site and the potential protective measures that may be required.

4.3.4 Annual Energy Production (AEP)

AEP is the total predicted amount of electrical energy generated by a WTG in a year. The AEP depends on the capacity of a WTG and the wind resource of a site. Each WTG has an associated power curve which provides electrical energy production capability for various wind speeds. Based on data obtained during surveying a developer can estimate the wind speed a WTG will be subjected to at a proposed site (the wind energy distribution) and estimate an AEP for a given WTG at that site. The wind farm AEP can be estimated by summing the AEP of each individual WTG within the development. By optimizing the WTG distribution within a wind farm, aerodynamic and electrical losses can be reduced, and the AEP increased, thus reducing the LCoE.

4.4 Offshore Wind Farm Detailed Design

The detailed design phase is the point at which a developer establishes the wind farm layout, that is, the positioning of WTGs within the lease area. This is done using data acquired during the various surveys, consultations, and AEP considerations. The wind farm design process consists of:

- WTG type selection
- Wind farm size and rating
- Energy production analysis
- Wind farm layout analysis

The following sections discuss each stage of wind farm design in more detail.

4.4.1 Offshore Wind Turbines

Modern offshore WTGs are more than 20 times more powerful than those first installed, leading to significant increases in economies of scale [56]. Progressive innovations, improving the efficiency of components, cables, substations and foundations have also contributed to reducing costs and LCoE [57]. The first offshore WTG was installed at the Vindeby wind farm in Denmark in 1991 [56]. The wind farm consisted of eleven 450 kW rated WTGs with a combined capacity of 5 MW [56]. Current projects due to be commissioned before 2025, such as the Sofia wind farm, developers are opting for 12+ MW WTGs [58]. Larger WTGs have played a critical part in reducing LCoEs for offshore wind farms and improving project economics [59].

As of January 2021, Hornsea 1 was the largest offshore wind project in the world [60]. Commissioned in 2019, the wind farm consists of 174 WTGs, each with a 7 MW rating. The largest WTG currently installed offshore is the GE Haliade X 12 MW demonstrator WTG, in Rotterdam [61]. This WTG model has been selected for installation at Dogger Bank in the UK, currently under construction and expected to be the world’s largest offshore wind farm when fully operational in 2023.

Table 4-4 shows the evolution of offshore WTG size since the 1990’s andFigure 4-5 shows various key dimensions of an offshore WTG.

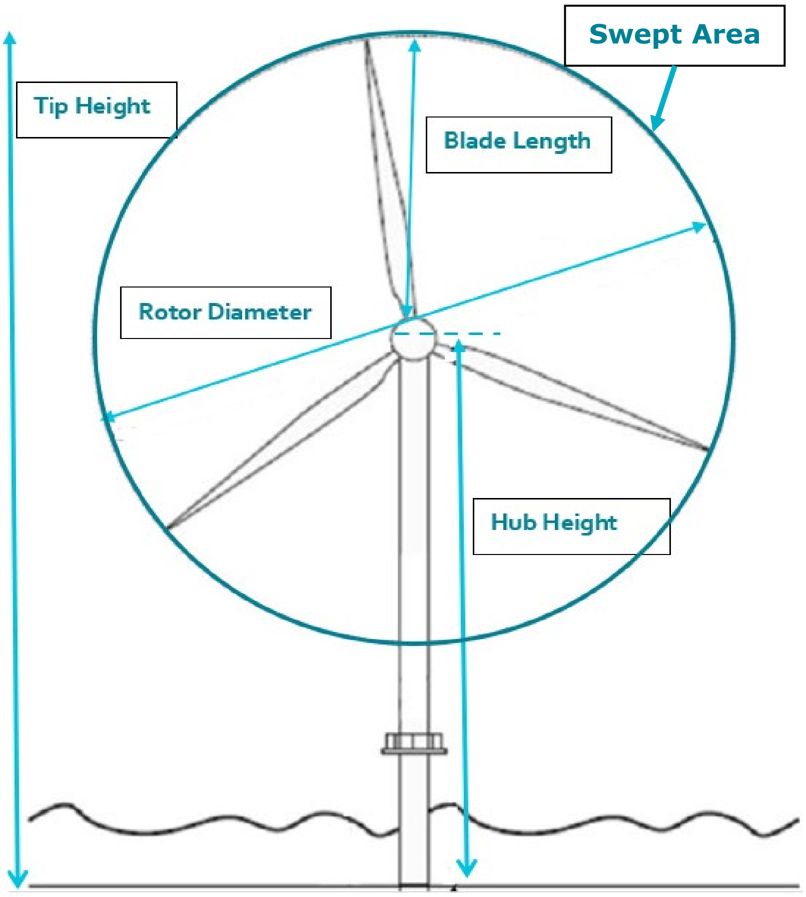


Figure 4-5 Schematic showing dimensions of an offshore WTG

Table 4-4 Evolution of offshore WTGs showing size increases

WTG (Rating)	Wind Farm	Year	Distance to shore (km)	Hub Height (m)	Tip Height (m)	Blade Length (m)	Rotor Diameter (m)	Tip Speed (m/s)	Swept Area (m²)
Bonus (450 kW)	Vindeby – Denmark	1991	2	35	70	30	35	64	960
Vestas V80 (2 MW)	North Hoyle	2004	7.5	70	110	39	80	80	5,027
Siemens SWT-3.6-107 (3.6 MW)	Burbo Bank	2007	8	80	130	52	107	73	9,000
Siemens SWT-7.0-154 (7 MW)	Hornsea 1	2020	145	115 (site specific)	190	75	154	-	18,600
Vestas V164-9.5 (9.5 MW)	Moray East	Under Construction	22	105	187	80	164	90	21,124
GE Haliade-X 12 (12 MW)	Dogger Bank	Commissioning due 2023	130	150	248	107	220	81	38,000

4.4.2 Offshore Wind Farm Size

Since 1991, offshore wind farms have grown, both in terms of individual WTG size, but also the number of WTGs. The potential size of a wind farm is constrained by the terms within the leasing license. Those seabed areas being leased through Round 4 with TCE are limited to a maximum project size of 1,500 MW. Table 4-5 shows the evolution of offshore wind farm sizes over the last 30 years.

Table 4-5 Offshore wind farm sizes since the 90's

Wind Farm	Distance From Shore (km)	Water Depth (m)	wind farm Area (km^2)	Number of WTGs	WTG Rating (MW)	Wind Farm Capacity (MW)	Location (commissioned)
Vindeby	2	5	0.45	11	0.45	4.95	Denmark
North Hoyle	7.5	5 – 12	9.64	30	2	60	UK (06/2004)
Inner Dowsing	5	6 – 8	8.81	27	3.6	97.2	UK (03/2009)
Sheringham Shoal	23	14 – 23	34.97	88	3.6	316.8	UK (04/2013)
Hornsea 1	145	23 – 37	407.34	174	7	1,218	UK (12/2019)
Triton Knoll	40	10 – 18	149.45	90	9.5	857	UK (01/2022*)
Dogger Bank A	130	17 – 31	515.21	95	13	1,235	UK (12/2023*)
Hornsea 3	121	30 – 40	695.83	160-231	14*	2,400	UK (01/2025) *

*expected

5 Wind Farm Layout

With the increasing size and scale of offshore wind, designing the layout of a wind farm is crucial to obtain maximum energy production from a site. Wind farm layout is the distribution of WTGs and balance of plant within the area of the leased site. When designing the layout, developers must consider numerous factors and constraints including:

- Location and space availability
- Water depth and seabed geology
- Prevailing wind direction
- Wind energy distribution
- WTG wakes and interactions between wakes
- Search and Rescue
- Environmental, marine and avian impacts
- Access rights for other users
- Electrical distribution system

The layout design process evaluates and compares layout options in relation to technical and financial feasibility. Ultimately, for the project to go ahead, the return must outweigh the investment – i.e. from a financial perspective, the overall capital and maintenance costs must be less than the predicted energy production for the life of the project.

As discussed previously, land availability is defined by the leasing agreement, and wind direction and wind energy distribution are established from surveying during the consenting process (detailed in section 4.3). The following sections give an overview of the wake effect, electrical collection and distribution system, seabed geology and access requirements for Search and Rescue (SAR) operations, as these are the most relevant factors that constrain the wind farm layout design during the detailed design stage.

5.1 Wake Effect

WTGs extract energy from the wind; therefore, the downstream wind must have less energy, and thus less wind speed than the upstream. This area of reduced energy wind speed downstream of a WTG is known as the wake. The wake effect is the aggregated influence on the energy production of the wind farm, which results from the changes in wind speed caused by the impact of the WTGs on each other [62]. The wake effect can extend up to 50km beyond a wind farm [63].

Velocity reduction in wakes can be 10 – 20%, with a turbulence increase of 8 – 10% which can have a significant impact on energy production. Wind farm production loss due to wakes can be 2 – 7%, therefore, WTG spacing is crucial to wind farm power generation economics [64].

The parameters that influence the total wake losses in wind farm are the WTG spacing and the WTG layout. WTG spacing is generally defined by the WTG supplier, with spacing requirements due to wake effects offshore greater than spacing onshore, due to:

- Increased mean wind speed offshore compared to onshore.
- A larger extension of the wake effect offshore due to lower ambient turbulence from the surrounding environment.

Onshore WTG spacing is often referenced as three to five rotor diameters, where offshore spacing is between five and ten rotor diameters depending on relative proximity and the prevailing wind direction. This means that as WTGs increase in size, they are also spread more widely apart. In a wind farm where there are many WTGs installed it is most likely that wakes can intersect and affect WTGs downwind at the same time. By optimizing the WTG distribution within a wind farm, losses are reduced (both aerodynamic and electrical) and the energy production increased, thus reducing the LCoE [65].

First generation offshore wind farms minimised the energy losses caused by the wake effect by having WTGs distributed in lines with each line being set perpendicular to the prevailing wind direction. Figure 5-1 shows a simple schematic showing conventional WTG distribution for first generation offshore wind farms with Barrow offshore wind farm as an example.

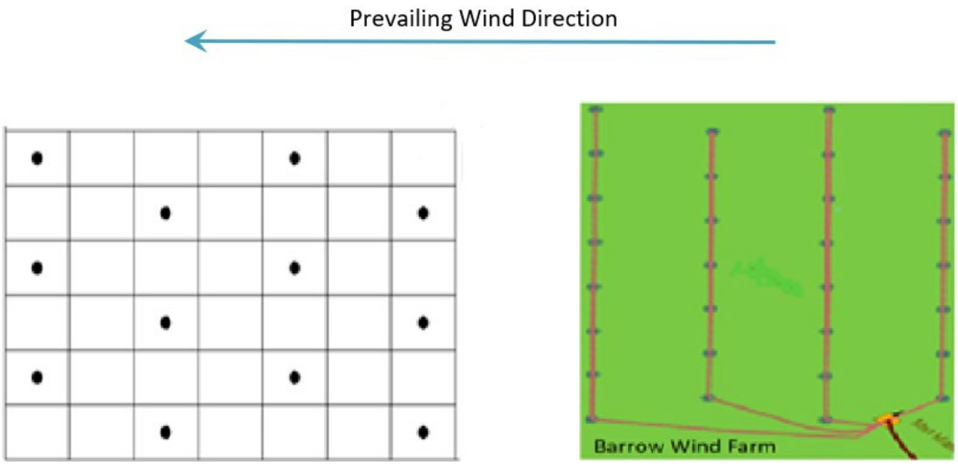


Figure 5-1 Traditional WTG distribution within a first-generation offshore wind farm [21], [18]

The wake effects are very sensitive to the wind direction. Small changes in the wind direction will change the power output of a wind farm significantly [66]. In order to minimise the impact that a change in the wind direction has on the productivity of a wind farm, second generation offshore wind farms were designed with the straight lines of WTGs not all facing in the same direction. This allows for a lesser impact when wind direction changes, making power output and grid integration more predictable and manageable. Figure 5-2 shows the WTG layout at Horns Rev 2. The straight lines of WTGs are all facing different directions, thus lessening the impact of wind direction change to energy production.

Figure 5-2 WTG layout at Horns Rev 2 designed to minimise the impact of changing wind direction on energy production [3]

As wake effects and their impact on wind farm energy production are studied and modelled further, novel layout techniques continue to emerge. A perimeter centred layout approach has emerged in recent years. This layout essentially eliminates the second row of WTGs, as wake losses were found to be highest in this region. This approach reduces the overall wake losses from a wind farm. Figure 5-3 shows Anholt, with a perimeter centred layout, and Burbo Bank along with Burbo Bank extension. Burbo bank is a first-generation offshore wind farm that was awarded consent in 2003 and was commissioned in 2007. The layout is very conventional when compared with the Burbo Bank Extension which was awarded consent in 2014 and was commissioned in 2017, which has a more perimeter centred layout.

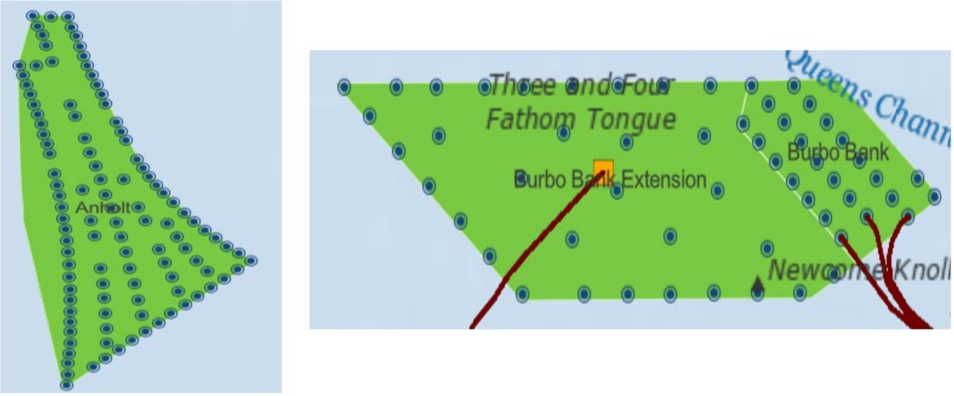


Figure 5-3 Anholt and Burbo Bank Extension wind farm schematic, perimeter centred layouts and Burbo bank, conventional WTG layout [3]

For wind farm layout it is very important to determine the total energy that can be obtained from it.

There are a number of modelling methods used by developers to find the best WTG arrangement within a wind farm. Wind farm power outputs based on wake modelling are well established and used in the offshore wind industry. Existing numerical tools include:

- WAsP/PARK, based on the Jensen Model
- Wind farmer, based on the Ainsly Model
- FLaP, using NS Solver

In recent years Genetic Algorithms (GA) have come into play for optimising wind farm layouts and have had a great measure of success. GA'S can be used to approach wind farm layout optimisation problems. Using the minimum WTG separations and the wind farm boundary as constraints the wind farm can be subdivided into cells making up a grid. The WTGs as individuals can be assessed for their possible layouts, and then the population, or the group of WTGs can best be determined for minimum cost per unit energy. However, one drawback of using GA is that due to their binary coding methods WTGs can only be placed at the very centre of cells, meaning any more productive positions within a cell cannot be considered [67].

As mentioned previously, as WTGs increase in size, they are spaced further apart to reduce wake effects. This is often considered an advantage for reducing radar clutter. However, the impact reduction from increasing the distance between WTGs reduces with wind farms further from shore. Therefore, WTGs at greater ranges from the radar (the far side of Dogger Bank wind farm 190km from shore) do not provide the same benefit for radar azimuth discrimination that they do when closer in (Burbo Bank, 7km from shore).

5.2 Electrical Distribution System

An offshore wind farms electrical transmission system accounts for a significant amount of a project's capital costs. Table 5-1 shows a basic breakdown of capital costs for an offshore wind farm development.

Table 5-1 Capital cost breakdown of an offshore wind farm project [68]

Project Component/Element	% of Project Capital Costs
WTGs and ancillaries	51
Support structures	19
Offshore electrical systems	9
Installation of WTGs and support structures	9
Installation of offshore electrical systems	6
Surveying and construction management	4
Insurance	2

An offshore wind farm electrical system consists of the following key elements:

- Offshore inter-turbine cables (electrical collection system)
- Offshore substation (if present)
- Transmission cables to shore
- Onshore substation (and onshore cables)
- Connection to the grid

Most offshore wind farms until now have been designed with an electrical collector system in a string arrangement. Cables are installed in single lengths from one WTG to its neighbour. The collection of single lengths forms a string, or collection circuit, that feeds into a substation if present. An offshore substation is generally required for large offshore wind farms and for those that are further from shore, to reduce electrical losses by increasing the voltage prior to exporting power to shore. The requirement for a substation brings additional costs to a project as the substation also requires a support structure.

The cables between WTGs within a wind farm are known as 'array cables' and are typically rated to between 30 – 36 kV. Figure 5-4 shows a simple cable array in a representative wind farm.

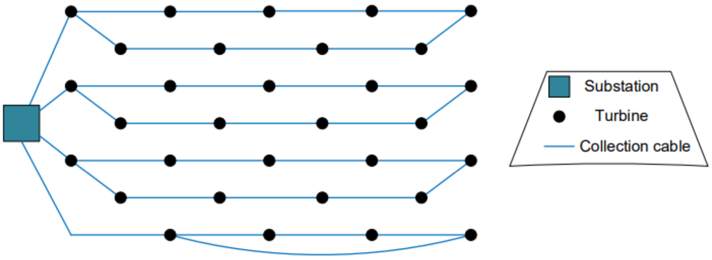


Figure 5-4 Schematic showing simple cable array within a wind farm [65]

Although string arrangements are the norm for electrical collector systems, there are other arrangements that have been used in order to reduce cable lengths, and thus reduce cable capital costs and electrical power losses which can have a significant impact on the wind farms operating economics [69]. Other configurations used include:

- Radial
- Ring arrangement, single or double sided
- Star
- Multiple hub-ring configuration

The radial configuration is the simplest with low cable costs, but reliability can be an issue. Figure 5-5 shows a radial cable configuration at Horns Rev 1 wind farm. A single sided ring configuration uses a redundant connection between the strings of WTGs which increases reliability but incurs greater cable costs. A star configuration allows for a reduction in cable ratings and affords a higher level of reliability and voltage regulation along cables.

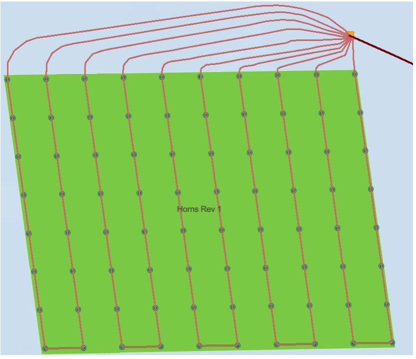


Figure 5-5 Schematic of Horns Rev 1 offshore wind farm showing a radial cable configuration

Generally, a ring configuration in offshore wind farms performs best, providing fewer losses and better grid security than simpler configurations, such as radial. Reliability is a key factor as cable repairs and replacements are very costly, with a common estimate of 75 – 80% of the wind industry's insurance claims relating to cable failure and individual cases causing losses of £10 million and more when lost power generation and repair costs are combined [70]. Typically, most failures in subsea cables occur due to errors in the manufacturing and installation phase, and only 13% of failures have been reportedly caused by external or environmental factors [71]. Array cables have been reported to have significantly fewer failure rates than the larger export cables [71].

Export cables transmit the power to shore and are designed for higher voltage between 100 – 320 kV and are rated to approximately 120 – 900 MW. Large capacity wind farms may therefore require more than one substation. Figure 5-6 shows Triton Knoll wind farm, with a capacity of 857 MW, requires two substations. As projects get bigger and further from shore Alternating Current (AC) transmission becomes less and less feasible. High Voltage Direct Current (HVDC) transmission is becoming the most cost-efficient transmission method due to reduced losses and increased capacity. Hornsea 1 has three substations to service its wind farm capacity of 1,218 MW.

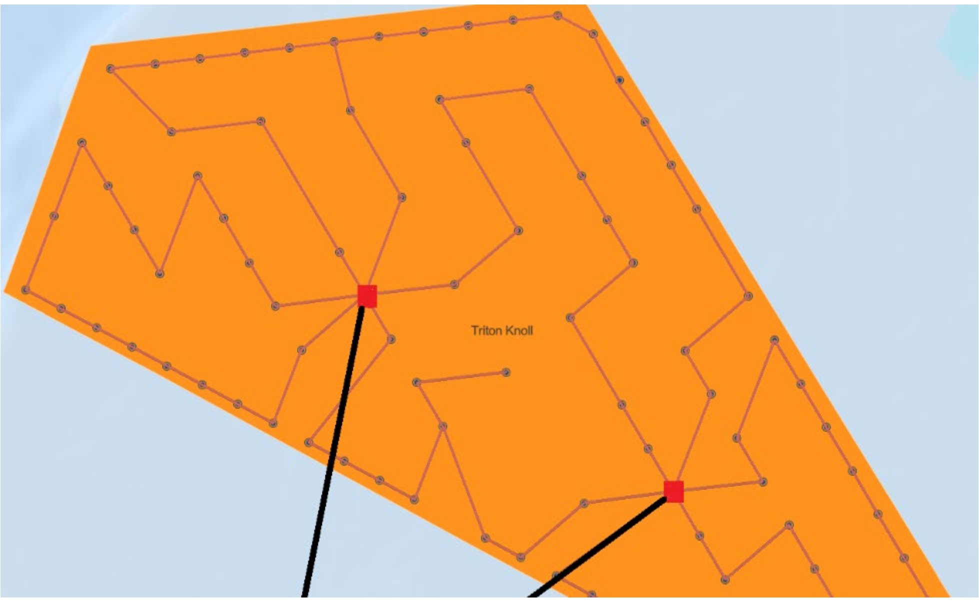


Figure 5-6 Triton Knoll wind farm showing array cables, 2 substations, and export cables [3]

The larger a wind farm, in terms of capacity and seabed area, the more array cables are required, and the greater potential for cable failures and faults. A prediction of industry growth from 2018 estimated that more than 19,000 km of array cables, worth up to £5.36 billion, are expected to be installed for collection systems by 2028 [72].

With array cables costing approximately €350/m, installation costs around €240 /m, and export cables costing approximately €650/m offshore, and €488/m onshore, it is essential that a wind farm layout is designed in such a way that minimal cable lengths can be used to reduce capital expenditure [73]. Table 5-2 shows some cable lengths used on offshore wind farm projects from the first offshore wind farm to 2021.

