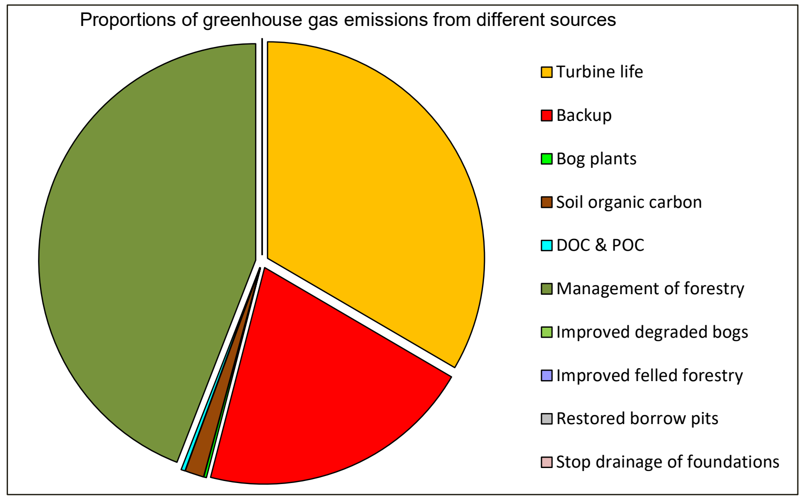
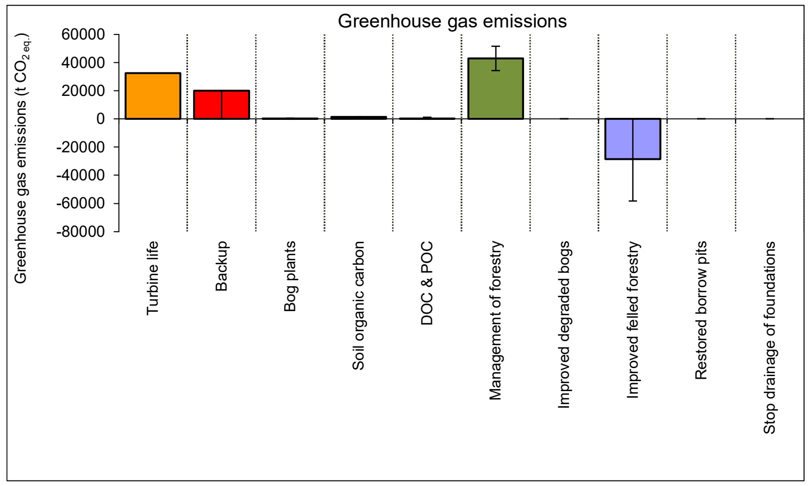
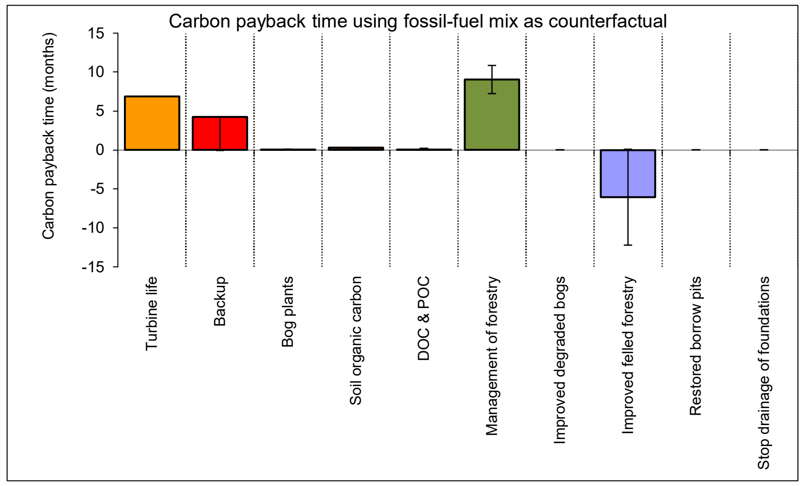
	Exp.	Min.	Max.
1. Windfarm CO_2 emission saving over…			
…coal-fired electricity generation ($tCO_2\ yr^{-1}$)	126954	125166	128147
…grid-mix of electricity generation ($tCO_2\ yr^{-1}$)	27809	27417	28070
…fossil fuel - mix of electricity generation ($tCO_2\ yr^{-1}$)	56962	56159	57496
Energy output from windfarm over lifetime (MWh)	4030301	3973536	4068144
Total CO_2 losses due to wind farm (t CO_2 eq.)			
2. Losses due to turbine life (eg. manufacture, construction, decomissioning)	32563	32563	32563
3. Losses due to backup	20057	0	20057
4. Losses due to reduced carbon fixing potential	181	61	497
5. Losses from soil organic matter	1379	826	1472
6. Losses due to DOC & POC leaching	284	0	1088
7. Losses due to felling forestry	42970	34376	51564
Total losses of carbon dioxide	97433	67825	107241
8. Total CO_2 gains due to improvement of site (t CO_2 eq.)			
8a. Change in emissions due to improvement of degraded bogs	0	0	0
8b. Change in emissions due to improvement of felled forestry	-28594	0	-58216
8c. Change in emissions due to restoration of peat from borrow pits	0	0	0
8d. Change in emissions due to removal of drainage from foundations & hardstanding	0	0	0
Total change in emissions due to improvements	-28594	0	-58216