Table 5-2 details of wind farms and lengths of their array and export cables

Wind Farm	Year	# of WTGs	Distance from shore (km)	Wind Farm Area (km²)	Capacity (MW)	# of substations	Total length of array cables (km)	# of export cables	Export cable length (km)
Vindeby	1991	11	1.8	0.45	4.95	0	3	1	1.3
North Hoyle	2004	30	7.2	9.64	60	0	18	2	24
Inner Dowsing	2009	27	5	8.81	194	0	16	3	20
Sheringham Shoal	2012	88	23	34.97	317	2	81	2	44
Triton Knoll	2021	90	33	118	857	2	144	2	115
Hornsea 1	2021	174	120	407	1,200	3	357	3	492

5.3 Seabed Geology

An offshore wind farm developer's ideal construction conditions consist of dense marine sand seabed, as that provides the best conditions for piling foundations for WTGs and burying subsea cables. In addition to challenges presented by seabed geology, such as hard rock bed preventing piling and trenching, there are several subsea geohazards that need to be considered and avoided during offshore construction, including, but not limited to [74]:

- **Bedforms**: relate to subsea environments exposed to hydrodynamic forcing, such as in areas of strong currents, capable of generating mobile bedforms. Mobile bedforms are critical to engineering design and vitally important for the positioning and installation of subsea cables. The challenges they can present are twofold: potential exposure of buried structures (foundations, cables, etc.) which can undermine the integrity of the design or excessive burial of thermally sensitive power systems (cables, subsea substations) causing them to overheat or malfunction.

- **Positive Reliefs**: are protruding topographic features such as reefs, outcrops, beach rocks, mounds and ridges. These natural features create obstacles that should be avoided in offshore construction projects involving subsea cables and other infrastructure to be installed on, into or under the seabed.

- **Negative Reliefs**: can present particular geohazards in the form of channels, canyons, gullies and steep slopes. These can produce risks to submarine cables and cable routes, and should be avoided where possible. Negative reliefs (such as submarine channels) are considered conduits for sediment transport and are therefore often linked to slope failures, sediment gravity flows and mobile bedforms.

5.4 Search and Rescue Operations

The Maritime and Coastguard Agency (MCA) is responsible for UK civil maritime SAR for the United Kingdom Search and Rescue Region (UKSRR). The MCA also provides aeronautical SAR coordination for

UK airspace. The MCA foresees an increase in emergency operations to assist vessels and people in distress around an ever-growing number of offshore renewable energy installations (OREI), including offshore wind farms.

The ACCSEAS (Accessibility for Shipping, Efficiency Advantages and Sustainability) project was funded by the EU INTERREG IVb North Sea Region Programme for three years, concluding in 2015. The project investigated navigation issues in the North Sea, noting that the growth of the offshore wind industry would populate large areas of the North Sea with wind farms, reducing the space for vessels to transit and manoeuvre. Coupled with the growth in shipping, in terms of volume and size of vessels, the situation could correlate with an increased risk of groundings or collisions [75].

The MCA is a statutory consultee within the planning process for development consent [76]. Developers are required to provide the MCA with detailed plans and drawings of a proposed site before final decisions are made on layout design. The MCA methodology policy document sets out the requirements that OREI, in UK waters, have to adhere to in order to allow for SAR, and emergency operations to be safely conducted both within and around the offshore wind farms [77]. It is necessary for OREIs to be located, constructed, equipped and operated in such a way as to minimise impacts and effects upon SAR and emergency response. Developers may also be required to provide suitable mitigations to help alleviate these impacts [77].

When designing the layout of an offshore wind farm it is essential that access for SAR operations is a priority consideration. If developers fail to give due regard to the recommendations and mitigations proposed by the MCA in the policy document, it may result in objections to their proposals [77]. If restrictions on SAR response to a particular OREI are considered by the MCA to be substantial, or particularly difficult, a marine licence condition may be placed on the developer or operator of the OREI to remove or otherwise alleviate the risk.

Wind farm layouts must be designed to allow safe transit through by SAR helicopters operating at low altitude in bad weather, and those vessels (including rescue craft) that decide to, or must, transit through them. For SAR operations a wind farm should ideally have a linear layout. This is due to the search patterns used by HM Coastguard which are in accordance with international standard practice. All search patterns are normally composed of parallel straight lines to ensure that a search-area is fully covered. A wind farm with WTGs placed in rows and columns is considered to be the safest layout by navigation stakeholders.

The layout of a wind farm should have at least two consistent lines of orientation. Figure 5-7 shows a diagram of the WTG layout for the UK's first offshore wind farm, North Hoyle. When a developer is planning a wind farm layout with only one line of orientation the MCA must be consulted, and a safety justification must be submitted for review. The justification must address how the risks to navigation and SAR associated with the proposed layout have been reduced to As Low As Reasonably Practicable (ALARP). These details should form part of a developers Navigation Risk Assessment.

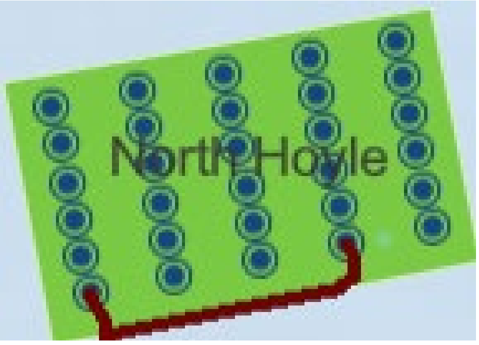


Figure 5-7 Diagram of North Hoyle wind farm showing 2 lines of orientation [3]

New developments are using a packed boundary approach, where there are lots of WTGs placed around the wind farm area perimeter where wind speeds and conditions tend to be more favorable, and fewer in the centre of the wind farm due to the wake effect (discussed in section 5.1). In this kind of layout design, as shown in Figure 5-8, the developer is encouraged to communicate with the MCA to address potential issues with SAR operations.

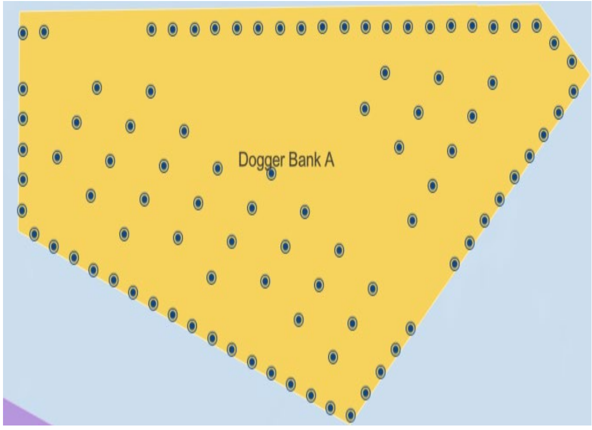


Figure 5-8 Diagram of planned layout for Sofia wind farm showing two lines of orientation and packed boundaries [3]

Where a wind farm is due to be extended or is less than one nautical mile from the boundary of another wind farm, consideration must be given to the requirement for lines of orientation that allow a continuous passage for vessels and SAR helicopters between both sites [76]. Figure 5-9 shows the layout design from Kentish Flats wind farm and its extension with continuous lines of orientation. A layout with zero lines of orientation will not be acceptable to the MCA, who would raise an objection to the proposed development.

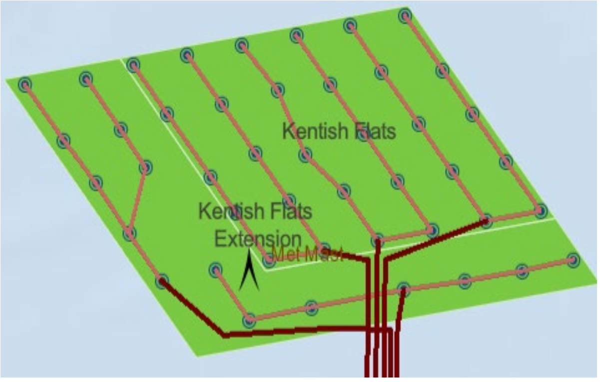


Figure 5-9 Kentish Flats wind farm and Kentish Flats extension showing lines of orientation [3]

Future offshore wind farms offer new access challenges, being larger and much further offshore. This may result in increased use of helicopters for transferring service crews. The MCA has assessed that any wind farm that will cover more than 10 nautical miles in one direction will require helicopter refuge areas to be built into the layout design. Refuge areas provide a safe airspace within a wind farm where a helicopter can manoeuvre and turn around in the event that the helicopter needs to evacuate. If weather conditions are such that a SAR helicopter must fly under Instrument Meteorological Conditions (IMC) flight rules, using instrument navigation techniques and electronic systems, the aircraft will not be able enter any WTG lane that is less than 500 metres wide.

5.5 Layout for Radar Mitigation

Current operational wind farms, those under construction and those with consent cannot change their existing layouts to suit aviation radars. Any optimisation of a wind farm layout for specific radar sites can only occur during the planning stage, with obvious consideration given to overall project feasibility once impacts from any radar mitigated layout are modelled and understood.

Due to the use of accurate range gating techniques, radars provide very precise resolution in range. This means that the radar is able to discriminate more than one “target” in range at relatively short distances (less than 100m). However, many legacy radars are unable to resolve more than one return within the beamwidth, where the physics of the radar beamwidth determines the actual azimuth (side-to-side) and elevation distance within which the radar can only see one return. The physical size of the azimuth and elevation “spot” increases proportionally with range from the radar head. More advanced signal processing can aide resolution within beamwidth and AESA based radars have techniques that can help to effectively “see inside” the beamwidth.

When looking at radar coverage specifically relating to wind farms, range resolution is still generally considered to be very accurate while the height can often be obscured to significant height above a WTG by sidelobes reflecting off the WTGs themselves – in some cases effectively “blinding” the radar to airspace well above the WTGs. Most often, the biggest cause of clutter for radar operators occurs in azimuth, causing smearing of the WTG return perpendicular to the radar LOS. This either makes a large part of the airspace unobservable or causes confusion for processing algorithms that can increase the false alarm rate.

The focus of most analysis to date has largely been towards reducing the impact on target detection, although false alarms and false tracks also have a knock-on effect for target detection as well as track seduction issues. It is presumed that gains could be made with regards to false alarms from the same layouts that have been discussed herein. However, there is currently limited evidence or modelling to investigate the particular question of false alarms and additional research is required.

Due to air defence radar classification, detailed analysis of multiple data sets to determine the quantitative differences of existing wind farm layouts is not available for this review. As such, the determinations within this section are based on modelling and assessment of releasable data. It is recommended that MOD and the wind sector work together to thoroughly assess the impact of layout on existing radars through analysis of historical data and potentially with the use of a mobile radar site for gathering any additional trial data.

The SAAB 'Air and Marine Defence Mitigation Study' suggests that the WTGs of an offshore wind farm could be arranged in a way that minimises the impact on a particular radar system, but the benefit would likely be limited [21]. The study stops short of suggesting a particular layout or template that could be utilised in mitigation.

It is expected that the different layout methodologies discussed herein will have varying impacts - depending on the specifics of the wind farm site in question, the prevailing wind direction for the site, the position of the primary radar site (including the relative position of other ADRs with radar line of sight over the wind farm), and the capability of the radar itself. While optimised layouts may reduce overall clutter and make more visible "lanes" between rows of WTGs, the issues of significant blind spots, tracking in clutter and false alarms will remain without an increase in overall radar capability.

The ultimate recommendation is that these layout considerations can be modelled during planning to determine expected impact to both AEP and radar mitigation, but must be balanced against the overall project viability – only being adopted if the layout impacts can be managed within the viability profile of the wind farm, and where the specific benefits outweigh the costs.

5.5.1 Rows aligned in range rings from the radar

Leveraging radar's accuracy in range, it is determined that the most effective layout mitigation strategy is for WTGs to be arranged in concentric arcs around range rings, with a reasonably large distance (ideally 1km or more) between each row. That would technically produce the most successful results for minimising clutter to the "rings" themselves, and maximising airspace sanitisation within the area of the wind farm [78]. The radial separation (determined by beamwidth of the radar) is less of a concern if the range arcs are accurate. While this may mean that the returns from the WTGs blend together in azimuth, importantly, they will be constrained in narrow range rings (less than 100 meters in range). These arcs will become less pronounced (straighter lines) the further the wind farm is from the radar. A representation of rows aligned in range rings is shown in Figure 5-10.

It is that clear air gap in the range rings that will allow inbound or outbound targets to be tracked effectively. Of note however, tangentially moving targets could still get "lost" along the arc.

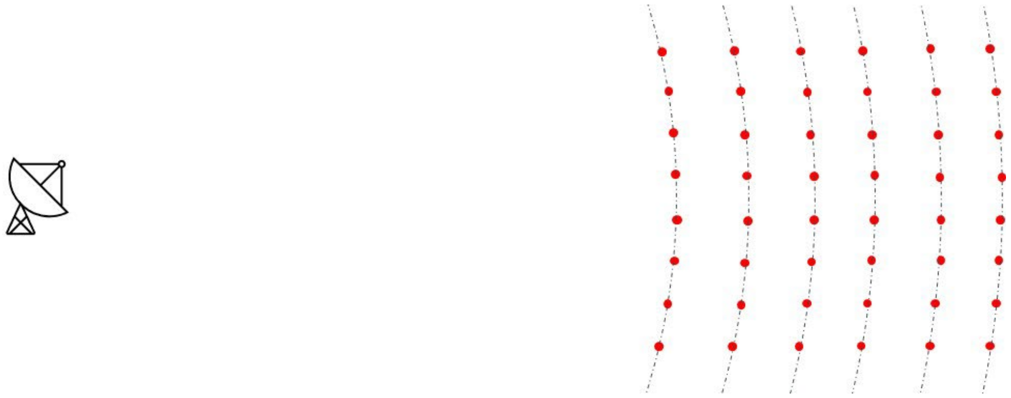


Figure 5-10 Tangential "bands" alignment of WTGs with range.

This could be a relatively helpful layout for one radar, but to mitigate for multiple radars would be significantly more complicated or even impossible. Also, this only helps a radar that has the capabilities of filtering the data appropriately. Further analysis may be required to understand the specific benefit of this technique provided to legacy radar systems, as well as any additional caveats (i.e. minimum range requirements between rings).

Also of note, the optimum distance between range rings may differ between different radar types and a wind farm may end up “optimised” to a single radar type at a single radar location/head. Overlapping radar fields of view, moving/ adding radar heads, or upgrading the radar may negate any potential benefit.

Practically, this alignment is likely to be difficult to achieve while still keeping the project feasible (primarily considerations with AEP, construction cost and SAR lane impacts). Pragmatically, and especially for projects that will be further out to sea, a standard grid layout with one axis aligned with the radar (i.e. the rows perpendicular to the radar LOS) should achieve most of the same benefit.

5.5.2 Radial alignment with radar LOS

This methodology assumes alignment of WTGs along radials, and separated radially by at least the beamwidth of the radar – in effect, lining up WTGs very accurately one behind another in radials out from the radar head, as shown in Figure 5-11. This method works well to reduce the RCS impact from the towers, but means that each of the WTG blades (the largest and most variable RCS of the WTG) in that column are providing additional clutter exactly along that radial line.

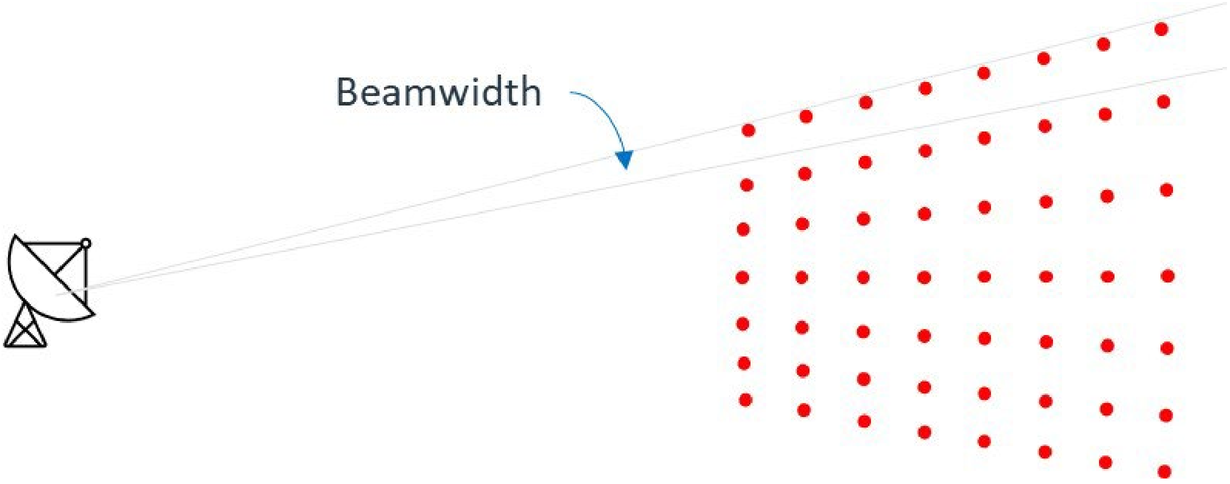


Figure 5-11 Example layout of WTGs arranged behind each other, at greater than beamwidth separation radially.

Arranging the WTGs at least one beamwidth apart (often approximately 1 degree – which equates to approximately 1 km spacing between WTGs at 60 km away from a radar with a 1-degree beamwidth) could allow identification of individual “lead” WTGs and helps to minimise RCS spread problems in legacy radars. However, as the beamwidth is an angle at the radar head, the beam will cover a larger distance the further away from the wind farm it is. This means that WTGs further away from the radar head would need to be spaced further apart than those that are closer.

For this method, there is limited data regarding the potential for significant shadowing with multiple WTGs exactly in a line from the radar. While there may be some benefit in reducing clutter from successive towers, the blades and nacelles will not be shadowed, and depending on the wind conditions may result in longer blind spots, false targets and poorer target detection and tracking along those radials. As such, it is possible that this compounding effect could cause other, possibly unconsidered problems for radar operation.

Practically, this radial layout may also be difficult to achieve, due to the high level of accuracy required in WTG placement to receive any potential benefit. On balance, it is not considered likely that benefits would outweigh the cost for adopting this technique.

5.5.3 Greater spacing between each WTG

As WTGs get larger, wind farms tend to space them further apart (in both axes) to minimise air flow interference between them and therefore maximise AEP. That can work to the benefit of the radar picture as it should allow the radar to discriminate between WTGs and effectively "see between" them.

This consideration is independent of alignment to a specific radar axis. As such, while it is expected that this could enable greater resolution of individual WTGs, it would still require significant improvements in filtering and processing capabilities from the radars to remove the clutter and isolate target tracks around the WTGs.

5.6 Floating Wind Farms

Floating offshore wind will make up an increasingly large component of deployed assets in the years out to 2050. Floating WTGs pose a clear dilemma for layout as a radar mitigation technique, as the majority of floating substructure designs proposed for UK waters currently rely on a slack mooring arrangement that will allow WTGs to move with the waves and tidal range. This means that for some FOW designs, the WTGs could move around in a circle of up to 30 m in diameter, effectively reducing the effectiveness of the radial alignment mitigation strategy, but having a relatively low impact on the range band or greater spacing strategies.

5.7 Practical Opportunities and Challenges for Mitigation by Wind Farm Layout

Over the course of this study, 30 interviews were conducted with stakeholders (Appendix 1) to gain their professional experience and opinion on whether and how a wind farm might mitigate the interference caused to aviation radar by adjusting its possible layout. During the course of discussions, it became clear that wind farm layout optimisation for aviation radar interference mitigation may have a role, but would not be a viable solution in isolation, and overall effectiveness would be site scenario dependant.

All proposed layout optimisations suffer from the same limitations: that they are all specific to the particular radar in operation, at the specific location, and only valid at the point of designing the wind farm. If radars are upgraded, replaced, relocated or additional radar heads added within the area, the wind farm layout mitigation could become ineffective or in the worst case, inadvertently cause greater levels of interference for the new scenario created by the change, while also potentially being detrimental to the wind farm AEP.

Additionally, none of the layouts discussed have a clear response to the challenge presented in areas where there are overlapping radar views. A layout optimisation to mitigate for one radar site may well exacerbate the interference caused to another radar system.

As discussed earlier, wind farm layouts are optimised for maximum AEP for the lowest cost, with respect to all the consenting and environmental constraints. Currently, wind farm layout considerations include seabed area as defined by the leasing agreement, seabed material, the effect a development may have on local wildlife populations, and other users including shipping lanes, fisheries, and access for SAR operations. What appears to be a minor adjustment to the location of a single WTG within a proposed wind farm could have a significant detrimental effect on the project's economic viability. The worst-case outcome may be that the project would be considered less financially viable, leading to a non-competitive CfD bid, which could mean that investment is not granted and the project would not progress. The impact of such a decision could mean that the UK struggles to meet its renewable energy targets and Net Zero obligations.

Operational wind farms and those under construction cannot now have their layout changed to mitigate for radar interference. It may be possible that layout can be altered in the future when considering repowering, however that will not help any current impacts. Layout mitigation will also have reduced effect in floating offshore wind farms, as each WTG will have the ability to move substantially within their mooring structure.

Regarding realistic layout consideration for radar mitigation, Figure 5-12 shows example trial data highlighting the benefits of aligning rows in range. Of note, this image shows multiple aggregated returns over an extended period of time, and doesn’t represent a single “sweep”. Additionally, the WTGs on the left image are much closer together than those on the right image. Therefore, understanding that these two images do not offer a direct “apples to apples” comparison of a single mitigation techniques, they do show how the azimuth return spread from the “off axis” WTGs means that any potentially useful gaps in range readings are lost as false alarms that spread in azimuth and any target plots will tend to blend with those false alarms and be lost. The right image shows that even though WTGs are not perfectly aligned in range, they are close enough to offer reasonable gaps for more effective tracking.

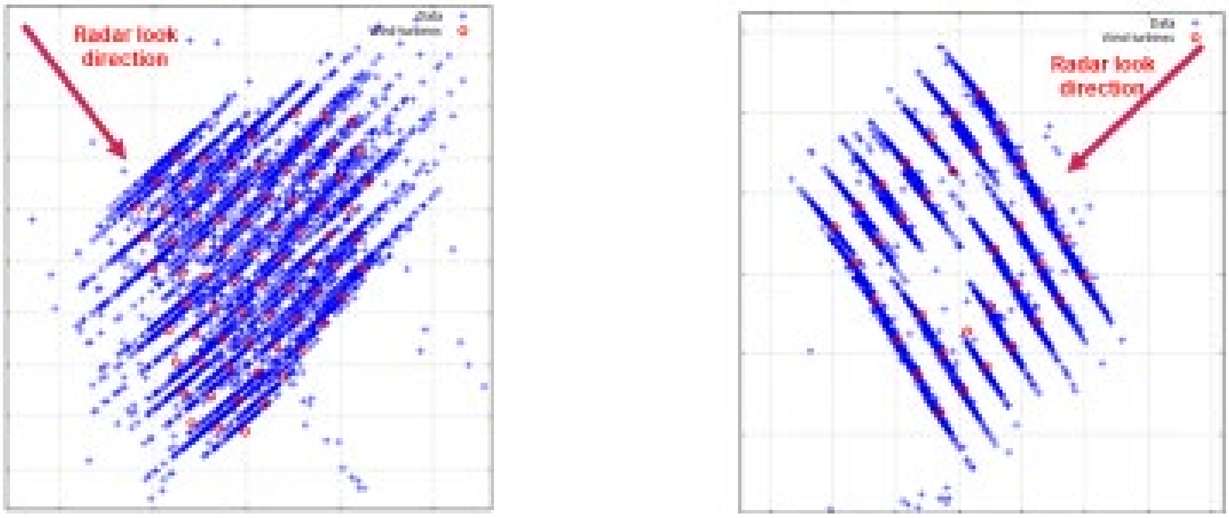


Figure 5-12 Trial data showing aggregated returns over two existing wind farm layouts [78].

Theoretically, the optimum “radar friendly” layout would be to have the WTGs aligned in range at a tangent to the primary mitigated radar (i.e. Range bands) with at least a beamwidth of distance in between each WTG. However, there are significant practical limitations to that approach.

While there may be some benefit to clutter reduction with specific layouts, investigation would be required on a project-by-project basis to assess the potential benefit of each layout methodology on the targeted radar operation, compared to the impact on that specific site wind farm AEP and capital costs. Additionally, maximum effect of any layout mitigations would need the corresponding increase in radar processing and filtering capabilities to remove individual WTG clutter, improve target detection and tracking and decrease false alarm rates.

Giving due consideration to continual improvements in latest generation radar systems processing and filtering capabilities, as well as the possibility of supplementing existing radar sites with infill radars, it is possible the only layout consideration required for an upgraded surveillance system may be simply increasing the spacing between each WTG.

Practically however, for most future wind farms, the “starting point” for pragmatic layout mitigation consideration could be a standard grid layout with increased spacing (while no definitive data, it is suggested ideally greater than 1 km) and one axis aligned with one radar – i.e. rows perpendicular to a single radar LOS. This should be considered but is obviously caveated assuming a manageable impact on overall project viability.

6 Stealth Mitigation

“Stealth” is the name commonly given to a set of technologies that have been able to achieve impressive results for military hardware in reducing radar returns. In recent years, there has been considerable interest in adapting aspects of this military proven technology for WTGs. Stealth aircraft and stealth WTGs share a common need for aerodynamism, which provides opportunities for technical read-across. It should be stated though, that in the case of WTGs, stealth mitigation would not provide full removal of the radar return, but rather focuses on the reduction of RCS by approximately 20 dB or more [6].

Stealth technologies reduce RCS by utilising one of two mechanisms: scattering or absorption. The former refers to deflecting RF signals away from the radar whilst the latter seeks to dissipate as much of the RF return signal as possible in an absorbent layer – thereby reducing the amount of reflected energy back to the radar signal receiver. Different WTGs will have different “untreated” RCS values, but they can have a reflection of up to 60 dB with the rotating blades causing flashes of up to 45 dB. As decibels are measured logarithmically, this means an optimal solution would be to reduce the reflected signal by at least 90% overall [79]. A range of studies have been conducted to determine the dominant component of a WTG’s RCS. Discounting Doppler effects, the predominant return is from the tower (75-80%), with the nacelle (5-15%) and blades (~5% each) following behind [80], [81]. Although it would be feasible to treat the tower and nacelle in a manner similar to other static structures such as buildings, the rotation of the blades causes a Doppler effect which creates large fluctuations in RCS [80].

The application of stealth technology would mean increased upfront costs for the design and production of the WTGs, and likely increased maintenance costs over the WTGs lifecycle. Some recent developments have shown promise, but they are not without drawbacks. So far, the only real-world deployment of stealth WTGs has shown an RCS reduction averaging 90% with a peak reduction of 99% which amounted to approximately 29.5 dBsm [82] , [83]. However, these results were limited to small WTGs in the 2-3 MW class with the techniques optimised to effect weather radar returns. Although stealth technology is scalable, there are significant concerns that stealth technology can only achieve so much with larger WTGs being developed, and that cost considerations are not yet fully understood [79]. Given that the trend in the renewables industry is for increasingly larger WTGs, there are questions about whether stealth will be a feasible solution for future developments.

6.1 Passive Stealth Techniques

Passive stealth is so named because once it is integrated into the target object, there will be an immediate RCS reduction without the need for any further actions. Consideration will be given to both traditional passive stealth techniques (shaping and RAM) and more novel techniques such as transparency, cloaking and metasurfaces.

6.1.1 Shaping

Shaping is one of the most common stealth techniques in use and is effective against most monostatic radars. It works via a scattering mechanism, with the target surface designed in such a way to ensure as little of the RF signal returns to the radar as possible.

There are two different approaches that can be taken towards shaping. The first is to adopt a smooth and blended geometry. This involves using shapes with a continuous curvature and can be seen in designs such as the Northrop B-2. The second approach is to adopt a faceted configuration where flat surfaces are angled in such a way to minimise both returning signals and glint. This can be seen in designs such as the Lockheed F-117A, shown in Figure 6-1 [84].

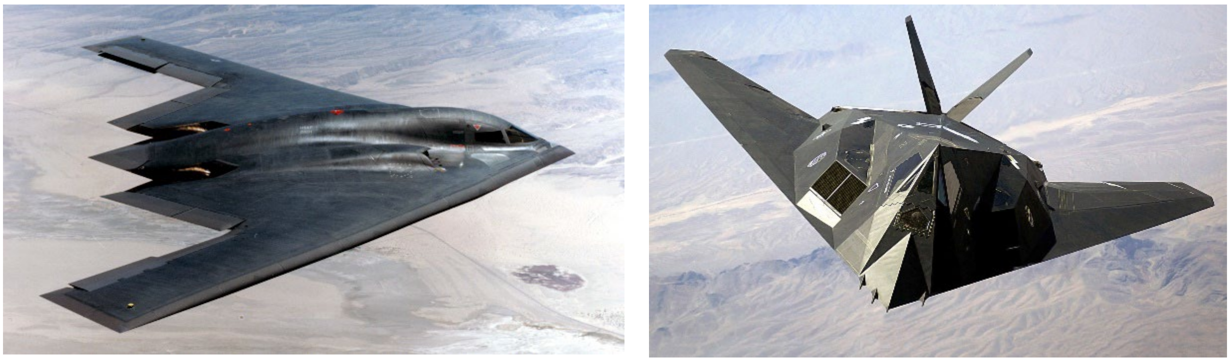


Figure 6-1 The Northrop B-2 (left) and Lockheed F-117A (right)

Shaping can become challenging when an asset is visible by multiple radar systems, as shaping to reduce the RCS on one system may result in the RCS being increased on another system. Modern military aircraft therefore utilise angular shaping and minimise the number of sharp right angles to ensure that they can successfully scatter RF signals from multiple sources simultaneously.

6.1.2 Radar-Absorbent Material (RAM)

RAMs are polymer-based materials which reduce the RCS of any given target surface. They work via the mechanism of absorbing RF signals leading to a reduction in reflected radar energy. However, RAM is not suited towards absorbing radar waves on every frequency at once. Instead, the composition and morphology of the RAM determines the frequencies that it is optimised for.

Originally intended for military purposes, there has been increased interest from the wind industry for use on WTGs. RAMs have been used on small numbers of RAF (Royal Air Force) operational aircraft since the 1970’s, but their use became commonplace from the 1990’s, due to the necessity of aircraft to have extremely low radar detection, driving the development of new RAMs.

Typically, they are applied to areas of high radar reflection, but they have also been adapted to cover the aircraft’s entire external skin. RAMs are typically used in combination with other stealth technologies, where they have successfully been able to *‘reduce the radar-cross section of a fighter aircraft to the size of a mid-sized bird’* [85]. Aircraft are subjected to many of the same external forces and hazards that a WTG would face (albeit, for much shorter durations and with a much higher inspection/ maintenance frequency). The RAMs used by stealth aircraft must therefore meet several specifications, including suitability for aerodynamic surfaces, resistance to erosion, and compatibility with a wide range of environmental conditions [86].

The most common polymer technologies used in aerospace are thermosets as they are stronger and stiffer compared to other polymers such as thermoplastics and elastomers. Furthermore, they are lightweight, ductile, and have environmentally durable characteristics. Nevertheless, the polymers used for RAMs can suffer from drawbacks including lacking overall strength, limited fatigue life, and low creep resistance [85]. Although such RAMs may be highly effective at the beginning of their lifespan, and potentially be embedded within composite blades, it is likely that in the constantly harsh, relatively low maintenance and exposed environment of offshore wind, they will deteriorate over time [18] – leading to potentially costly in-service support to maintain optimum RCS reduction.

The two major kinds of RAMs are broadband RAMs and resonant RAMs. Broadband RAMs are so named because they are particularly suitable for dealing with a wide range of frequencies. By using several layers of different materials, they can give the treated area a dielectric gradient which helps to dampen the strength of any reflected RF waves. They can also be designed with a lossy surface using dielectric, magnetic or ferritic materials.

One example of this is iron ball paint, which contains tiny spheres coated in ferrite or carbonyl iron which are suspended in an epoxy-based paint. A similar example is neoprene sheets containing ferrite or carbon black particles. When struck by a radar signal, as shown in Figure 6-2, molecular oscillation converts the electromagnetic radiation into heat which reduces the RCS. Both RAMs have seen successful application for stealth aircraft such as the Lockheed F-117 Nighthawk [85].

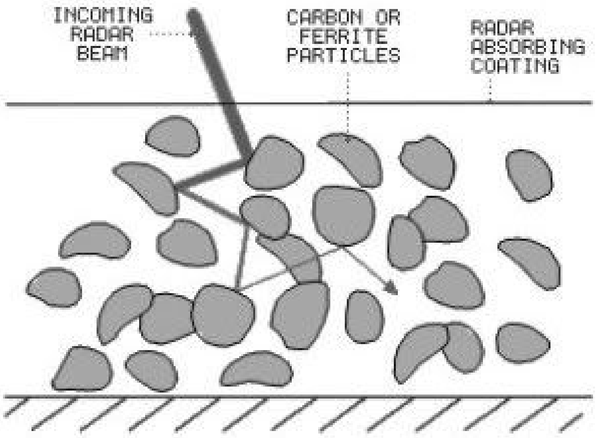


Figure 6-2 A demonstration of a radar beam being absorbed by RAM coating [87]

Resonant RAMs are best suited for a situation when the specific frequencies are already known. They work by using thin parallel materials separated by precise distances to produce an internal reflection of received signal. This allows them to capture and dampen the signals, hindering them from being reflected back from the outer surface.

Notable examples of resonant RAM include the Dallenbach layer technique and the Salisbury screen. The Dallenbach layer is a simple technique which uses a lossy layer placed in front of the target surface, with the thickness corresponding to a particular frequency. By contrast, the Salisbury screen consists of several thin layers of lossy material separated from the skin of the target surface by a lossless dielectric, with the number of layers ensuring that it can handle a wider range of frequencies, as shown in Figure 6-3 [84].

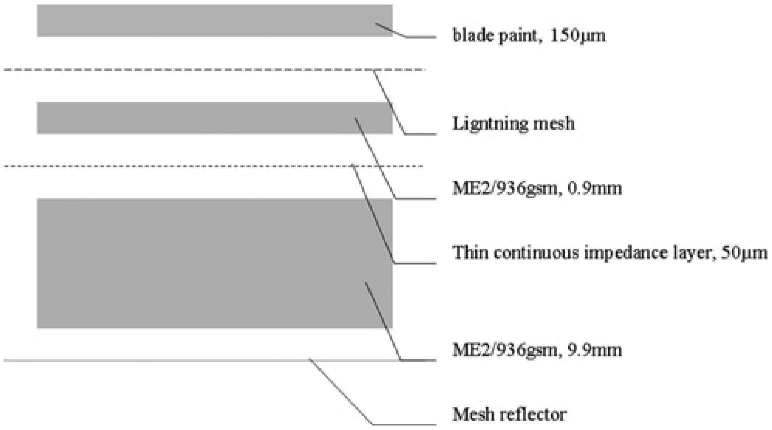


Figure 6-3: Salisbury Screen structural absorber [81]

The RAM's ability to absorb frequencies depends upon its composition, and presently no RAM can handle every possible frequency. This necessitates either the foreknowledge of what frequencies the affected radars are operating with or the further development of RAMs which can handle multiple radar channels. This poses an issue for future proofing as the MOD reserves the right to upgrade or replace any radars without any constraints. There can therefore be no guarantees that any given radar will continue to operate on the same bandwidth, which could risk RAM treatments becoming less effective [18]. Currently there are RAMs that can absorb two different radar bands (S-band with X-band, and L-band with X-band). Whilst it would be ideal to develop a RAM which can handle more than 2 bands, such a product may still be some years away [2].

6.1.3 Transparency

This is an older technique, dating from the 1940's, that could be revived to keep up with modern material advances. A material is considered transparent when its impedance matches that of free space. This can be achieved by adding fillers with different refractive indexes, which leads to the scattering and absorption of light particles. This helps to ensure that the overall refractive index of the composite is as close to one as possible. A notable historical example of transparency is the De Havilland Mosquito, which was a plane constructed from wood and canvas during WW2. Although its design was motivated by economic considerations, this reduced its RCS which gave it an advantage in the field.

Modern day transparency can be deliberately achieved by using composites with a low density (such as glass-reinforced polymer (GRP), honeycomb or structural foam). Composites are already beneficial as they are low weight yet possess high strength and fatigue resistance. However, their design is also well-suited for maximising their RF transparency. Several different materials can be utilised for stealth purposes in these composites, the majority of academic literature investigating their development focuses upon the use of RAMs as a filler material. These can range from graphene, ferrites, magnetic material-coated conductors, carbon black and more.

A Frequency Selective Surface (FSS) is also capable of reducing the RCS of a target surface by providing transparency. They are commonly used on the radomes of stealth aircraft, which protects their own radar antenna. This allows stealth aircraft to transmit and receive radar signals without compromising their own position. The FSS achieves this by using geometric patterns to produce either a band-pass or band-stop filter. This allows the antenna to operate at the specific frequency used by the aircraft's radar whilst reducing its RCS for all other frequencies [88].

6.1.4 Passive Cloaking

The first true cloaking devices were released in 2006 [89]. Initially there were very limited applications of cloaking technology due to it only working for very narrowband applications and the cloaking material being far too thick to be practical. Further research is being conducted with the aim to make cloaks thinner and able to conform to practical shapes. This is likely to be achieved through advances in alternate techniques, such as scattering cancellation, and design [6].

Cloaking brings together two techniques: 'negative' refractive index materials and Transformation Optics. Waves are guided by the cloak around an object and then emerge unperturbed on the other side, thus not reflecting the signal back to the radar.

6.1.5 Metasurfaces

Metasurfaces are the newest passive stealth techniques of those mentioned in this report. They are the 2D equivalent of metamaterials, which refer to engineered materials designed to have superior properties to any naturally occurring substances through the specific design and manipulation of the structure at nano scale. This technique was first introduced in 2012 and has since gained particular attention as a stealth technology owing to their ability to overcome several key weaknesses faced by RAMs. This ranges from the relative simplicity of fabricating metasurfaces compared to other techniques, their ultrathin and lightweight properties, and their ability to cover a large number of bandwidths [6]. Research has grown significantly in this area, as shown in Figure 6-4.

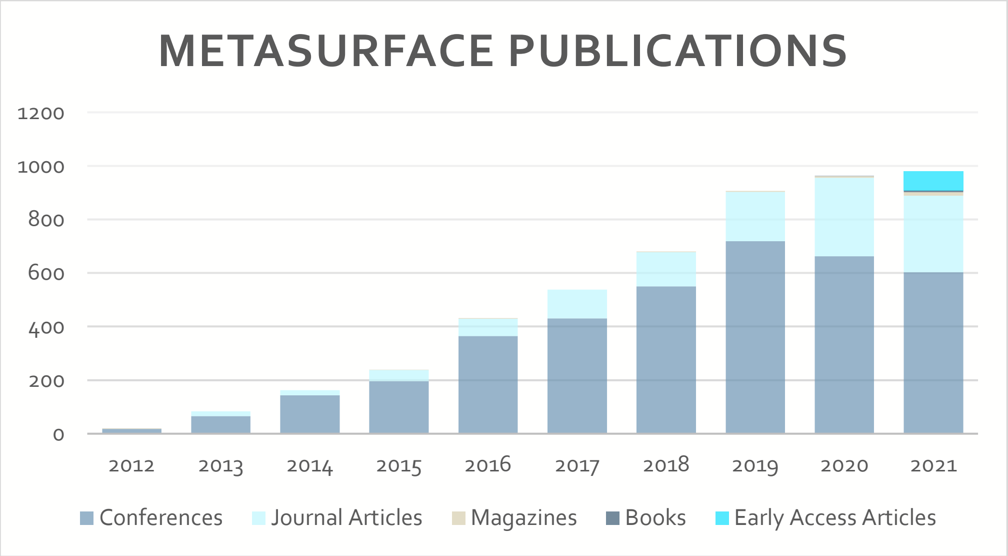


Figure 6-4: Chart showing the growth of metasurface publications from IEEE

Metamaterials are comprised of plastics or metals, otherwise known as unit cells, which are assembled in a periodically arranged surface pattern designed to vary the reflection magnitudes and phases of the RF signal. It achieves this through scaling the patterns, to be smaller than the RF waves which they meet. This controlled signal scattering enables surfaces to reflect at angles independent of the physical shape, as shown in Figure 6-5. This can help guarantee RCS reduction whilst retaining aerodynamism.

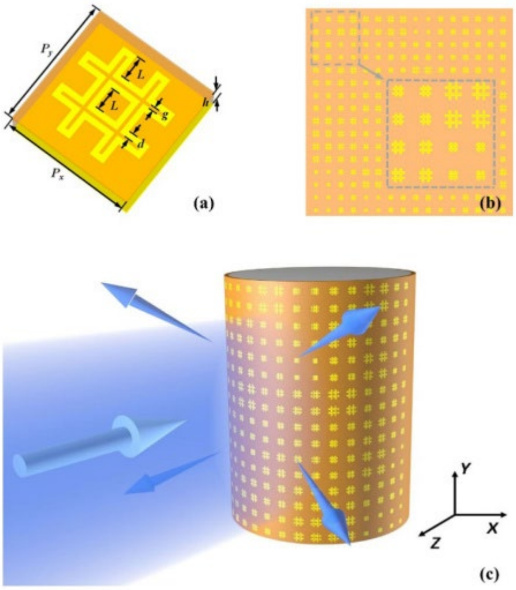


Figure 6-5 Example showing (a) scatter element, (b) layout of the metasurface, and (c) coating of the metasurface on a metallic cylinder [90]

3D metamaterials have been held back from widespread use owing to challenges in both design and fabrication. The traditional method of lithographically patterned metallic structures is not ideal for large-scale use and would therefore be unsuited for WTGs. However, metasurfaces have become the most promising example of metamaterials because of their simpler fabrication process. For example, one proposal focused the random absorption of chemically synthesised silver nanocubes onto a nanoscale thick polymer spacer layer on a gold film. This metasurface could then be easily tailored by adjusting the cube size or spacer thickness [91].

Owing to their electromagnetic capabilities, research on metasurfaces has consistently demonstrated their potential in reducing the RCS of a given target area. Table 6-1 summarises several notable papers over the last decade which have shown strong results at reducing the RCS over a broadband.

Table 6-1: A summary of metasurfaces with demonstrated RCS reduction [92]

Reference	Configuration of unit cell	Total thickness (mm)	Frequency range with 10dB RCSR (GHz)
Ghosh et al. (2015)	Split ring	2	7.8-12.2
Zhao et al. (2014)	CSRR	2	7.3-10.4
Su et al. (2016)	Spit ring and cut wire	3	7.9-31
Wang et al. (2014)	Wind mill	4	7-13
Galarregui et al. (2013)	Jerusalem cross	1.27	14.5-21.8
Esmaeli et al. (2016)	Saltire arrow and E-patch	2.28	9.4-23.2
Lu et al. (2019)	Arrow and square cut patch	3	7.5-22.5
Li et al. (2014)	Split ring	2.5	7.8-17
Fang et al. (2019)	Split ring	3	8.6-17.7
Song et al. (2016)	Disc with concentric ring	3	7-12
Zhao et al. (2016)	'#' shaped ring with square ring	4	7.6-12.1

Although the research has shown promising results, it should be noted that practical application as a real-world stealth technology has yet to be seen. Despite the theoretical potential of metasurfaces as stealth technology, this technology is fairly new and has a low TRL, which would necessitate further development for commercial use. Any application of metasurfaces as a stealth technique is therefore unlikely to be a solution realised in the short-term. Nevertheless, it represents an incredibly rich ground of future research which could be realised in the longer term.

6.2 Active Cancellation Stealth Techniques

The concept of active cancellation stealth dates from the 1960’s, but it has only recently been the focus on modern stealth technology developments [93]. Compared to passive techniques, active cancellation stealth is a smart and adaptive technique which makes use of electronic countermeasures to cancel out the radar return. It achieves this through the principle of producing an out-of-phase return signal which matches the amplitude and frequency of the incoming radar signal. This would suppress the real echo of the target to the radar, leading to a greatly reduced RCS.

The advantages of active stealth techniques are that there is no need to either shape or treat the WTG with RAM, which minimises any performance or manufacturing issues. Furthermore, it can be adjusted according to the parameters of any given RF signal and is suited for working against a plurality of wavebands [94].

There is limited available information on active stealth techniques which are presently developed due to the information being classified [6]. However, it is known that there are two primary options available: active surfaces and active cloaking.

6.2.1 Active Surfaces

Active surfaces work by modulating the external surface’s RCS, which allows it to dynamically react to incoming target signals. One of the methods of achieving this is through a phase-modulated surface. By using binary phase modulation, they are capable of shifting the signal’s returns into the sidebands which lie outside the bandwidth utilised by the radar.

By replacing the surface’s resistive layer with a switchable impedance layer, the target surface will be capable of switching between very high and very low resistance states. This allows it to use phase modulation like the Doppler effect, which successfully scatters the incoming signal and diminishes the surface’s RCS [95].

At present, it is not likely to be practical for modern WTGs owing to their scale.

6.2.2 Active Cloaking

Active cloaking technology is currently at a low TRL, however, if development continues the long-term results appear promising. This technology used transformational mathematics – like those employed in passives cloaks – to synthesise a local wavefront. This local wavefront will then combine with the incident signal to guide it around the object or effectively cancel it out.

Active cloaking does not require any material coatings or absorbers but does require an array of antennas, located on the object that is being cloaked, and a sophisticated control system. This illustrated in Figure 6-6 below.