RESULTS	*Exp.*	*Min.*	*Max.*
Net emissions of carbon dioxide (t $CO_{2\ eq.}$)	**68839**	**9609**	**107241**
Carbon Payback Time			
…coal-fired electricity generation (years)	0.5	0.07	0.9
…grid-mix of electricity generation (years)	2.5	0.3	3.9
…fossil fuel - mix of electricity generation (years)	**1.2**	**0.17**	**1.9**
Ratio of soil carbon loss to gain by restoration (TARGET ratio (Natural Resources Wales) < 1.0)	**No gains!**	**No gains!**	**No gains!**
Ratio of CO_2 eq. emissions to power generation (g / kWh) (TARGET ratio by 2030 (electricity generation) < 50 g /kWh)	**17**	**2**	**27**







Data used in barchart of carbon payback time using fossil-fuel mix as counterfactual

Greenhouse gas emissions

	Exp.	*Min*	*Max*
Turbine life	32563	0	0
Backup	20057	20057	0
Bog plants	181	120	316
Soil organic carbon	1379	553	93
DOC & POC	284	284	804
Management of forestry	42970	8594	8594
Improved degraded bogs	0	0	0
Improved felled forestry	0	0	0
Restored borrow pits	0	0	0
Stop drainage of foundations	0	0	0

Data used in barchart of carbon payback time using fossil-fuel mix as counterfactual

	Greenhouse gas emissions			Carbon payback time (months)		
	Exp.	*Min.*	*Max.*	*Exp.*	*Min.*	*Max.*
Turbine life	32563	0	0	7	0	0
Backup	20057	20057	0	4	4	0
Bog plants	181	120	316	0	0	0
Soil organic carbon	1379	553	93	0	0	0
DOC & POC	284	284	804	0	0	0
Management of forestry	42970	8594	8594	9	2	2
Improved degraded bogs	0	0	0	0	0	0
Improved felled forestry	-28594	-28594	-29622	-6	-6	-6
Restored borrow pits	0	0	0	0	0	0
Stop drainage of foundations	0	0	0	0	0	0
	68839			15		

AVIATICA

MOSSMULLOCH WIND FARM, SOUTH LANARKSHIRE: AVIATION ASSESSMENT

November 2024

Report No.23/1093/SLR/3

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1. Introduction

1.1 This document reports on an assessment of the potential impacts on aviation of a proposed wind farm at Mossmulloch, South Lanarkshire. This work was commissioned by SLR Consulting Ltd on 22 November 2023.

1.2 The Mossmulloch wind farm will consist of up to five turbines with maximum tip heights of 200 metres above ground level (m agl) at the locations in Table 1.

Table 1: Mossmulloch wind farm turbine details

Turbine no.	*Easting*	*Northing*	*Tip height (m AOD)*	*Tip height (ft amsl)*
1	263230	641753	447	1467
2	263520	642134	452	1483
3	263265	641188	452	1483
4	263640	641439	449	1473
5	263957	641739	449	1473

2. Aviation baseline

2.1 The Mossmulloch site is located approximately 30km south east of Glasgow Airport. The site is within uncontrolled airspace between ground level and 4500ft above mean sea level (amsl). Above that level is the Class D controlled airspace of the Scottish Terminal Control Area (TMA) (see Figure 1). All aircraft require a clearance from the NATS En Route (NERL) Prestwick Centre to enter the Scottish TMA and are under mandatory ATC instructions while flying within it. Most of the air traffic in this part of the Scottish TMA consists of airliner and other Instrument Flight Rules (IFR) traffic operating to and from Glasgow Airport.