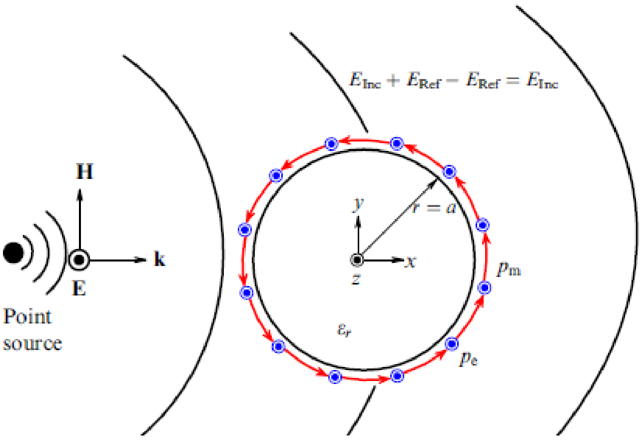


Figure 6-6: Active cloaking of the central cylinder by the blue emitters [6]

The antennas used have low power requirements and are typically lighter than some absorbers. Number and location of these antennas needs careful consideration though lower frequencies require fewer antennas.

Even though air platforms have been considering active cloaking technology for the last 20 years, to date no system has been deployed. This is due to intrinsic complexities such as the complex control of waveforms needed. As such, it is not likely that this technique will be utilised in WTGs in the near to medium term.

6.3 Wind Turbine Stealthing

While there is broad interest in the option sets around WTG stealth, there is no significant detail or open-source data on exactly what the overall costs or benefits of employing this technology would be as a part of a radar mitigation strategy. The underlying goal of all stealth technology is to maximise the overall RCS reduction and bandwidth over both the operating frequencies and angles of incidences, whilst minimising thickness, mass, cost, and changes to the manufacturing process [80]. To date, the limited number of demonstrated solutions have utilised a mixture of shaping and RAMs to deliver a substantial RCS reduction. Shaping would generally be considered the preference for the tower (structure permitting) and nacelle whereas internal RAMs would likely be the preferred approach for the blades [78] [6]. As stated previously, existing stealth technologies that could be fitted to WTGs will only ever reduce the RCS, they will not remove it completely, and as WTGs increase in size, so too does their RCS.

Not all the stealth techniques discussed in the previous section can be applied to WTGs. Primary consideration is given to techniques which are most developed and have been demonstrated in trials or advanced simulation. Other techniques are mentioned as they are in their infancy, however with regards to application on WTGs, it is unclear how significant their future role in stealth could be and no information is available on expected costs. Additionally, the trials completed so far have been predominantly land based, optimised for a particular radar system and there is little, if any, available information with regards to scaling up to 15 – 20 MW WTG or full offshore wind farm applications.

Although providers of stealth technologies continually strive to minimise any changes to the manufacturing process, an increase in cost for new designs, material and manufacturing is still expected to be significant. As limited trials have been conducted there has been little detail published on the specific cost to modify offshore WTGs to implement shaping or RAMS. Additionally, the amount of lead time before such WTGs could be fielded commercially is also significant - with design, testing and certification processes likely leading to many years of development and trials ahead of large-scale manufacture and deployment. There will also be increased O&M (Operation and Maintenance) costs to maintain stealth treatments in a continuously operating and harsh environment. ORE Catapult has no definitive detail on these cost increases, and can only make assumptions based on previous analysis by QinetiQ. [83]

Work conducted for a 2007 report by BAE Systems outlined the key requirements for signature reduction through stealth technology. These specifications were originally based upon a Vestas V82 WTG, a smaller WTG (1.5 – 1.65MW) compared to modern WTGs now reaching as much as 15MW. Table 6-2 details these specifications, with adjustments for modern WTGs where known [96].

Table 6-2 Key requirements for reduced RCS WTG systems

Property	Requirement
Electromagnetic	
Operating Frequency Range	2.7 – 3.1 GHz and 9.1 – 9.41 GHz
Radar Cross Section Reduction	20dBsm in total
Lightning Strike Protection	Compliant with IEC 62305 1-5 2011
Physical/Mechanical	
Mass Increase	Minimised
Manufacturing	Maintain existing methods / processes
Environmental	
Temperature Operating Range	-40°C to +60°C
Exposure Resistance	UV
Other	
Cost	<10% increase in total manufacturing costs
Service Life	>30 years
Security Classification	Unclassified

Although it may be possible to extrapolate these requirements onto other WTGs, it should be noted that these were intended for a small land-based WTG intended for trial purposes. There are concerns over how well stealth technology may scale for larger WTGs, such as those common in offshore wind farms. Stealth can bring sub-megawatt WTGs below the radar detection threshold, but their effectiveness is outstripped as the WTG scales in size. Nevertheless, it is of course possible to apply stealth technologies to larger WTGs in order to reduce their RCS, if that is borne out to be necessary as part of the overall mitigation strategy. [97].

The RCS of each offshore WTG can be very large, however there does not appear to be any publicly available specific data to differentiate between the different component effects, such as the difference between the tower or nacelle or stationary blades versus rotating blades. With no data for direct comparison, anecdotal feedback from some radar operators is that the picture is significantly improved when there is no wind and blades are not turning. This suggests that towers, nacelles and static blades have less of an impact on the radar image than the motion of the rotor, due to the doppler effect of the rotating blades.

Stealth applications prove challenging as WTGs are becoming larger and the swept area for the blades is ever increasing. Additionally, their RCSs are variable by nature, due to the continuous rotation with varying speed and pitch of the blades, coupled with the changing orientations as the WTG turns to face the prevalent wind direction and blade aeroelasticity during operation.

There are additional considerations outside the wind farm control when applying stealth technology to WTGs. Any solution must be fit to work alongside the affected radars, which can be further complicated as the MOD reserves the right to upgrade radars without constraint. This can lead to a change in radar frequencies, meaning the ability to cover two or more bands is therefore essential [18].

For the above reasons, previous work conducted in the field points towards stealth technology as potentially playing only one part of a holistic solution. While providers of stealth technology are keen to emphasise that their solutions work under a “fit-and-forget” principle where stealth can provide an immediate and noticeable RCS reduction [98], stealth alone is not valid as a full coverage mitigation strategy, even with maximum effort to manufacture and maintain the stealth technology.

There is also suggestion from radar OEMs that stealth WTGs may be unnecessary in light of evolving data processing techniques, and that in a worst-case scenario they may even diminish the effectiveness of any radar filters [99]. The following sections will therefore discuss what stealth techniques could be used as part of a mitigation solution.

6.3.1 Blade Stealthing

Many of the techniques mentioned above are proven in use for military hardware and can be theoretically utilised for stealthing WTG blades. However, this may prove more challenging in practice. Shaping would not be possible for blades as they are already designed to meet stringent aerodynamic specifications. Instead, other techniques such as transparency and RAMs must be considered.

As the primary material of current blades is GRP this would suggest that transparency techniques could be promising, especially for lower frequencies such as VHF (Very High Frequency) (30 – 300MHz), UHF (Ultra High Frequency) (300MHz – 3GHz) and L-Band (1 – 2GHz). To increase the transparency of the GRP blades the manufacturing process would need to be adapted to bring the refractive index closer to one and an investigation into the impact of structural strength should be completed.

Blades contain more reflective materials such as the metallic components of the lightning protection system (LPS), therefore transparency alone will not be capable of fully stealthing a blade. A key challenge faced when stealthing the blades would be the degradation of the LPS as RAM solutions can also make use of thin metallic layers such as a Salisbury screen absorber as well as ferromagnetic coatings. These could greatly reduce the LPS efficacy, efficiency and necessitate greater O&M costs [100].

A suggested solution to resisting lightning strikes involves coating only certain parts of the blade, as shown in Figure 6-7. A study by researchers from the University of Manchester concluded that a partially coated blade would still be able to reduce its RCS by up to 15dB whilst retaining lightning protection. It was also suggested that RAM with wide angular properties or a strip of RAM along the leading edge of the blade may be able to make further reductions in RCS without necessarily compromising the WTGs' LPS [101]. Another study concluded, after completing some modelling, that there was no significant reduction in a WTG's RCS by using only nonconducting materials in the blade [102]. However, further research may be required to ensure that any proposed RAM coatings that contain metallic particles will not act as a lightning conductor, reducing the efficacy of the LPS and posing a risk of lightning striking the coating and damaging the blades.

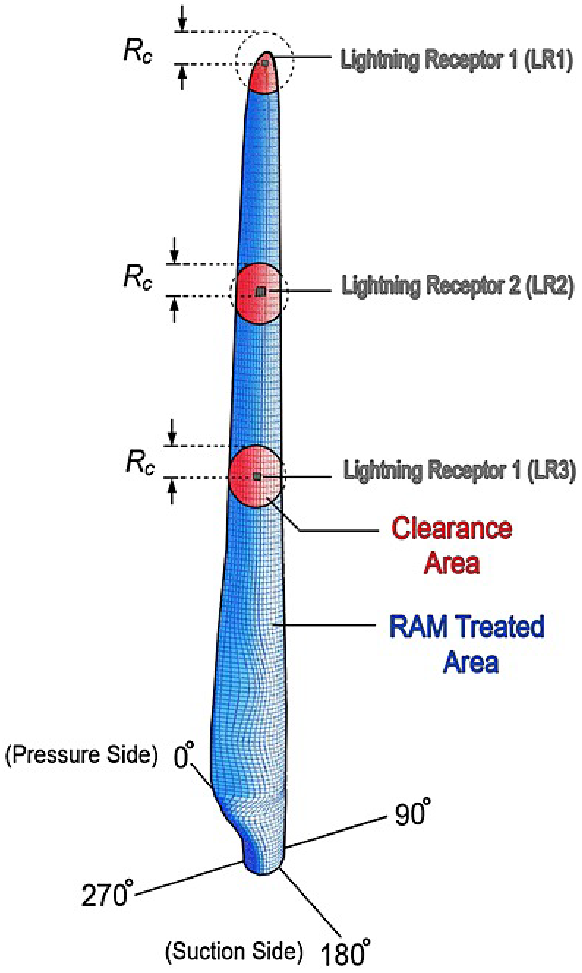


Figure 6-7: A partially coated stealth blade, with untreated areas surrounding the LPS [101]

Another difficulty of applying RAM to the blade is their mass. Blades are designed to be lightweight and aerodynamic for maximum rotational speed. When Vestas investigated using RAM methods such as coating the blades with iron ball paint, they discovered it could increase the blade weight by up to 1.2 metric tonnes – which represented a 3% increase.

Furthermore, outer coatings may be less effective due to change in areo-foil shape and wear over time. A key challenge for applying RAMs to WTGs is the effect of weather erosion to surface coatings on the blades. Although RAMs used for aerospace purposes must meet specifications to cope with similar environmental pressures, WTGs face additional hazards from longer operational periods with fewer inspections and interventions. Blade leading edge erosion is a well understood challenge for the industry and there is a question of the possible impact it could have on the efficacy of RAMs as the outer layers are gradually worn away over time. Also, no research has been identified that considers any potential effects if a build-up of dust or salt residue from the sea forms on the surface of the blade.

The low fatigue lifespan of polymers used within RAMs are also a cause for concern, as this could add an increased requirement for blade inspections and reapplication of surface RAMs. This could significantly increase operational costs and WTG downtime throughout the lifetime of the WTG, resulting in further revenue loss for the developers on top of the costs of applying stealth technology. Offshore wind farms in particular already face a greater cost barrier to overcome, and substantial increases to O&M costs and shutdown times would run the risk of making new wind farm development an unprofitable venture altogether.

The most successful efforts to apply RAM to blade designs incorporates treatments into the structure. A test WTG demonstrated by QinetiQ had stealth blades which made use of fabric interlayers within the laminates ordinarily produced during the blade manufacturing process. By using composite materials and impedance matching, the blade could also remain much thinner compared to traditional RAM methods such as the Salisbury screen. Such a solution shows that it is possible to deliver RCS reductions without any significant changes to the manufacturing process or properties of the blade [98].

Similar research from the Sandia National Laboratories estimated that two thin layers of RAM could be integrated into the blade using a vacuum-assisted resin-transfer moulding process for approximately 10% extra cost per blade, or around 1 – 2% per WTG. One of their key methods involved the replacement of two existing layers within the blade with glass-reinforced epoxy and plastic foam. These RAM layers were then able to capture and absorb incoming RF waves, reducing the overall RCS of the blades [103]. Their treatment appears to not only be economical but successful, reducing the blade’s RCS by roughly 20dB. Nevertheless, it should be stressed that a full blade and rotor plan never proceeded, giving their solution an approximate TRL 3 [104]. It is still necessary for new materials to undergo a detailed analysis of strength, fatigue life, and resultant manufacturing cost to determine ultimate feasibility. The balance of cost verses benefit to radar mitigation verses impact to wind farm AEP needs to be discussed between the affected parties: OEMs, wind farm operators, MOD, Radar operators, DSTL, CAA etc.

Another recent solution is the result of a partnership between Loughborough University and Trelleborg. The Full Radar Absorbing Materials and Equipment (FRAME™) is one of the technologies currently taking part in the DASA competition. It uses fillers incorporated into a polyurethane matrix, which is a durable material which already sees use in leading edge erosion for WTG blades and has a lifespan of 20-25 years [79]. The technology is claimed to deliver a lightweight nano-composite solution which keeps both costs and thickness to a minimum. The material is tuned at a range of 1-12GHz which makes it multi-band, and it is claimed to absorb up to 99% of radar waves [105], [106]. Although Trelleborg has yet to apply FRAME™ to any active wind farms, they have performed well in WTG trials, and it is expected to take approximately 2 years to develop a product for commercial use. Although this would solve several flaws with existing stealth applications, it has an approximate TRL of 6 [2].

The most notable example of real-world stealth technology is a collaboration effort between QinetiQ, EDF Energies Nouvelles and Vestas which resulted in the world's only active stealth wind farm. They made use of an innovative material that applied stealth techniques to WTGs without any structural changes. The solution claimed to reach an average RCS reduction of 90%, with up to 99% in ideal scenarios. This paved the way for the world first installation of the Ensemble Eolien Catalan wind farm in 2016, where thirty-five onshore WTGs coexist alongside the Opoul weather radar [82]. Lightweight RAMs were applied to an existent WTG design, which meant that there were minimal changes required to the manufacturing process. These RAMs made no changes to the external surface materials or shape, which minimised any risk of long-term performance degradation. Neither rain nor frost has been found to have detrimental effects, although ice is known to de-tune the performance of the stealth design. Although this is the most successful real-world example of stealth technology in action, it should be stressed that the wind farm was specifically tuned to be effective for weather radar. Performance against aviation radar is not known [83].

The theory of using a passive cloak on blades has been considered and significant limitations have been found [6]. It was found that the cloak applied on blades was only optimised for perpendicular incident wavefronts. It is highly unlikely that waves would interact with blades only within this specific condition as it would require the WTG to be directly facing the radar and for no discernible twist or curve to the blade profile. In practice a WTG will be optimising the direction it faces depending on the wind direction and modern-day blades typically have a twist in the blade profile. Although it is likely that application for WTGs is limited, it should be emphasised that this technology is in the early stage of testing. Further study will be required to determine which scenarios it may fit or whether it can be ruled out as a useful stealth treatment.

Active cloaking technology could be placed inside the blades. This technology has a low power requirement, though this is higher than passive techniques which have no power requirements. The location of antennas and the control system would require careful consideration. Though active cloaking techniques have been implemented in air platform technologies, which can have similar geometries to blades, the scale required for blades is significantly larger. Therefore, significant effort would be required to implement active cloaking technology on future WTGs.

6.3.2 Nacelle and Tower Stealthing

Research collected by the Sandia National Laboratories have indicated that discounting the Doppler effect, the towers and nacelles are responsible for up to 80% and 15% of RF radar returns respectively. At the same time, it should be considered that this is likely a secondary consideration as radar processing is more adept at filtering out static man-made structures [80]. Nevertheless, it is common for stealth treatments to make changes to both the tower and the nacelle for the purposes of maximum

RCS reduction. There are a number of substantial improvements that can be made to the tower and nacelle to help further reduce the overall RCS of the WTG.

Shaping is the stealth technique best suited for towers and nacelles. As nacelles are designed to cover and protect critical WTG components, they do not have the same aerodynamic concerns that the WTG blades do. A notable example is BAE Systems work with commercial companies to design a reshaping for a Vestas V82 nacelle, shown in Figure 6-8. They removed the typical large vertical slab sides in favour of sloping sides with an 8° angle to the nacelle sides, as well as adding foil lining on the inside to minimise any internal scattering. Altogether, modelling indicated that treating the nacelle in such a fashion achieved peak reductions of 30 dBsm [81].

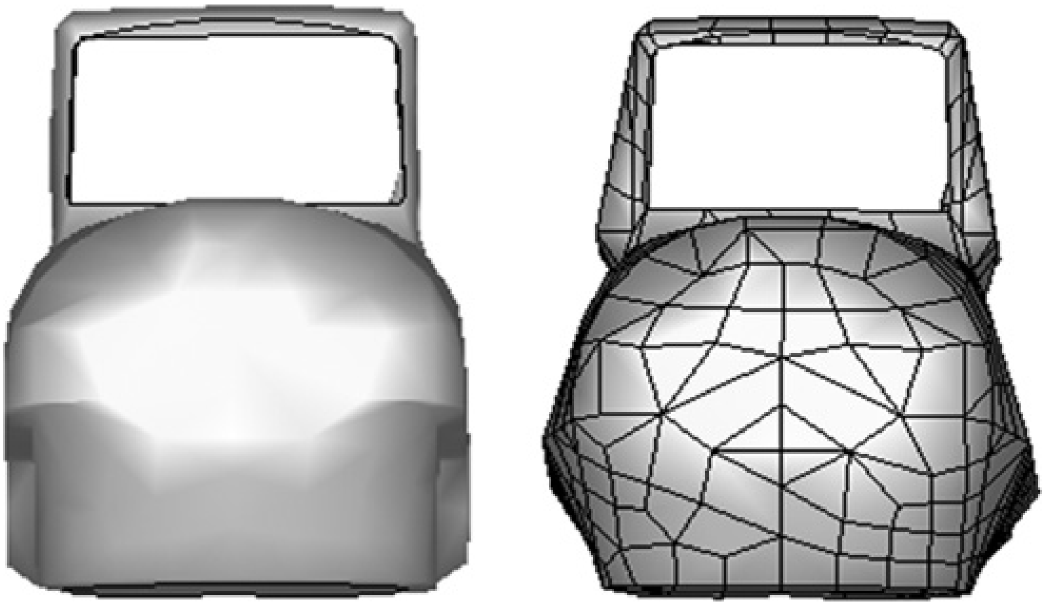


Figure 6-8: Original (left) and shaped (right) nacelle [81]

Unfortunately, despite the relatively simple redesign, this design was never tested on a real WTG owing to commercial reasons and therefore there is no real-world data on its effectiveness [6]. As nacelles rotate shaping may work better in some orientations than others, a combination of shaping with RAM may provide more consistent results.

When it comes to towers, shaping alone could be enough to reduce the RCS sufficiently. Assuming that the tower redesign is structurally feasible, introducing a more slender, elliptical profile or a polygonal shape can reduce a tower's RCS considerably. In the case of BAE's work on the Vestas V82, the replacement of its cylinder and truncated cone with a single conical structure could theoretically reach an approximate RCS reduction of just over 40 dBsm. Such a reduction meant that the blades would become the dominant cause of signal scattering in most conditions.

However, such a high level of reduction would not be practical in a real-world scenario. Although the tower can be shaped to the centre frequency for any given band, the variation within the frequency means that it is unlikely for the whole benefit to be realised. Further factors such as the curvature of the earth and the height of the radar must also be considered. Instead, Figure 6-9 illustrates a realistic reduction of approximately 30 dBsm, which is considered feasible for real-world use through simple shaping methods [81].

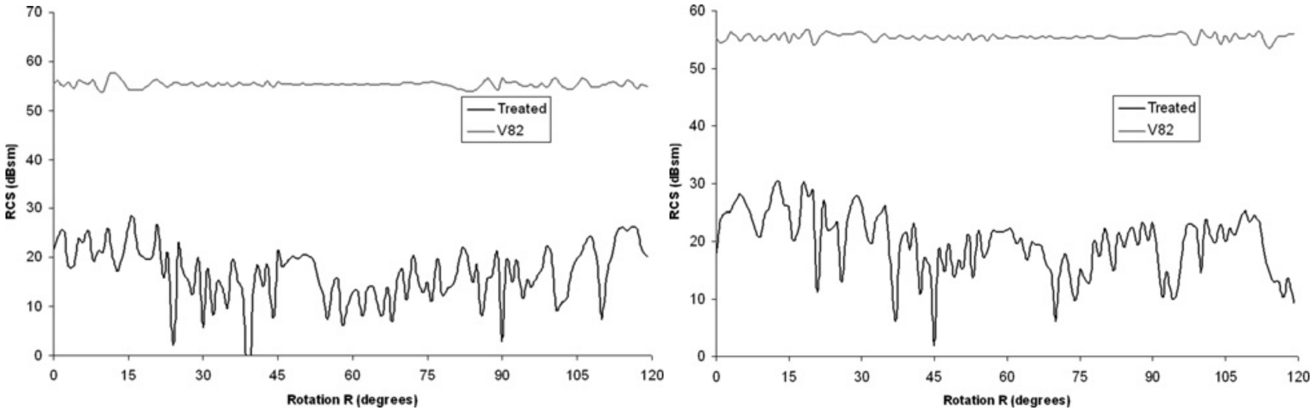


Figure 6-9 Total RCS of the V82 and the shaped tower at 90° yaw (left) and 0° yaw (right) [96]

Theoretical solutions may also be able to provide significant RCS reductions in the future. An omnidirectional cylindrical passive cloak could be applied to the tower of a WTG; however, this is currently impractical as the cloak material thickness required would result in the structure being too large and heavy [6]. It is expected that the weight will reduce as the technology continues to develop. Metasurfaces could also be applied to tower and nacelle structures, though they are currently limited by the technology's low TRL. Scaling up of the technology application is required before use on a full WTG scale. Research has shown metasurfaces would achieve an effect equivalent to shaping, with the additional benefits of being ultra-thin and lightweight [6].

Partial RAM treatments have also seen use for towers and the nacelles. It would be unfeasible to treat the entire surface area, but RCS reduction can still be achieved by selectively coating specific target areas. One demonstration was shown by Vestas and QinetiQ during a 2011 test with an experimental WTG situated in Norfolk, where they utilised an experimental stealth rotor. Both the tower and the nacelle were coated in a 5mm layer of RAM. The substrate made use of the principles behind iron ball paint to absorb the RF, whilst the thickness ensured destructive interference. An overall reduction of over 20 dBsm was achieved, although it should be noted this was in combination with blade stealthing too [103].

Although RAM can be applied to the nacelle and the tower with good results, it will be far costlier to cover the entire WTG due to the large surface areas involved. Whereas RAMs have been most effective for the blades, shaping has theoretically been proven to have better results for reducing the RCS of both the nacelle and the tower. Due to cost/benefit considerations, shaping should be the main stealth technique used for the nacelle and WTG with a partial RAM treatment as a secondary technique. In future, it may be possible to rely solely upon shaping modifications and forgo RAM treatments altogether for the nacelle and tower [96].

As towers become taller and of greater diameter, they become harder to stealth. Careful consideration would be required if the WTG is visible by multiple radar systems as reducing the RCS in one direction may increase in another. This implies that towers may need to be shaped for specific locations which adds complexity to both the design of the wind farm and the tower structure. Furthermore, elliptical towers are significantly more challenging to manufacture than a cylinder, which would add additional time, cost and complexity to the manufacturing and installation process. There also remains the question of how necessary it is to stealth the tower and nacelle. As previously mentioned, radars are already equipped to filter out static structures such as buildings [80]. Further research may be necessary to determine how well radars can cope with specifically filtering out the tower and nacelle, and what level of RCS reduction is necessary for optimal results.

6.4 Stealth Conclusion

No combination of stealth techniques has the capability to fully remove a WTG from the radar picture, however it is possible for them to make substantial reductions to a WTG's RCS. Using currently available technology, RAM and shaping could be implemented to reduce a WTG's overall RCS. The exact numbers will differ according to the precise technique, but a range of 20-30 dBsm should be considered realistic. This has been verified through both demonstration WTGs as well as the active stealth WTGs at Ensemble Eolien Catalan wind farm. As new technology develops other options such as passive cloaking and metasurfaces may become capable of delivering substantial RCS reductions.

However, there are several obstacles for stealth technology. Stealth technology is generally very difficult and expensive to retro-fit, therefore realistically, they can only be applied to new wind farms, which means that any existing wind farms will have to seek other solutions in order to provide an improvement on air picture. Every solution will also involve significant increased costs to the wind farm developer (in both Capex and Opex), which may affect their willingness to invest in new sites. There are also questions of how these costs will scale as the WTGs increase in size over the coming decades. There is therefore a necessity to determine the optimal cost/benefit – which may vary from site to site (depending on the WTGs utilised, the radar horizon at that range, the fields-of-view of overlapping radars, etc).

Providers of stealth technology have claimed to be able to reduce up to 99% of the RCS of a WTG. While this is an impressive number, these numbers may not be applicable to all radar. For example, while the Ensemble Eolien Catalan wind farm boasts such results, the site is measured against weather radar rather than aviation radar. It is also notable that such a reduction would not necessarily meet the requirements put forward by the MOD. Even these fully-stealthed WTGs exceed an RCS of 1m^2 and would therefore still be detected by and potentially cause interference concerns for aviation radars [18].

Furthermore, current stealth technology is also constrained by other factors such as single-band absorption, narrow absorption bandwidths, and an inability to provide high strength absorption for larger WTGs [107]. Solutions which are expected to provide wider coverage are still under active development and are not presently available for commercial use. Unless these technologies - alongside other theoretical technologies such as cloaking and metasurfaces - can improve upon these factors, stealth alone cannot presently meet aviation requirements.

As a single approach, stealth is therefore unable to provide complete wind farm mitigation for radars. While stealth technology on WTGs could potentially form part of a holistic solution, the goal of stealth technology in offshore wind can only be to complement radar solutions to create an improved air picture [83]. However, as modern radar developments trend towards capturing as much information as possible before discriminating against unwanted targets through the use of AI, there is a risk that hiding wind farms through stealth may be counterproductive. Interviews with radar OEMs have provided anecdotal statements raising concerns that deliberately reducing the WTG RCS may make new processing techniques perform less well. Furthermore, it will become more difficult for data processing to fully eliminate what remains of the stealthed WTGs from radar returns, which could potentially lead to more clutter than if the WTGs were left untreated [108], [99]. As there is no hard data which allays these concerns one way or another, this is a blind spot which should be prioritised in future studies regarding stealth technology.

Despite the drawbacks, there are still promising avenues for research. Further studies need to determine what the optimal ratio of stealth treatment is in order to best complement current and near future radar processing technology. It also needs to be established to what extent components such as the tower and nacelle benefit from an RCS reduction compared to the blades. More detailed analysis on the strength and durability of stealth treatments in offshore wind usage scenarios is required to understand the real lifecycle costs.

Although it may be difficult to convince wind turbine manufacturers that the present benefits of stealth mitigation are worth the cost, this may change in the future as new research angles are explored and new technologies become readily available.

7 Data and Information Mitigation

This section will discuss how data-driven solutions could provide mitigation techniques. It will cover what signal and data processing solutions exist, as well as the application of machine learning techniques to radar surveillance. This section will also cover techniques that make use of the radars themselves, as well as what the wind industry can do to assist with these efforts.

Several mitigation solutions which are currently deployed will be covered, ranging from the use of TMZs (Transponder Mandatory Zones), NAIZs (Non-Auto Initiation Zones), MRT (Multi-Radar Tracking) systems, infill radar and clutter cell blanking. Other data-driven solutions such as the application of improved classification algorithms, cognitive radars, holographic radars, and controlled shutdowns will also be discussed. The advantages and disadvantages of each will be discussed, as well as whether they merit further attention as part of a future-proof solution.

There are very few trials and practical implementations publicly available to comprehensively review the mitigation techniques discussed, meaning there are few reliable figures for performance and cost. Those that are mentioned are mainly based on small sample sizes. As such the methods are evaluated on largely theoretical performance from studies, with assumed practicality and reliability.

In terms of improving the radar sub-clutter visibility, this can be addressed by enhancing the transmitted waveform and the associated RF technologies to decrease their susceptibility to WTGs, and improving the processing methods (i.e. signal processing and machine learning) to better reject WTG clutter within the signal processing chain [6]. These techniques are discussed in further detail in the following sections.

7.1 Anatomy of a Radar

As discussed in Section 2, the basic concept behind a radar system is its ability to transmit radiofrequency electromagnetic waves before receiving ‘echoes’ of those same waves whenever they are reflected from an object. Although the particulars of any given radar model might differ, they all function similarly and thus contain the same components.

7.1.1 Continuous and Pulse Waveform Radars

Radars can be separated depending on whether they utilise a continuous or pulsed waveform. With a continuous wave, both the transmitter and receiver are constantly in operation. This typically necessitates the use of a bistatic radar. By modulating the frequency, the continuous wave radar can determine the range of any given target.

By contrast, a pulsed waveform radar alternates its use of the transmitter and the receiver. This allows it to emit strong waves during a short timeframe without damaging the components of the receiver. This timeframe is called the pulse width, which is typically measured in micro-seconds. The time from the beginning of one pulse to the next is called the pulse interval, and the number of pulses emitted in a second is called the PRF.

The PRF is responsible for determining the strength and range of a radar’s signals. As the transmitter and receiver must alternate their functions, this means that there is a trade-off between how far and how strong a radar’s waves can be. A low PRF will produce a longer range at the cost of weaker waves, whereas a high PRF will produce a shorter range in return for stronger waves.

7.1.2 Constant False Alarm Rate (CFAR)

Detection works by setting a threshold against which returning data signals are compared. This threshold is often adaptive and can automatically adjust due to the radar’s CFAR algorithm. The CFAR detector works by feeding measurements into an algorithm, which can automatically adjust the detection threshold to cope with changing circumstances. This ensures that the radar can maintain a consistent probability of false alarm.

If a radar operator were aware of the precise levels of interference that may affect their system, they would be able to determine a threshold level to reduce the probability of false alarm. The difficulty with WTGs is that the parameters are constantly changing owing to the movement of the blades and the direction of the prevailing wind.

The Cell Averaging (CA) CFAR detector is one of the most common models deployed in radar systems and is often used as a baseline comparison for other CFAR models [109]. It utilises a simple algorithm which computes a threshold by estimating the average interference surrounding a given resolution cell. By drawing up a reference window, it can adjust the threshold to each cell in a specific area one-by-one.

Despite the success of CFAR in mitigating other forms of clutter, it is not a valid mitigation method for WTG clutter. Whilst the algorithms excel at removing background noise and clutter, the returns from a wind farm can often be significantly stronger than the desired targets, causing shadowing of a large area. Any adjustments made to the CFAR algorithm would cause detection shadowing in the range cell where the WTG is located, as well as neighbouring cells. This can cover distances up to a few kilometres from the WTGs, thus greatly reducing the probability of detecting genuine targets [110].

7.1.3 Target Detection Filters and Algorithms

Moving Target Indication (MTI) and Moving Target Detection (MTD) are two methods of target detection which have been used to reject false alarms created by clutter. MTI is a simple filter which subtracts reflected pulses from the previous one. This allows radars to readily eliminate static clutter whilst ensuring that moving targets remain in sight.

MTD is a composite algorithm which provides a modern and comprehensive approach. It consists of a variety of filters ranging from Doppler filters, zero velocity filters, subtracting the clutter map and more. These are then fed into CFAR which undergoes post processing to eliminate much of the detected clutter.

Clutter maps have been the focus of novel approaches. They are created by the radar by giving a separate entry to every range, azimuth, and elevation cell. More complicated maps can take advantage of other information such as the Doppler effect. They are filled in through estimated measurements from several scans before being added to the CFAR filter.

It is possible that a continuous waveform radar may be able to apply a 5D clutter map (measuring range, azimuth, elevation, Doppler, and time) to the wind farms themselves, allowing for individual WTGs to be blanked. Alternatively, image recognition software could be used to detect moving targets which do not fit the parameters of a WTG.

Trials held by Sensis and the RAF in 2006 demonstrated the results from improvements to a 2D S-band Watchman ATC radar. A few notable examples include a high-resolution clutter map (30 meters in range by 0.775 degrees in azimuth) which made it possible to control false alarms between WTGs as well as allowing detection between them. MTD Doppler processing reduced the magnitude of blade returns by separating them into eight different Doppler increments. Plot and track filters, especially when combined with track initiation inhibit within the wind farm area, were very efficient at reducing the number of false alarms caused by the WTGs and improving the tracking capabilities of the radar [111]. However, on occasion gaps of around 1km still occurred where no target was detected during the trials. Estimating from the report tracking figures around 17% of target plots were missed in these trials.

7.1.4 Cell Blanking

Cell blanking is one of the crudest mitigation techniques available to digital radars. It refers to blanking the affected areas in a radar feed. This eliminates both the wind farm but also signals from everything else within the blanked cell. It resolves the problem of WTG clutter at the cost of the inability to track other targets.

At best, such an approach can only be utilised for small wind developments such as lone WTGs. This would minimise the number of cells required to be blanked. As the UK establishes greater number of wind farms in more sensitive locations to meet its climate commitments, cell blanking will become an extremely limited mitigation technique.

Its efficacy leaves a lot to be desired and it cannot be relied upon as a future-proof solution. While cell blanking has a use as the first step to many mitigation techniques (such as patching in infill data as discussed in Section 7.5 or being supported by a TMZ, Section 7.2.4), it is unsuitable as a solution by itself unless the offending clutter originates from lone or otherwise isolated WTGs.

7.2 Radar Systems

Many mitigation techniques revolve around adaptations to the radar themselves, whether it is specific adjustments made to individual radars or more comprehensive solutions regarding the radar network. Modifying and upgrading radars are expensive solutions, but they can give radars the extra capabilities they may need to cope with the demands of WTG clutter. This section will discuss what techniques can be applied to both the radar hardware and network, and whether they are feasible solutions.

7.2.1 Data Integration

One of the most vital parts in the radar system is the data processing unit, which allows radars to handle radar tracks in a specific format. At its most basic, a radar track will contain information regarding a target’s position, heading, speed and their unique track number.

By using a standardised data format, radars can share information more readily with one another. This is especially useful for multi-radar tracking systems as well as integrating multiple radars into the wider picture. One of the most used application layer protocols used for data integration is ASTERIX (All Purpose Structured EUROCONTROL Radar Information Exchange). It was approved in 1986 by EUROCONTROL, which is a collaborative European effort to ensure safe and secure air surveillance across the continent.

ASTERIX was swiftly adopted as a standard format for data transmission between radars, superseding a wide number of custom data formats that were used previously. This allowed them to be converted into a standardised format without risk of losing resolution or other data. ASTERIX transmits as much data as required with the smallest data load, which makes it especially suitable for limited bandwidths.

There are up to 255 ASTERIX categories which describe different ways of encoding data. The most relevant categories for this report are cats 034, 048, 017, 018 and 007. Each of these govern data used by Mode S radars. The amount of data handled by each category is vast; the two most important of these, cats 034 and 048, can be summarised as encompassing monoradar service messages and monoradar target reports respectively [112], [113].

Older radars utilised other formats such as RDIF, AIRCAT, CAA and CD. They still see use in select radars today such as the Watchman S Radar series. However, because ASTERIX was designed to ensure cross-compatibility between different radar formats, it is possible to use technologies to convert these legacy formats for use with modern systems.

Despite its widespread usage and ease at handling data integration, ASTERIX is not without its problems. It has come under increasing scrutiny over its lack of security mechanisms to cyber-attacks, which the Asterix Maintenance Group (AMG) are aware of. Casanovas et al have demonstrated this weakness by developing a method to perform man in the middle attacks on ASTERIX data, allowing them to manipulate the contents without either host being aware [114].

7.2.2 Modification and Upgrades

By modifying the software and hardware of the radars, it is possible to reduce clutter more efficiently. However, modification is not a simple task. This is because it is difficult to anticipate at which point the noise might become apparent in the radar’s returns. It is necessary to look at almost every component of the radar, from signal generation to track extraction, to ensure that it is capable of handling noise.

Utilising antenna that incorporates electronic beam steering would allow radars to use multiple elevation beams. Not only would this allow the radar to avoid dealing with as much clutter from the ground or the sea, but it also makes it easier for the radar to detect aircraft flying over a wind farm.

The beam shape could also be altered to create a null in the antenna pattern facing the wind farm, which would reduce interference. Such an approach has been utilised by ATC radars in the past such as the ASR 8. Although this would necessitate heavy processing power, it could form the basis of a solution.

Ensuring that the radar can adjust its PRF can assist with wind farm mitigation. By raising the PRF, there is a greater likelihood that the WTG will return more pulses before it has had a chance to rotate to a significant degree. The result is that there could be a higher chance of a radar being able to effectively see through the WTG rather than having to write off the entire WTG’s arc as a loss.

Increasing the dynamic range of the receiver can eliminate as much saturation as possible from clutter, ensuring that the signal processor has an easier time handling the raw radar returns. Although this is not a solution by itself, it does allow for other mitigation techniques to work more effectively.

It would also be possible to mask the wind farm from the radar by lowering the antenna. Ideally, this would allow for the radar to continue scanning an airspace without receiving clutter from the wind farm. This is only a partial solution and is best complemented with infill radar or other mitigation solutions to make up for the loss of information.

Radars could therefore be upgraded entirely instead of undergoing minor modifications. This can extend the lifespan of radars and enhance their capabilities at a cheaper cost than replacing them altogether. This approach has already been adopted by the MOD: BAE Systems have been awarded a contract to provide key technology upgrades to their Watchman ATC radars over the last few years. This allows them to utilise new hardware such as transmitters and signal processing technologies from their Sampson, Artisan and Commander Radars without having to replace the entire unit.

7.2.3 Replacement

Not all radars are suitable for upgrades and modification. Investment must instead be focused upon their management and future replacement. One such programme is Project Marshall, which was awarded to Aquila in 2014. In response to studies that found that much of the military air traffic control infrastructure would be unable to comply with modern needs and international standards, it was decided that £1.5bn was to be invested over a 22-year period to manage and replace infrastructure in over 100 locations [115].

Analogue models in particular struggle with clutter compared to modern digital radars. Not only do digital radars have greater resolution, but their enhanced data and signal processing capabilities ensure that it is easier for them to detect and track targets.

Another advantage of modern radars is that they are capable of streaming data externally, often onto laptops or other computers, which represents a substantial boost to the processing power at their disposal. A substantial number of long-range security radars are older and unable to take this approach. This is because they tend to be hard-wired, which limits their potential in being able to make good use of any data flow from the wind farms. This would therefore necessitate a change in hardware.

The use of DSP is linked towards the hardware design as well as the algorithms used. Digital radars can make use of advanced functions such as adaptive MTI filters, waveform generators, space-time adaptive processors and more. Although some algorithms can be applied to analogue radars, it is virtually impossible for others owing to hardware limitation. Advanced DSP techniques therefore necessitates the use of modern digital radars [116].

DSP brings many advantages to radars. Not only does its ability to compress the radar pulse boost the operating range by a considerable distance, they are also able to filter the received signal better as well as generate different pulse shapes. This means that returns fed into digital radars suffer from less noise and can be fine-tuned to track different targets in a more efficient way.

Older radars are generally limited by their lesser processing power and have a lesser scope of vision, as they often operate on a single frequency, antenna, polarisation, and node. In comparison, a modern radar can afford to increase these numbers. By using multidimensional detection, a digital radar can sample data from more than one dimension. This allows the radar to draw from multiple signals, allowing it a more complete vision of the world compared to simpler analogue radars.

The most immediate downside is that replacement is a costly endeavour. Modern radar systems show much promise in managing wind farm clutter, but no trials have established a future-proof ability to fully mitigate by themselves. The cost of replacing analogue radars with new digital models is an expensive undertaking which can rival the cost of installing new wind farms.

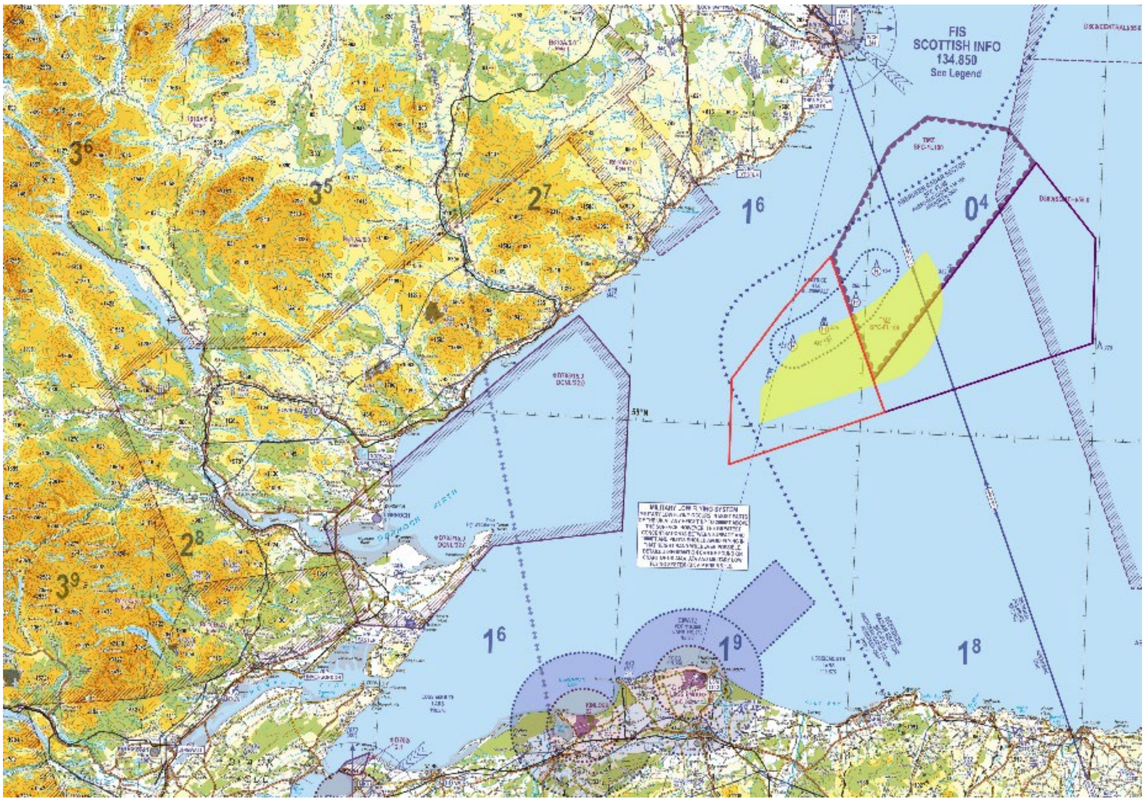
7.2.4 SSRs and Transponders

One mitigation technique that has been utilised in the past revolves around the use of transponders. At its most basic, a transponder is a device that receives one signal and sends back another signal in response. Most aircraft are outfitted with radio transponders. While PSRs can detect objects of all sizes whether they have a transponder or not, SSRs rely upon the signals emitted from an aircraft’s transponder to detect a target.

Transponder Mandatory Zones (TMZ) therefore seek to mitigate WTGs by making greater use of the SSRs. They work by delineating an affected area around the wind farm and mandating that all passing aircraft have a functioning transponder. The CAA is responsible for the implementation and review of TMZs throughout the UK, and it has been utilised as a successful mitigation solution for several existing wind farms. Due to the simple fact that WTGs do not have transponders, the SSR will ignore them whilst picking up returns from the aircraft. This allows the PSR to blank any cells affected by WTGs whilst friendly aircraft can rely on the SSR to detect and track their movements.

As a simple and cost-effective solution that makes use of existing equipment, TMZs have already been utilised in sites across the UK for both NATS and MOD purposes, such as Moray Firth, Burbo Bank, and the Greater Wash & Humber Gateway. At present their use in the UK is relatively rare compared to certain European countries which have blanketed much of their airspace in TMZs and rely upon SSRs as their primary tracking device [18]. HeliOffshore have recommended the use of TMZs around offshore wind farms as they say that they could assist with ATC in the vicinity of WTGs [117]. It is possible that policy could be introduced to mandate transponders on all aerial craft offshore below 10,000 ft. However, as TMZs are reliant upon cooperative aircraft, they would be unable to provide a comprehensive solution for AD purposes. If unknown or hostile aircraft are approaching, other mitigation techniques will still be required to be deployed. TMZs are therefore best thought of as a safety and mitigation solution for ATC which can be supplemented by other techniques for AD.

Figure 7-1: Two existing TMZs (purple) with a third proposed TMZ (orange) situated at the Moray West Offshore Wind Farm [118]



7.2.5 Non-Auto Initiation Zone (NAIZ)

A non-auto initiation zone (NAIZ) can be established with modern radars. They are a low-cost solution that can be implemented with existing technologies and have been accepted as an interim mitigation solution by the MOD in the past. Radars such as, but not exclusively, the TPS-77 based their successful performance on their ability to seamlessly utilise 3D NAIZs [119].

By determining the coordinates of interfering wind farms, a 3-dimensional boundary can be drawn around their position. The data is then entered into the radar which will no longer initiate any tracks from new returns that occur within the NAIZ. At the same time, the radar will continue to monitor those tracks which originated from outside the NAIZ – even as it crosses the boundary. While a 2D radar will have to establish a NAIZ across the entire wind farm, it is possible for advanced 3D radars to define their NAIZs around each individual WTG so long as they are separated enough. This means that there may be possible benefits to integrating a NAIZ with sparsely populated wind farms.

The immediate benefit of a NAIZ is that it goes a step beyond simply blanking the location of the wind farm, as it can ensure the radar can track aircraft flying through the zone. At the same time, no WTG returns will be processed or tracked, which drastically reduces the chance of any false alarms. This ensures that targets can be tracked as they navigate their way past wind farms.

Nevertheless, they are not without their flaws. Older radars that lack the necessary processors will be unable to establish NAIZs, and therefore the cost of installing modern radars must be factored into NAIZs. The inability to form tracks on aircraft originating within the NAIZ means that it is possible that a sufficiently skilled pilot would be able to avoid detection altogether. Following the results of recent trials, the DASA competition document cites NAIZs by name as a mitigation method which has been unable to provide their required aviation specifications [33].

Their usefulness also correlates negatively with the size of the wind farm. Airports which had successfully utilised NAIZs in the past have encountered issues when the number of NAIZs became too many for efficient ATS. With the size of wind farms only growing, both physically and in numbers, it is unlikely that NAIZs alone can be tasked with successfully mitigating their returns as an enduring solution.

That is not to say that NAIZs cannot prove useful as part of a toolkit solution. They could serve a need as a baseline solution upon which other mitigation methods are applied. Their significance may decrease as wind farms get larger, but as the construction of wind farms spans multiple years NAIZs may still represent part of a solution in the short-to-medium-term.

7.2.6 Multi Radar Tracking

Multi Radar Tracking (MRT) refers to connecting multiple radar systems to a single reporting post using a radar tracker. By drawing measurements from multiple radars, the MRT system can monitor different updates at the same time and utilise algorithms to form tracks for any given target.

The immediate advantage is that the MRT system is therefore able to predict a target's destination more accurately than a single radar could. Furthermore, there is less chance of false alarms being triggered as any errors encountered by the individual radars are smoothed out and averaged.

Typically, a radar track will consist of a few measurements. Beyond a unique track number, this will include the position (whether 2D or 3D), the heading, the speed, and the intention (if friendly). Compared to traditional IFF technologies, this provides the radar with a lot more information regarding each aircraft in its line of sight.

However, it is worth noting that whilst multi-sensor tracking can help overcome the impact of wind farms for civil aviation, they would be a poor fit for security purposes. While SSRs can provide up to 90-95% of the picture for civil aviation, they cannot be relied upon for the AD sector as a possible enemy aircraft can simply choose not to respond.

MRT systems have been successfully utilised for civil aviation, with NATS maintaining a network that is fed by a mixture of overlapping long-range radars as well as airfield radars. Once collected, the data is streamed into control centres situated in Swanwick and Prestwick where it may be used to provide air traffic service to pilots in the air.

NATS' functional network has allowed for objections to wind farm projects to be lifted in the past. Since the MRT system already collects a large amount of data and ties together several overlapping radars, it is possible for affected radars to blank the wind farm and make use of infill data from those unaffected radars. The result is that continuous coverage is guaranteed.

Despite its successes, MRT does have a noticeable drawback in that it relies upon enough radars covering the same airspace. If a wind farm happens to be in an area where there are not enough radars with overlapping coverage, then the infill data may not be enough to provide a clear image without some noise in the result.

The solution to this problem would therefore be to install more radars into the MRT system which can make up for the shortfall in range, whether this is integrating existing radars into the system or constructing all new ones.

Another solution might be to consider strategic siting of the WTGs as discussed in Section 3. By earmarking the areas that are covered by the overlapping radars, it is possible to lift objections at some sites. However, this is a short-term solution, and the result is that either new radars or new solutions will be required to make up the shortfall.

7.3 Wind Turbine Telemetry

The vast increase in computational power since the 1990s means that modern radars can make greater use of telemetry beamed from the wind farms. With this rise, WTGs have started utilising sensor technologies that can report at higher frequency such as Lidar (Light Detection and Ranging) for measuring wind conditions.

However, with SCADA Systems this information is often aggregated for compressed storage (typically 10 minute) and may not always be available remotely at raw sensor frequency. For real-time telemetry from existing sensors a separate server would need be set up for each WTG site to temporarily hold and control access/connections to the high frequency data.

Real-time data telemetry could also be easily achieved through the use of remote sensors for sites with an available internet connection. Where a connection is not available this would entail additional antenna installations on or near the sites.

By feeding data about the location of the wind farm and its surrounding environment to the radar processor, comparison algorithms and filters can be utilised to improve the signal-to-noise ratio of the radar.

7.3.1 CMS (Condition Monitoring System)

CMS are comprised of precision sensors and instruments which allow the components of the WTG to be monitored in real time. They are primarily used to avoid complete failures by keeping track of WTG's conditions. This ensures potential breakdowns can be detected and necessary repairs are organised in time, thus reducing O&M (operations & maintenance) costs.

CMS most commonly comes in two forms: one which monitors vibrations and the other which monitors gearbox oil samples [120]. Vibration monitoring is the more common and costlier option and involves the attachment of sensors to the WTG's components to provide real-time data streams. Whilst it is useful for pinpointing specific faults in the WTG, it can also lead to an overabundance of information that may make real-time analysis difficult.

In-line oil sampling consists of counting the amount of metal particles in oil to detect frequency changes. Although inexpensive, its accuracy can be easily compromised, and it only measures the health of the WTG's gearbox. Its data is therefore unnecessary for wind mitigation purposes. Some other factors CMS systems might measure include gearbox temperature, torque, oil pressure and RPM.

There are several other CMS systems, such as those applied to the rotor blades or offshore support structures. They are all focused upon fault detection rather than picking up additional information that may be useful for radars. Although CMS sensors can supply information regarding wind speeds and directions, there are other methods which can provide all of that and more.

7.3.2 SCADA

SCADA stands for Supervisory Control and Data Acquisition and refers to a system of hardware and software elements, part of which collects data and transfers it to a central computer system. It both monitors and controls the connected site, with most controls performed automatically via remote terminal units or programmable logic controller.

Although SCADA is technically not a CMS system, it is nevertheless used for condition monitoring purposes as it can enhance CMS results [120]. The monitoring system itself primarily consists of wireless sensors which transmit data to an embedded microprocessor mounted onto the WTGs. The raw data is stored in the hard drive of the monitoring system as well as being stored within the central computer's internal database.

SCADA data contains information regarding the entire wind farm's operations. It covers details such as wind speed and deviations, power output, rotational speed, blade pitch and azimuth, yaw angle, tower acceleration, drive train acceleration, and component temperatures. SCADA datasets are typically sampled at 1Hz and stored as 10-minute averages, but they also come with the minimum, maximum, and standard-deviation values for each 10-minute interval too.

The data collected by SCADA is unlabelled regarding radar interference mitigation but is labelled regarding optimisation of WTG performance. The academic literature counts many proposed AI techniques to refine their analysis. Methods such as ANNs (Artificial Neural Network), fuzzy systems, and adaptive neuro fuzzy inference systems (ANFIS) have all been successfully used to analyse the collected data [121].

7.3.3 Mechanical and Sonic Anemometers

Anemometers are a traditional device used for measuring wind speeds and directions, with the basic design changing little over the years. One of the most common mechanical designs is the cup anemometer, which consists of hemispherical cups mounted on horizontal arms extending from an axis which sits upon a vertical shaft.

When wind meets the cups, it generates torque on the axis which causes the anemometer to spin. This allows for average wind speed to be measured. A tag can be attached to one of the cups, which causes changes in the cup wheel speed as it moves with the wind, allowing for the wind direction to be measured.

Modern wind resource assessments make use of three-cup anemometers. However, mechanical anemometers such as these are incapable of measuring rapid wind changes. They are also prone to suffering in colder weather as they can freeze, becoming inaccurate if not entirely inoperable. Additionally, they are mounted directly on the WTG so the accuracy of readings can suffer from the wake of the WTG rotor.

Ultrasonic anemometers are a more recent development based upon similar principles and have become a more common sight in the wind industry. Although they are more expensive, they are increasingly perceived as more reliable than mechanical anemometers.

They consist of an ultrasonic sound emitter and a receiver at opposite ends and base their measurements off transit times of soundwaves between transducers. These measurements are immediate and can be taken with exceptionally fine temporal resolution of 20Hz or better. Moreover, their lack of moving parts makes them suitable for long-term uses in challenging environments as they are less prone to breaking down or freezing [122].

Larger sonic anemometers called Sodar (Sound Detection and Ranging) can take the place of a met tower and determine measurements at different elevations. Although they were originally intended for atmospheric research purposes, they are now more commonly being used for wind farm monitoring. They are notable for a strong performance regardless of weather, which makes them useful for gathering data where other methods might fail.

Sodar acts much like traditional sonar systems which use air instead of water. By emitting short wavelength soundwaves, it is possible to derive the Doppler shift and thus wind speed. They are likewise capable of providing accurate data in real time. Like SCADA, Sodar data comes in two forms: the raw returns and a time-averaged profile. It can consist of wind speed, direction, standard deviation as well as average backscatter strength [123].

7.3.4 Lidar

Lidar stands for Light Detection and Ranging, and it is a remote sensing method which shares some similarities with radar and sodar technology. Lidar technology can capture ranges by targeting an object of interest with a pulsed laser and measuring the time for the reflected light to return to the receiver.

Lidar systems are becoming more common throughout the wind industry as they are extremely useful for measuring wind parameters [124]. It achieves this by applying the Doppler effect to the reflected wave, granting it an insight into future wind speeds. By mounting Lidar upon the WTG, the system is capable of measuring wind conditions in real-time in front of the WTG blades. This allows the WTG to pre-emptively respond to incoming wind conditions, helping to reduce wind-induced load and fatigue.

To accomplish this, the Lidar gathers a vast number of measurements regarding incoming wind conditions. This can range from wind speed, direction, shear, veer, wind yaw misalignment, turbulence, and rotor equivalent wind speed. Lidar brings several advantages at an increased cost compared to standard mast mounted anemometers such as faster response times to changes in wind speed, faster data collection rates and reading wind speed in front of the WTG before turbulence is induced [125].

Much like radar, the particular model used can offer different methods to distances. Leosphere's Wind Iris TC can reach distances of 200m, whereas the ZX TM boasts distances of up to 550m.

7.3.5 Transponder-based Mitigation

It has also been proposed that additional telemetry could be created through use of a transponder mounted upon the WTG itself, as illustrated in Figure 7-2. Wang suggested that this solution would take advantage of the SSR's ability to detect targets that respond to signals and could therefore represent a realistic mitigation technique [126].

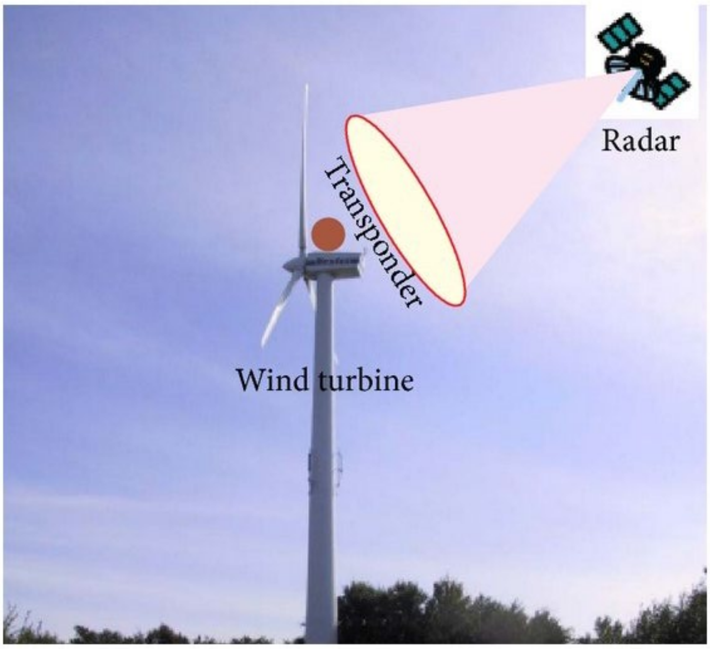


Figure 7-2: The proposed transponder-based mitigation scheme [126]

By utilising a low-noise amplifier and omnidirectional antennas, the transponder could create artificial Doppler frequency shifts which will simplify the detection of the WTGs and any subsequent radar signal processing. The use of algorithms, from plot filtering to Kalman smoothing filtering, can then successfully identify targets despite the presence of the WTG clutter.

The key advantage of this solution is that it utilises existing technology and is low-cost. The installation of a transponder should not prove too difficult. German companies have commercialised equipping transponders onto WTGs to comply with a mandated aircraft detection light system. It would also be theoretically possible for wind developers themselves to design future WTGs with an in-built transponder should this technique prove suitable for wind clutter mitigation purposes.

However, in actual practice, a solution based around combining SSRs and WTG-mounted transponders would be currently unfeasible. In order to overcome uncertainty of the source, metadata derived from SSRs can only be associated with a target after they are captured in motion. As a WTG does not move, the SSR metadata therefore cannot be linked to the WTG's plot. A possible solution may be to investigate using the turns of the blades to provide the motion required by the SSR metadata to verify that the returns originate from a known WTG [18].

7.4 AI, Machine Learning & Deep Learning

Artificial Intelligence (AI) is a field of computer science that aims to simulate the neurological processes of the brain towards problem solving, reasoning and decision making. While theoretical concepts of general AI exist, whereby machines are capable of self-awareness and independent problem solving, AI at its current state is focussed on training the machines to perform particular tasks based on specific input datasets. The most practically applicable sub-field of AI is machine learning (ML), which comprises development and application of algorithms to enable automated learning from data to address specific problems. This section provides an overview of machine learning methods and how these apply to the problem of radar mitigation.

7.4.1 Machine Learning

Machine learning (ML) techniques have been applied to numerous other engineering fields and offer a solution to many limitations that radars have historically faced. It has been suggested that ML techniques could be applied to clear clutter, to detect targets, and to classify them into useful categories.

It should be noted that ML techniques for providing wind farm mitigation are not as advanced as other applications. Many of the studies discussed in this section have instead been tested upon weather radars or the removal of sea clutter. However, these are still valuable results, and it is precisely because ML has been so successful in other fields that ML has been cited as a worthwhile approach to providing wind farm mitigation.

In contrast to deterministic algorithms, ML does not explicitly define the relationship between the input and the output. Instead, it uses existing data of the inputs and (optionally) associated outputs to train an algorithm to infer this relationship. ML accomplishes this by taking information from an environment and learning from it, allowing the algorithm to then improve its knowledge so that it may perform its task more effectively.

ML can be divided into two types. Supervised algorithms are used to handle labelled datasets, i.e. ones where the output values are known for a given set of inputs. These are divided into classification and regression methods, depending on whether the output to predict is discrete or continuous, respectively. Unsupervised algorithms are capable of handling large numbers of unlabelled datasets and use approaches such as clustering or association to group data points together or to establish relationships between the different variables. For radars there is a relatively small amount of labelled data available, so an unsupervised algorithm could be preferred.

A 2012 study compared the efficacy of four different machine learning techniques on clutter identification and removal [127]. Models based upon a Support Vector Machine (SVM), Artificial Neural Network (ANN), k-nearest neighbour classification (kNN) and decision trees (DT) were all pitted against one another to clear clutter from MET Office returns. All four algorithms performed well at removing both the ground and sea clutter from the feed and each achieved an accuracy of 98-99%, which is further illustrated in Figure 7-3. In particular, SVM was noted as giving the clearest results. Although this study was focused upon meteorological radar, the high level of accuracy demonstrates the strong potential of machine learning and what it could do for wind farm mitigation.

Other studies have investigated the use of SVM and kNN algorithms to the identification of sea clutter [128]. The data originated from an experimental radar called NetRAD and consisted of elevation, azimuth, wind direction and speed, temperature, and time of each experiment. The results were that the kNN algorithms triggered less false alarms and identified more targets than SVM. The study also exposed the difficulties of training algorithms without large datasets, although it concluded that this is less of an issue for deep learning algorithms.

A novel technique proposed in “A Comparative Study of Track-Before-Detect algorithms in Radar Sea Clutter” sidestepped the ML classification problem and instead relied upon the use of track-before-detect (TBD) algorithms [129]. Rather than setting a detection threshold and risking false alarms, TBD algorithms operate by using the raw radar feed as a measurement input. This has the potential to avoid the issue of clutter altogether. The study therefore sought to demonstrate how well they might operate at tracking targets in a cluttered environment. Three different algorithms were compared to one another: the histogram probabilistic multi-hypothesis tracker (H-PMHT), the Bernoulli filter and the multi-Bernoulli filter. The results showed that the potential has yet to be achieved as none of the algorithms displayed strong results against the simulation. It was concluded that such algorithms are therefore unlikely to be of any use in a realistic environment for the time being.

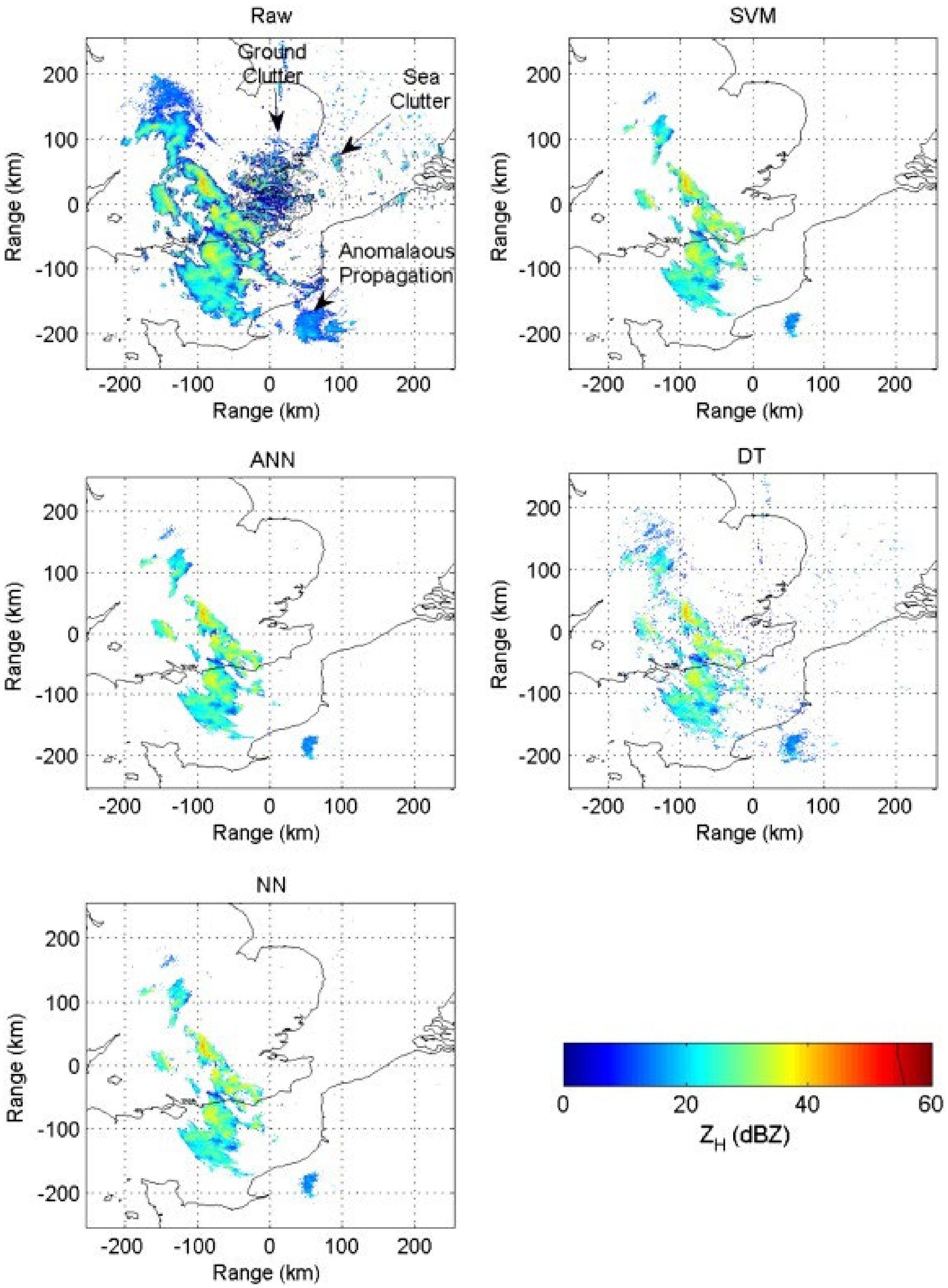


Figure 7-3: Results of the four techniques identifying and removing clutter from the raw radar data, from [127].

7.4.2 Deep Learning and Convolutional Neural Networks

The concept of deep learning was first introduced in a 2006 paper, and describes a learning method inspired by the human brain's visual cortex [130]. One example of deep learning algorithms is Convolutional Neural Networks (CNN). These networks are comprised of multiple layers. Each individual layer is responsible for analysing unique patterns, and this hierarchy allows deep learning models to successfully learn what makes up any given target.

Since the radar will be handling detection of multiple objects within an image, it will be necessary to modify a traditional CNN to ensure that it can perform multiple object detection. The most common approach is to use a region-based convolutional neural network (R-CNN). Multiple variants of this approach have been produced over the years to reduce the time spent, such as Fast R-CNN, Faster R-CNN, and Cascade R-CNN.

In particular, Faster R-CNN has seen several studies dedicated towards its use for target detection. A study has demonstrated its potential in identifying and extracting targets obscured by sea clutter [131]. Training sets were obtained by pre-processing the sea surface echo signals from a measurement trial into images. The study found that Faster R-CNN compared very favourably to traditional detection methods, with a detection probability 28% higher than CFAR and 21% higher than Basis Pursuit Denoising (BPDN). Although this study was concerned with the detection of a single signal, it successfully demonstrated the strength of deep learning and its ability to learn from small datasets.

Faster R-CNN has also been applied for the purposes of detecting and eliminating sea clutter [132]. A model was trained upon real radar databases and used greyscale processing and image cropping to reduce computational cost. A processing time of 0.7s was achieved, thus demonstrating Faster R-CNN models are not only quicker but more accurate than traditional R-CNN models, and furthermore demonstrating the advantages of large databases alongside using fewer but more accurate regional proposals.

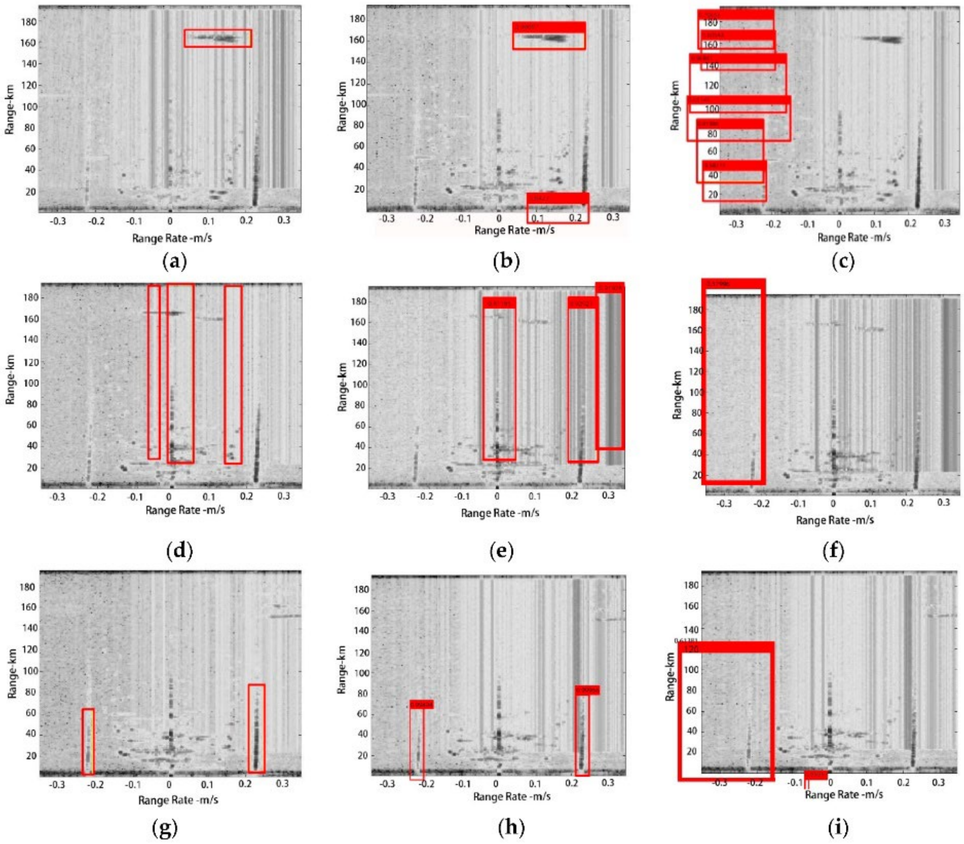


Figure 7-4: Comparison of raw data, Faster R-CNN and R-CNN. (a-c) ionospheric clutter, (d-f) radar frequency interference, (g-i) sea clutter.

As single-channel CNNs can exhibit unreliable results when handling different target characteristics in a complicated sea environment, Dual-Channel Convolutional Neural Networks (DCCNNs) have been implemented and tested on two real radars [133]. DCCNNs allow the model to use both the time-Doppler spectrum and the amplitude information from the signal. Two inputs are fused at the fully conventional layer. In addition, a false alarm controllable SVM and a variable threshold softmax classifier are utilised. The radar datasets were obtained from two sources: one focused upon a floating target and another focused upon a manoeuvring target [133]. They also covered a different number of sea states and polarisations to ensure a variety of environments.

It was concluded that the DCCNN was more efficient at feature extraction and more accurate at classifying targets and clutter than both single-channel CNN and traditional algorithms. Target samples and clutter samples were accurately classified 90% and 97.02% of the time, respectively. It was also noted that the computational needs of the algorithm were equivalent to that used by CFAR, which is promising for the practical use of deep learning models.

Most studies in this field have been trained and tested upon sea clutter. Such datasets have proven easier to acquire than those with WTG clutter. Nevertheless, they demonstrate the feasibility of deep learning solutions in removing cumbersome clutter and consistently outperform traditional techniques. It is therefore likely that they will meet similar successes when trained to detect targets obscured by WTGs.

7.4.3 Generative Techniques and Autoencoders

Another method of deep learning is based around Generative Networks. They are so named because they can use unsupervised learning methods to generate synthetic labelled data from which the model can train. Two modern algorithms are autoencoders and the Generative Adversarial Network (GAN).

GANs were first described in 2014 and use deep learning to enhance their training [134]. The technique creates a supervised learning scenario by pitting two sub-models against one another. The generator model is trained to generate new data, whereas the discriminator model attempts to classify the data as real or generated. This adversarial scenario continues and both sides improve themselves with every iteration until the generator model is generating a satisfactory result.

One of the key benefits of GANs is their adversarial component. This means that the model is most often trained on what it is bad at guessing correctly, making the model more robust against unexpected inputs. GANs are most commonly semi-supervised learning algorithms, which allows them to realistically predict missing data from a small initial dataset.

Autoencoders work by compressing the input data to allow the model to study the most vital information about it before using what it has learned to reconstruct the data as its output. This ensures that they are data-specific and only construct data like what they have been trained upon. However, autoencoders are focused upon studying as much information as possible rather than only the relevant information and seek to reconstruct rather than to understand the data it is handling.

Denoising adversarial autoencoders (DAE) have been successfully applied for use on WTG clutter. The research presented in “Target/clutter disentanglement using deep adversarial training on micro-Doppler signatures” merged the concepts 0f an autoencoder with adversarial techniques found in GANs, and was trained on data provided from the micro-Doppler signatures of a drone, a WTG, and an X-band radar [135]. The experimental set-up proved successful as the DAE was able to remove much of the WTG clutter in its output.

A 2015 paper was able to combine the results of a supervised Artificial Neural Network (ANN) and an unsupervised Autoencoder as inputs into a Random Forest model [136]. The results were positive for the feasibility of detecting targets in the presence of WTG clutter. Moreover, they note that their Autoencoder-based approach can be applied to new and unmapped wind farms, which removes the need for site specific historic data and training of models for individual sites.

Deep convolutional autoencoders (DCAEs) have been applied to the suppression of sea clutter. The framework developed in “Sea clutter and target detection with deep neural networks” allowed a DCAE to filter sea clutter before feeding the data to a logistic regression classifier for target detection [137]. The results demonstrated that such an approach was more accurate than other machine learning methods such as hidden Markov models or support vector machines. Although it was based upon sea clutter, the potential is there for wind mitigation applications.

CNNs can be combined with a type of neural network called a multilayer perceptron (MLP). In “Classification of the Wind Turbine Generated Radar Detections by Artificial Intelligence”, this technique was used to allow the radar input to be separated into two different sets: one vector contained attributes such as radial velocity and estimated RCS and was fed to the MLP, whereas the second vector contained a high-resolution Doppler spectrum and was fed to the CNN [138]. The outputs were then merged to allow for classification. The model was trained on data from a Thales Ground Master radar. It covered 7 hours of data spanning one week, with the dataset specifically chosen as it contained a diverse amount of environmental and weather conditions which affected the WTGs’ orientation and speed. The classification algorithm achieved a 97% success rate, with less than 5% of false alarms being triggered. This has demonstrated the potential of mixing various kinds of data to attain strong results.

7.4.4 Cognitive Radar

A growing area of potential is the use of cognitive radar, which refers to an adaptive radar system with a learning component, this has been likened to the echolocation of a bat [139]. There are three key elements of the cognitive radar: intelligent signal processing which would adapt to its environment, feedback from the receiver to the transmitter, and the preservation of the information content of radar returns.

The core element of a cognitive radar is the perception-action cycle, giving it the capability to continuously perceive and learn from its surrounding environment. It would draw information from both its own knowledge and its learned experiences to assist with decision-making. This would allow the radar system to then adapt its operating and processing parameters reliably to account for changes in its environment.

Compared to adaptive radars, the cognitive radar will not just learn from the environment but be capable of learning from its mistakes and refining its future approaches. The performance of the cognitive radar will therefore rest upon its ability to correctly evaluate information.

There has been a rapid growth of research over the past decade, but many of the results have been theoretical rather than practical. No existent radar model available on the market is fully cognitive. However, it is notable that the Aveillant Theia 16a shares some similarity with these theoretical models owing to its staring capabilities.

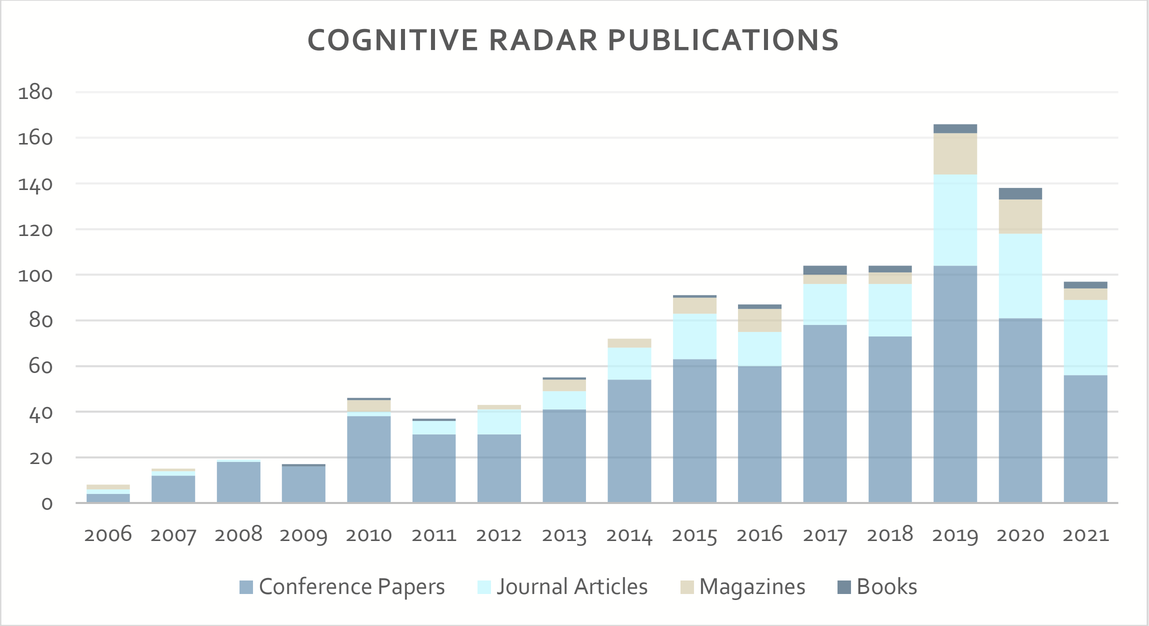


Figure 7-5: List of publications regarding cognitive radar. Sourced from IEEE Xplore.

Given the sheer amount of research that has been produced over the last 15 years, there have been multiple proposed techniques for achieving a cognitive radar. These include adaptive waveform design, dynamic programming, optimisation, all-digital radar arrays, machine learning and deep learning [140]. Despite its vast potential, experimental validation is still underway. Only within the last 5 years have institutions began testing cognitive radar applications on radar testbeds [141], [142].

Should cognitive radars become a reality, there may still be some remaining difficulties. They are unlikely to be built around providing a worst acceptable performance given the increased cost of investing into cognition, which may slow down their procurement compared to non-cognitive radars. There are also concerns about the out-of-band transmissions, which will inform steps to ensure that the cognitive radar does not interfere with existing communication devices.

Cognitive radars are a very promising but theoretical field. Although software and hardware developments may allow for cognitive radar models in the future, other interim solutions will have to be adopted in the meantime. Nevertheless, cognitive radars may have the potential to provide a full mitigation solution and should be considered a priority for research.

7.4.5 Limitations of Machine/Deep Learning Techniques

The previous section has discussed many optimistic results from studies conducted in the last decade. However, it is important to reiterate that machine and deep learning cannot be relied upon as a 'silver bullet' solution. There are several complications that may hinder their proven successes when confronted with a real-world scenario.

The most prescient issue is that it remains uncertain whether these algorithms would be able to successfully pass certification trials to reach the standards set by CAA, NATS or the MOD. Many of the tests discussed have taken place in simulated environments or have only dealt with singular WTGs rather than large wind farms. Technological limitations such as a lack of suitable hardware have also hindered machine learning algorithms from reaching their full potential.

One key challenge in training machine learning algorithms is ensuring that there exists enough representative data to create an effective model. It is imperative to ensure that algorithms can deal with new and unknown scenarios. These datasets are not always readily available, especially for applications in defence such as stealth aircraft. It can be both costly and time-consuming to create them from scratch. Many of the discussed algorithms have outstanding results, but they are often built upon limited datasets.

Neural networks especially tend to degrade when dealing with entirely unfamiliar scenarios. Advances such as GANs have made headway in overcoming the limitations of small datasets by synthesising their own data which can then be used for further training, but even this approach has limitations. As with all ML algorithms, the model may be unable to cope with unexpected outliers in a real-world scenario and is reliant upon the original dataset being accurate.

Due to this nature, machine learning models can be vulnerable to attack from engineered inputs as demonstrated in [143]. Such attacks can cause the algorithm to misclassify or report false information. These attacks can be carried out when the attacker has access to the underlying model or can easily brute force a variety of inputs.

Data quality, and in particular the problem of bias, must also be considered when training algorithms. Machine learning models are only capable of learning from the data it is trained upon. If the models are trained upon inaccurate or otherwise flawed datasets, such as all data coming from one radar or one particular site, then the results will not transfer to other real-world scenarios and will therefore be of little use.

The problem of interpretability is also inherent with deep learning algorithms. Although the model may be capable of learning and providing accurate results, the exact process which connects input and output can remain opaque. They are often referred to as 'black boxes' which are simply fed data and deliver results. This might not necessarily be problematic if results are all that matters, but it is a concern for scientists wishing to interpret the model or develop conclusions. It can be difficult to understand the root cause of any flaws within the output or to make further improvements to the model. Despite all these limitations, it should nevertheless be recognised that the potential of machine and deep learning techniques for radar are huge. They have led to incredible advancements in other fields despite these constraints, and there is no reason it cannot do the same for radar applications too. No other solution boasts the same potential in providing a full and comprehensive solution. Given enough time and research, ML could become an integral aspect for the future of wind farm mitigation. However, the reliability and accuracy shown in existing studies does not meet the required performance parameters of this project.

In conclusion, the existing ML techniques discussed could improve overall performance when used alongside other mitigation techniques discussed in this paper. Without further research and development, they are not a standalone solution.

7.5 Infill & Gap Radars

A promising avenue to explore is infill and gap radars. They are one of the proven and operationally deployed mitigation techniques and have been utilised as a successful fall-back option when other alternatives have been exhausted.

Infill makes use of multiple radars working in tandem. The idea behind infill is that an affected radar can blank out the area affected by the wind farm clutter. A second radar, whether newly positioned or already existent, will remove the clutter by supplying its own clear feed to the radar operator. This is achieved through methods such as terrain screening or advanced data processing.

Infill radars are flexible and can be deployed in multiple approaches to best fit each individual wind farm. Some can utilise the terrain to shield the clutter from the final radar image, whereas others have in-built wind farm tolerance integrated into the radar.

7.5.1 Advantages and Disadvantages

Whilst infill radars are not necessarily a low-cost solution, their consistency and efficacy mean that they strike a good balance between their cost and their results. They can be deployed from existing onshore radar locations, as well as on offshore substations and WTGs. This flexibility is notable especially as offshore wind farms are predicted to reach out further into the sea over the upcoming years.

Infill can be supplied from conventional radars, giving them the benefits of a long range of sight. Specialist infill radars may have a shorter range but are able to use finer resolutions which allows them to separate returns from WTGs and aircraft.

However, there are areas of concern which have prevented their wholesale adoption at the present time. The shorter range that characterises smaller specialist infill radars is one such issue. Whilst this means that they are more affordable than conventional radars and could be situated on offshore substations, this can limit their potential when dealing with high elevations or particularly large wind farms. Evidence also suggests that stationing infill radars on offshore substations would be a suboptimal approach compared to placing them on an offshore structure of their own. This would also allow the radar to be sited in the best location for any given WTG.

Nevertheless, depending on the size of the WTG, it may be necessary for multiple units of these smaller radars to work in tandem to cover the same wind farms. Not only might this mean additional costs in terms of installing the radars and obtaining additional spectrum licenses, but it may lead to concerns over data security. While this does not mean that objections cannot be lifted, there are understandable risks.

A successful alternative to having a short line of sight would be the utilisation of conventional radars, which are able to cover much longer ranges. However, if a conventional radar does not already exist in a suitable location, then this would necessitate the scoping out and construction of a new onshore radar site. Whilst this may be preferable to building no wind farms at all, it cannot be discounted as an additional factor that might slow down the wind industry's drive to reach the government's targets.

When used alongside 2D radars, such as those utilised for Air Traffic Control, infill radars can suffer from problems with seamlessly integrating their data into the final radar return. Slant range errors can occur when the distance and altitudes of the aircraft and the radars are not in sync. Similarly, different radar rotation frequencies can mean that each radar may detect the aircraft at different time without interpolation. However, as this a primarily an issue which would face civil aviation, this can be alleviated with a "height cut" from the transponders which respond to the SSR.

A trial of two infill radars alongside a Digital Airport Surveillance Radar (DASR) for use in air traffic control was carried out at Travis Air Force Base (USA). This trial concluded successfully, improving the tracking within the wind farm interference area. The infill radars improved clutter mitigation, had a higher probability of detection and a lower probability of false alarms than a standalone DASR [144].

It should be noted that the above trial was carried out onshore at relatively low range (10.5 miles), target altitude of 5300ft for published results, and with one infill radar perpendicular to the DASR. This arrangement will not always be possible, particularly for offshore solutions.

There are some concerns about the quality of data being degraded when merging multiple datasets from different radars. It is possible for the infill data to be corrupted, especially around the boundaries. Despite demonstrating excellent detection performance, trials of infill radars have also shown higher rates of false alarm and perform less well at detecting aircrafts at higher elevations. However, these are issues which may be dependent upon the model used and can be resolved through additional fine-tuning and testing [145]. Trials for offshore WTG mitigation with infill radars based on [144] would be a good starting point if this method is pursued.

7.5.2 Civil and Military Case Studies

Despite the possible drawbacks, it cannot be denied that the potential of infill radars is huge. They have been deployed successfully for both civil and military aviation needs. One case study is Glasgow Airport, which was one of the first to adopt infill radar techniques in 2011. Between 2012-2016, over 90% of applications submitted were approved, which would pave the way for 704 MW to be generated from local wind farms [146].

The TERMA Scanter 4002 has become a common sight in airports across the country following the 2015 contract between TERMA and NATS. The very first was installed in Liverpool in 2016, with other airports such as Edinburgh and Newcastle making use of the same model to provide infill data [147]. The 2019 installation of new TERMA Scanter 4002 radars allowed Glasgow Airport to lift objections to even larger wind farms such as the Kype Muir development [146], and furthermore at Glasgow Prestwick, where it is expected to become the one and only ATC PSR.

Terrain shielding has allowed also 2D infill radar to provide coverage over the affected area. There are plans to mitigate the Hallburn & Solway Bank Wind Farms at RAF Spadeadam by means of a shielded radar at Berry Hill, which would combine its data with the affected radar at Deadwater Fell.

7.6 Notable Radar Models

Both civil and military aviation have made use of a variety of models from different companies. The following is a non-exhaustive list of notable models which have been considered for use in mitigating wind farm clutter. Some have an operational history, whereas others have yet to undergo successful trials. Nevertheless, they all represent avenues worth exploring.

7.6.1 AN/TPS-77 Long-Range Air Surveillance Radar

The Lockheed Martin AN/TPS-77 is the primary ADR radar used in the UK. It is 3D radar designed as a small but mobile variant of the AN/FPS-117. Its mobility is one of its key selling points, as it can be transported easily by truck. The two radars share up to 80% of their technology with each other, with differences such as smaller antennas allowing for increased mobility. As an L-Band radar it can transmit up to 19.9 kW and features a long range of up to 470 km which makes it an attractive choice as a radar [22].

The major feature of the TPS-77 is that it utilises pencil beam architecture. By using an active electronically scanned array (AESA), the radar can produce multiple pencil beams rather than a single beam, allowing individual beams to tailor their parameters to its environment. This provides it with complete elevation coverage, alongside the ability to reduce the effects that weather and clutter as required. The pencil beams alone set the TPS-77 apart from stacked beam radars, giving it a much higher percentage chance of detecting low-flying targets that may otherwise be obscured by wind farms [148]. Regarding data processing, the TPS-77 also utilises moving target indication (MTI) and Doppler as well as adaptive beam forming processing [149]. It is suitable for ASTERIX data outputs with a proven track record of integration with both SSRs and PSRs [148].

The TPS-77 was initially able to meet aviation specifications thanks to its in-built NAIZ technology, after the successful 2008 trial at the Horns Rev wind farm. Initially, the MOD found that the TPS-77 maintained a high probability detection of >95% for all targets, even when near the wind farm itself. This led to a wave of objections lifted as new radars were outfitted across the country [150] [151]. However, recent empirical trials in 2018 have baselined the TPS-77’s performance. An MOD safeguarding statement provided to Pager Power is quoted below:

"The MOD has recently conducted a trial looking at the real life impact of 2 offshore wind farms in the vicinity of the Humber Estuary on the TPS 77 radar that was situated at Remote Radar Head Staxton Wold. The trial determined that the wind farms had a detrimental effect on radar operations, specifically probability of detection and the aviation specification performance. The detrimental effect was not expected and the MOD needs to consider the findings of the trial further. As a result, the MOD must pause the receipt and assessment of any technical mitigation reports/submissions e.g. SERCO reports, relating to the TPS 77 radars and multi-turbine wind farms with immediate effect. Technical mitigation reports relating to single turbine developments will still be received and assessed by MOD.

The MOD is aware of the impact that the pause may have on wind farm projects seeking to provide mitigation for the TPS 77 radars and is working to minimise the duration of the pause. Further upgrades to the radar software are being scoped and it is hoped that this will improve the situation." [152]

A later update from June 2019 is quoted as follows:

"The MOD has also conducted 2 trials regarding the impact of specific wind farms on specific Lockheed Martin TPS-77 radars that have provided further evidence on which we base our understanding of the current issue … The MOD will continue to work with industry to resolve the current issues and will, on a case by case basis, consider certain developments where impact on operational capability is deemed to be acceptable. TPS-77-based mitigation reports will now be considered where suitable mitigation can be adequately modelled. The MOD will continue to receive and assess TPS-77 based mitigation reports for single turbine developments following the results of a previous trial relating to these developments." [153]

The TPS-77 is a radar with proven mitigation capabilities, but it is presently unable to provide acceptable mitigation for every wind farm without being complemented by other techniques.

7.6.2 Indra Lanza PSRs

Indra provides 3D radars suitable for both civil and military aviation. Owing to their use of AESA technology and other advanced signal processing techniques, their PSR 3D L-band radars have in-built wind mitigation capabilities. High-resolution clutter maps, improved tracking algorithms, and multiple pencil beams which can be electronically tilted allow their radars to reduce the impact of wind farms during the early stages of detection [154].

Lanza is a family of 3D radars provided by Indra, with a number of available configurations depending on the purpose. They share solid state amplifiers and foldable planar array antennas in common, which allows them to achieve ultra-low sidelobes. Furthermore, they also make use of techniques such as pencil beam architecture, adaptive MTI, and high PRF variability to overcome clutter [155].

Indra cites itself as having won every tender offered by NATO over the last 15 years and offers radar models to 60 countries over five continents, which they claim demonstrates its capabilities in a wide number of environments [156] [157]. Their radars are commonly utilised for both military and civil aviation purposes in northern Europe. In 2017, they were contracted by the Danish ATS provider Naviair to provide support for Billund International airport, the second busiest in the country [158].

One notable member of the Lanza family is the LTR-25. As a long-range radar, it can observe distances of approximately 450 km. It was designed as a mobile deployable radar, with its equipment integrated for ease of transport [159]. Since its development in 2012, approximately 50 models have been deployed across the world. NATO is one of its most notable customers following a 2015 agreement to integrate the LTR-25 into their Air Command and Control System [160].

It was first acquired by the UK in late 2020, with the RAF favourably citing its ability to provide a desirable ATS by rotating at two different speeds as well as its wind farm mitigation capabilities [161]. The LTR-25 has replaced the TPS-77 at the Staxton Wold position, where a series of site acceptance trials were conducted throughout 2021. As of the time of writing, it is unknown whether it exceeds the TPS-77's capabilities [162].

7.6.3 TERMA Scanter 4002

TERMA provides a 2D radar with a history of success across airports, as discussed in previous sections. It has been primarily used for civil aviation purposes, but the potential for defence purposes also exists. The Scanter 4002 can reach distances of 83km and operates in X-band, which provides it with a high resolution. It works by providing the radar system 2D tracks which might then be fed into a 3D recognised air picture.

It makes use of several techniques such as an adaptive CFAR, a high dynamic range, and MTI and Doppler processing. It provides its data using the standard ASTERIX format. Alongside its high resolution and adaptive clutter maps, this has allowed the radar to effectively mitigate the impact of WTGs. It is small enough to be stationed on an offshore substation and is not reliant upon terrain shielding like other 2D infill radars [147].

Trials were first held in Copenhagen airport in 2012 before follow-ups at sites across the USA and UK. It proved adept at tracking both helicopters and planes as they fly behind and across the wind farms and has even been able to initiate a track from AW-169 helicopters detected inside the wind farm. The radar boasted a track probability of 98% over a wind farm with false alarm rates of 10^{-7} [163].

By 2015, it had successfully passed both NATS and CAA trials and was adopted for civil aviation purposes. The last half of the 2010s saw its installation at airports across the UK, from Chester Harwaden and Newcastle Airports in 2017 to Durham Tees Valley Airport in 2021. There have also been recent steps towards utilising the Scanter 4002 for military purposes. In 2020 the Wemeldinge radar was installed in the Netherlands as part of the Military Approach Surveillance System, which handles both military and civil air traffic across the Netherlands and neighbouring countries [164].

Compared to other models, the Scanter 4002 primarily suffers from being a 2D radar with a much shorter range – neither of which is ideal for Air Defence purposes. However, as there has been a trial of the radar temporarily being installed on an offshore substation, it may be that it could be utilised as part of toolkit to provide infill data as part of a successful mitigation solution.

7.6.4 Aveillant Theia 16a 3D Holographic Radar

Holographic radar utilises a new yet promising radar development to provide a mitigation technique, if not an entire solution by itself. Aveillant describes its radar as one that 'stares' rather than scans. Traditional radar relies on a rotating antenna which sweeps a narrow beam around.

By comparison, the holographic radar utilises a static staring array which can maintain continuous coverage in its line of sight. Furthermore, the radar comes equipped with classification algorithms which are designed to separate ground, sea, and airborne targets from one another. In terms of data transmissions, it utilises ASTERIX for its data output, which allows for simple integration with primary radars [165].

The biggest drawback of holographic radars is precisely because they are a novel technology, they have little operational record. Although the Aveillant Theia radar was first unveiled in in the early 2010s, it was not until 2016 that the CAA granted approval for its first commercial installation, which took place at East Midlands airport, where it now acts as an infill radar for aircraft flying over the Spondon wind farm [166].

Without a long operational record, there may be hesitance to adopt them en-masse until their efficacy can be proven. Although holographic radars have been certified by CAA regulations and represents a future for civil aviation purposes, the question remains whether it is able to service the AD sector.

Trials were due to begin in 2019-2020 under the auspices of Project Green Blade, complete with MOD observation. The first phase involving extended range trials were scheduled to take place through 2019, but disruptions owing to COVID-19 have meant that the trials have yet to move past the second phase. It remains an innovative technology but requires further testing and evaluation before it can be adopted.

As part of the DASA Challenge Phase 2, Thales is investigating potential use of a network of multistatic staring radars (like the Aveillant Theia) as a system wide mitigation technique.

7.6.5 MOD Joint Concept Demonstrations

Throughout 2020 and 2021 the MOD has been carrying out a series of Joint Concept Demonstrations aimed at demonstrating real world performance of potential air defence radar mitigation solutions (albeit against the current wind farms) that could mitigate the impact of future offshore wind farms. Eight systems of varying types were seen including LR and medium range ATC and AD, active and passive radars, and an electro-optical system. Initial results were shared with task force members in May 2021 with the full results shared in February 2022. After the initial results were shared task force members considered that they had seen moderate evidence of one or more tolerable mitigation solutions being available. MOD are currently developing a procurement competition that aims to provide technical mitigation for wind farms anticipated to begin operating between 2025 and 2028

It is expected that publicly available information regarding these demonstrations will be available in Q2 2022.

7.7 Controlled Shutdowns

A potential solution is the use of controlled shutdowns as a mitigation technique. The temporary shutdown of WTGs could clear up the feed and allow for the detection of enemy aircraft.

The technique would involve shutting down the WTG altogether – whether manually or automatically – whenever any objects of interest are detected nearby. Only when there was no more risk would the WTG be allowed to continue its operations.

WTGs cannot be stopped immediately and can take up to five minutes (dependant on weather conditions and WTG size) to fully stop rotation once a controlled shutdown is initiated. This means any potential target would need to be detected and predicted to fly through the WTG interference area minutes before entering for a shutdown to help with target tracking. They can be stopped quicker in an emergency, however this generally causes additional wear and tear on the hardware.

There is also lingering debate as to whether the worst contributor to radar noise is the motion of the WTG blades or the static WTG towers. Estimates have ranged from 75-80% of the WTG's RCS originating from the tower, although these studies do not account for the Doppler effect [80], [81]. Additional analysis and trials would need to be conducted to investigate if WTG shutdowns can improve target detection and what the impacts would be to wind farm operation and financial implications.

7.7.1 Use in reducing bird fatalities

Controlled shutdowns have been utilised for WTGs for other purposes, such as mitigating their effect on migratory bird fatalities. The Barão de São João wind farm serves as an interesting case study. Due to its sensitive location in the middle of bird migration routes, it was decided that a radar-assisted shutdown on demand (RASOD) protocol should be tested and monitored there in return for its development [167].

Using the wind farm's SCADA system, the operators were able to shut down and restart WTGs as required. Up to 60% of shutdowns were handled automatically by software upon radar detection. In terms of efficacy, the solution worked very well for its intended purpose. Bird fatalities declined to zero for five consecutive years with only a loss of 0.2 – 1.2% of wind farm activity.

When monitoring began in 2010, it took an average of 4.5 minutes to shut down the WTGs with an annual shutdown period of just under 105 hours. By 2014, these figures decreased by 91% and 86% respectively, with WTGs shutting down within 24 seconds and an annual shutdown period of just over 15 hours. However, it should be noted that these are relatively small (2 MW), onshore WTGs. Modern offshore WTGs are significantly bigger, meaning that they will take longer to slow down and experience much higher and potentially damaging breaking loads on the structure and drivetrain if they are stopped too rapidly.

7.7.2 Use for the German Air Force

Controlled shutdowns have been effectively used for military aviation purposes too. One notable proponent of shutdowns is the German Air Force, which has utilised shutdowns at WTGs surrounding multiple Bundeswehr airfields.

Following a one-year testing phase, the German Air Force was able to adopt software called FlightManager to mitigate the effects of WTGs on their radars. Like SCADA, it works by giving the radar operator control over the WTG shutdown, with start-ups occurring automatically after a fixed time delay.

This allows the German Air Force to take off, land, and cross by neighbouring wind farms without risk. The successful adoption of FlightManager across 11 Bundeswehr airfields allowed the construction of new wind farms in areas which had had previously been rejected. Between 2015-2017, the use of controlled shutdowns as a mitigation technique paved the way for an additional output of 400 MW, which represented 5% of Germany's onshore wind farm expansion [168].

However, it should be noted that FlightManager was not a perfect solution for all military aviation requirements by itself. The German air force was primarily concerned with using it to provide safe passage in the skies nearby their air bases, rather than for the detection and classification of hostile targets.

Its efficacy was also reliant upon the model of radar used. At Wittmundhafen Air Base, there were initially only 30 hours of shutdown per month. However, these times jumped dramatically to 100 hours per month following the installation of ASR-S radars. These new radars were less successful in separating the returns from WTGs and aircraft, and therefore necessitated a drastic increase in the number of mandated shutdowns [169].

7.7.3 Advantages & Disadvantages

The most obvious advantage is that a controlled shutdown would eliminate all movement from the WTG, which would likely reduce WTG clutter from radar scans. With experienced operators, controlled shutdowns can prove to be an agile solution which can react quickly to potential targets.

Nevertheless, it should be reiterated that rapid shutdowns are very unpopular within the wind industry. Whilst they would reduce shutdown times, they can cause increased strain upon the WTGs themselves which would lead to vastly increased O&M costs and much reduced profits.

Slower shutdowns can be used in a controlled scenario as Wittmundhafen demonstrates, but the removal of clutter would still be reliant upon radar processing. Their futureproofing is dependent on the model of radars that the shutdowns are assisting. Since not all radars can ensure the length of controlled shutdowns are viable, this narrows what radar models can be used. A balance would have to be struck between the cost of installing new radars or lengthy shutdown periods.

It would also be necessary to successfully bridge the gap between the radar operators' desire to utilise shutdowns freely and the wind farm developer's desire to maintain a consistent level of energy production. Without an arrangement that pleases both sides, controlled shutdowns cannot be utilised as a solution.

Trials of radar shutdowns with the different types of radar in use would need to be carried out to prove that shutdowns will sufficiently improve radar returns enough to justify the action. Any proposed shutdown control will meet significant resistance from the wind industry as it will directly influence profits due to loss of revenue and maintenance costs due to significant added strain on the system of every WTG affected. Compensation agreements may be necessary where excessive use of shutdowns could be expected. Furthermore, there would also be concerns for the energy grid as a whole if large WTGs are expected to shut down with little warning. This may lead to an inconsistent ability to cope with demand which would be counterproductive for meeting the UK’s Net Zero goals.

This could also be significantly detrimental to the country’s electrical grid network. With offshore wind expected to provide 80% of the total UK electricity requirement by 2050, if whole wind farms are shut down at short notice, it will be incredibly difficult to balance the grid and ensure there is enough electricity to maintain the demand supply. Controlled shutdowns are therefore not a solution that is likely to see much adoption as a standalone solution. There is a case for their use as an extreme backup option and in controlled scenarios where they might constitute a simple solution for strategic airbases and flight paths. However, shutdowns would not be an effective solution for most wind farms.

8 Conclusions

8.1 Layout

Wind farm layout is already constrained by many considerations including the seabed area as defined by the leasing agreement, the effect a development may have on local wildlife populations, other users including shipping lanes and fisheries; geology and access for SAR operations. Developers optimise layout within these constraints for maximum power performance to provide cheapest possible energy for consumers, while ensuring profitability based on wake effect, electrical losses and electrical system costs. Adjustments to the location of WTGs within a proposed wind farm could have a significant detrimental effect on the project's economic and energy production viability.

The different layout methodologies will have varying impacts and will depend on the specifics of the wind farm site in question and the position of the primary radar site (including the relative position of other ADRs with radar line of sight over the wind farm). While optimised layouts may reduce overall clutter and make more visible “lanes” between rows of WTGs, the issues of significant blind spots, tracking in clutter and false alarms will remain. Therefore, optimising layout for radar mitigation may have limited value unless combined with capability upgrades for the radar processing and filtering.

The potential impact of wind farm layout on radar false alarms and false tracks is not yet widely understood. The focus has largely been towards reducing the impact on target detection, although false alarms and false tracks also have a knock-on effect for target detection as well as track seduction issues. It is presumed that gains could be made with regards to false alarms from the same layouts that have been proposed for improving target detection, however that is a speculative opinion currently, with no observed evidence or modelling to investigate the particular question of false alarms.

Existing analysis suggests that the most pragmatic layout mitigation strategy for consideration is a standard grid layout with increased spacing (while there is no definitive data, it is suggested ideally greater than 1 km) between rows that are perpendicular to the axis of a single radar. That approach would take advantage of radar’s inherently small range cell – providing observable “clear air” between WTG rows. That would technically produce the most successful practical results for minimising clutter and maximising airspace sanitisation within the area of the wind farm.

Optimising layout will be significantly more effective if coupled with upgrades/ replacements to surveillance systems that can take advantage of more “clear air” within the wind farm. If layout mitigations are progressed in advance of radar improvements (upgrades, replacements, relocations or additional infills added), the layout mitigation implemented would then be fixed and so have to be accommodated when developing any future radar improvements , while the specifically designed layout also potentially negatively impacts the wind farm AEP.

Additionally, none of the layouts discussed have any answer to the challenge presented in areas where there are overlapping radar views. A layout optimisation to mitigate for one radar system may well exacerbate the interference caused to another radar system.

The proposed layout mitigations obviously cannot be applied to existing operational wind farms or those currently under construction and might also be less effective for floating offshore wind farms, which are free to move within their mooring structures.

8.2 Stealth

The application of stealth technology for WTGs is still in its infancy and evidence of real-world effectiveness is scarce, but there have been some positive steps forward over the past few years. The potential “pros” of stealth technology as a mitigation technique are as follows:

- “fit and forget” – after stealth technology is applied during the manufacturing process, it will provide notable RCS reductions immediately.
- Its long history of use within the aerospace sector makes it an established technology, and ensures that stealth treatments are aerodynamic and capable of reasonable environmental resistance. While some lessons can be learnt from the aerospace application, it is crucial to note that the operational conditions are incredibly different and serious consideration needs to be given to the longevity and resilience of any stealth technologies proposed.
- Some minimal treatments are designed to ensure that there are limited changes to the manufacturing process, which helps to minimise costs.

The most developed techniques are the application of RAMs and shaping. They have performed well in both trials and real-world situations over the past decade. Reductions of approximately 15-30dBsm are achievable depending on the precise technique applied, and multiple studies cite an immediate cost uplift of approximately 10% - although there is significant doubt amongst the industry that implementation and maintenance of shaped towers and nacelles and RAM-embedded blades will only cost that much. Stealth WTGs such as those at the Ensemble Eolien Catalan wind farm utilise a mixture of both techniques to boast a claimed RCS reduction of 90-99% against weather radar. However, these results have yet to be replicated for aviation radar and have yet to be disseminated widely.

Although shaping has been proven to provide substantial RCS reductions, the method has been limited in the past by costs – certain designs have been tested but were not manufactured owing to commercial reasons. RAMs are primarily held back by the need to provide broadband coverage spanning a minimum of 3 bands. While such models are under development, they are not predicted to be commercially available until at least two years from the time of writing.

Other techniques, such as passive or active cloaking and metasurfaces, have only been considered in theory and in low TRL demonstrations. While research currently demonstrates a strong potential for RCS reductions, there are currently no known physical applications on WTGs. These technologies therefore exhibit a TRL of approximately 3-4. Despite their potential, there remains much work done to be done to properly demonstrate these technologies on test WTGs, let alone determining whether they would be economically viable solutions.

All stealth techniques would involve increased costs to the wind farm developer for every WTG. Although estimates exist for the costs of acquiring the designs and manufacture, it is unknown how costly it may be in the long run to provide maintenance to prevent degradation to the stealth treatments. It should also be considered that it will be cost prohibitive to retrofit any old WTGs, therefore stealth treatments can only apply to WTGs built in the future. Other solutions will have to be sought for currently existing WTGs to minimise their impact on radar.

One of the greatest challenges for stealth WTGs is meeting the stringent requirements put forward by the CAA and MOD. Even in cases where up to 99% of the RCS is eliminated, the latest generation 12MW+ WTG’s would still have a remaining RCS that exceeds the desired levels and would likely still cause potential problems with target detection, tracking and false alarms. At the same time, there are also concerns stealth WTGs may yet prove counterproductive with emerging radar processing technology.

The main drawbacks of stealth technology must therefore be considered:

- Effectiveness against aviation radar – insufficient information exists in the public domain to determine exactly what needs to be “stealthed” on the WTGs (e.g., blades, towers, nacelles) and how effective the respective stealth technologies will actually be in improving the radar picture. This means significant joint analysis between MOD, radar providers and the offshore wind industry is needed if stealth is to be seriously considered.

- Detailed cost/benefit analysis – The amount of stealth required to provide the necessary benefit against the lifecycle costs (i.e.. Determining the best bang-for-buck) is not yet being thoroughly investigated. As investment decision lead times for wind farms and design to certification cycles for new technology are usually many years, it’s not likely that any significant stealth technology will be deployed in wind farms before 2030 at the earliest (assuming said analysis were to start immediately).

- Environmental durability – Although the technology has seen long-term use in the aerospace sector, the use and wear profiles are very different. Stealth aircraft are not constantly deployed unlike stealth WTGs, which may lead to significantly different O&M times and costs.

- Exactly how much stealth is required would likely be site specific – meaning development, build and maintenance costs would vary depending on the intended location of the wind farm, and may vary within the wind farm. Additionally, overlapping radar fields-of-view will further complicate stealth employment.

- Uncertainty over providing effective RCS reductions over multiple bands – the MOD’s rights to replace or upgrade radars means that any stealth technology must futureproofed against a range of radar bands.

- Adoption of stealth technology will only ever reduce the RCS – it will not remove it. Other mitigation techniques must still be used in conjunction.

- Can only be applied to WTGs during manufacture – the cost prohibitive nature of stealth retro-fit means older wind farms will have to use other solutions.
- Necessity (Civilian ATC) - evidence suggests that certain radar processing techniques can already “eliminate WTGs” to an acceptable level for civilian ATC radars. Upgrading to this surveillance technology may negate the need for stealth mitigation for civilian ATC.
- Necessity (Military ADR and ATC) – evidence demonstrates that certain existing radar processing techniques can improve the radar picture significantly. It may be that further development will enable mitigation through improved radar performance alone. However, this is not yet the case and until fully wind farm tolerant radars are available for military ADR and ATC, a system of systems approach potentially including stealth amongst other approaches cannot be entirely discounted.

As stealth alone is presently unable to provide full wind farm mitigation for radars, and the technology is neither developed or fielded yet for larger WTGs, it will be difficult to convince wind farm developers and manufacturers that the benefits are worth the cost. Further joint (MOD, CAA, wind farm developers, radar and WTG OEMs) research projects should therefore be undertaken to determine the real-world viability and feasibility of stealth technology in a wind farm and whether it will still be significantly beneficial to emerging radar technologies.

8.3 Data and Information

The ML techniques discussed in this paper show promise in reducing false alarms and improving target detection within a wind farms interference area significantly. For studies focused on sea clutter mitigation, target classification accuracies of up to 97.02% have been achieved with a DCCNN approach.

However, various limitations have been discussed, most notably that existing literature is focused on sea clutter mitigation with very few examples of WTG mitigation for low flying aircraft being explored. Further analysis of the use of ML to improve radar airborne target detection and tracking within wind farms is strongly advised.

At a high level, the typical cost for developing a ML solution of any size can range from $20,000 – $1,000,000 USD [170]. The proposed radar mitigation problem fits a mid-sized ML solution with tight tolerances on accuracy so it could be expected at around £100,000–£250,000 (est.) for cost of development and implementation. Depending on the approach taken and the current availability of data, the additional cost of gathering accurate and varied enough training data of low flying aircraft above wind farms could add significantly to this figure.

Several radars have been used to provide wind farm mitigation using a variety of data processing techniques. Radars with NAIZ capabilities are especially valuable, as they will be able to continue tracking targets that pass by wind farms. The primary ADR used in the UK has been trusted to provide mitigation over much of the last decade by using NAIZs allowing radars to continue tracking plots through wind farms. However, they are no longer considered satisfactory for the future scale of OSW mitigation in the UK and new radar systems are being trialled.

Instead of relying solely upon conventional radars, infill radars have been shown as an effective solution for improving tracking and reducing clutter. Their effectiveness has been proven in a wide number of examples, from 2012 trials at Copenhagen airport and Abilene to the 2018 trials at Travis Air Force Base [144] [163]. Infill radars such as the TERMA Scanter4002 have allowed several wind farm objections to be lifted over the past few years, and some have the potential to be installed offshore, current options being considered are on substations and WTG foundations, both of which may come with unique challenges to meet optimal performance and capability requirements and integration. Optimised and discrete placement sites either within or nearby to wind farms could also be further explored. The number of infill radars required may also depend on the number and spread of wind farms in the area. More infill radars will be necessary to fill new gaps as more wind farms are constructed.

Holographic radars such as the Aveillant Theia 16a demonstrate great potential at mitigating clutter as they stare rather than scan. However, as a relatively recent radar model, there is limited evidence regarding their effectiveness against WTGs. Cognitive radars are another fresh development which describe radars capable of learning from their surrounding environments. This would allow them to continually update their parameters and adjust to any changes, such as the clutter caused by WTGs. Theoretically, such a radar would be able to provide greater mitigation than any existing radar model. However, as experimental validation in a lab environment has only begun within the last few years, they possess a very limited TRL of 4.

TMZs are a feasible solution that involve the use of SSRs or even ADS-B to track cooperative aircraft flying through wind farms. They are more commonly used in mainland Europe, to the point that a few countries have declared the majority of their airspace to be TMZs. While they would undeniably help, it would require a policy shift to adopt them in such a widespread manner in the UK, beyond the current project by project approach seen to date. Also, TMZs provide limited benefit against targets in the air defence environment. There has also been consideration given to installing transponders on the WTGs themselves, but this is currently considered an unreliable technique as SSRs cannot handle static targets.

The value of energy produced by a wind farm depends upon reliability as well as volume. Controlled shutdowns initiated by radar operators would negatively affect both of these outputs and will meet significant resistance from the wind industry, and for large scale projects and zones, it would also require considerable engagement with national grid as GW of generation capacity is taken “off line”. Shutdowns will also shorten the lifespan of WTG components due to extra stresses of stopping frequently, increasing maintenance costs for operators and customers in the process.

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Appendix 1 Stakeholder Engagement

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KTN	Steve Morris
MOD	Kevin Walton
NATS	Mark Balsdon
ORE Catapult	Thomas Wildsmith and Ben George
Orsted	Daniel Mortensen
QinetiQ	Vince Savage and Thierry Le Gall
RenewableUK	Juliette Webb
RES	Sam Johnson
RWE	Nicholas Taylor
Scottish Power	Anne Mackenzie
SSE Renewables	Ian Toothill
TCE	Louise Rich
Terma	Michael Riis
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