2.2 The uncontrolled airspace below 4500ft is mainly used by light civil aircraft including those operating to and from Strathaven airfield, 4.5km north east of the Mossmulloch site.

2.3 The Mossmulloch site is wholly located within the Glasgow-Prestwick Avoidance Area in the UK Military Low Flying System, where military low flying does not normally take place.

2.4 The Mossmulloch site is within the assessment area for Instrument Flight Procedures (IFPs) at Glasgow and Prestwick Airports.

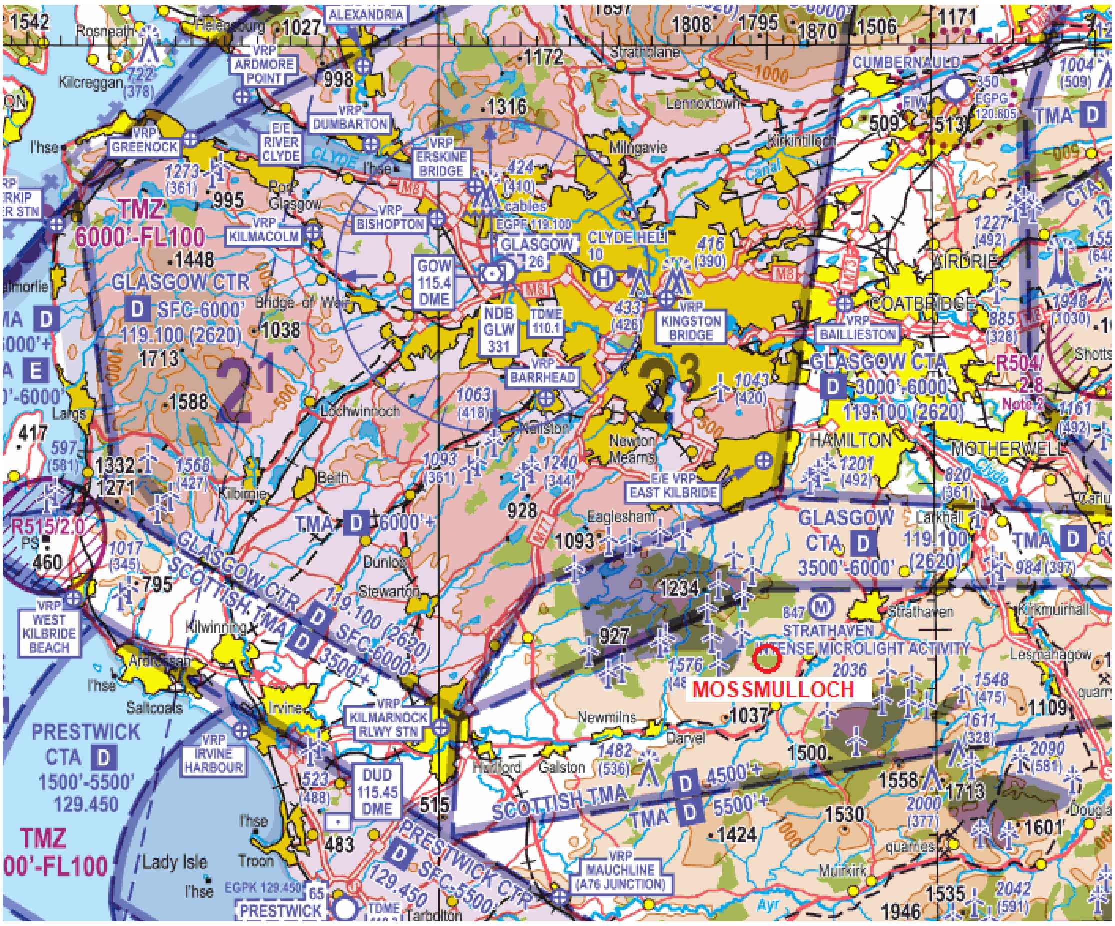

Figure 1: Controlled airspace structure in the vicinity of Mossmulloch

3. Radar line of sight assessments

NATS En Route Lowther Hill

3.1 Radar line of sight analysis shows that the Lowther Hill Primary Surveillance Radar (PSR) will have line of sight to all turbines on the Mossmulloch site (see Figure 2).

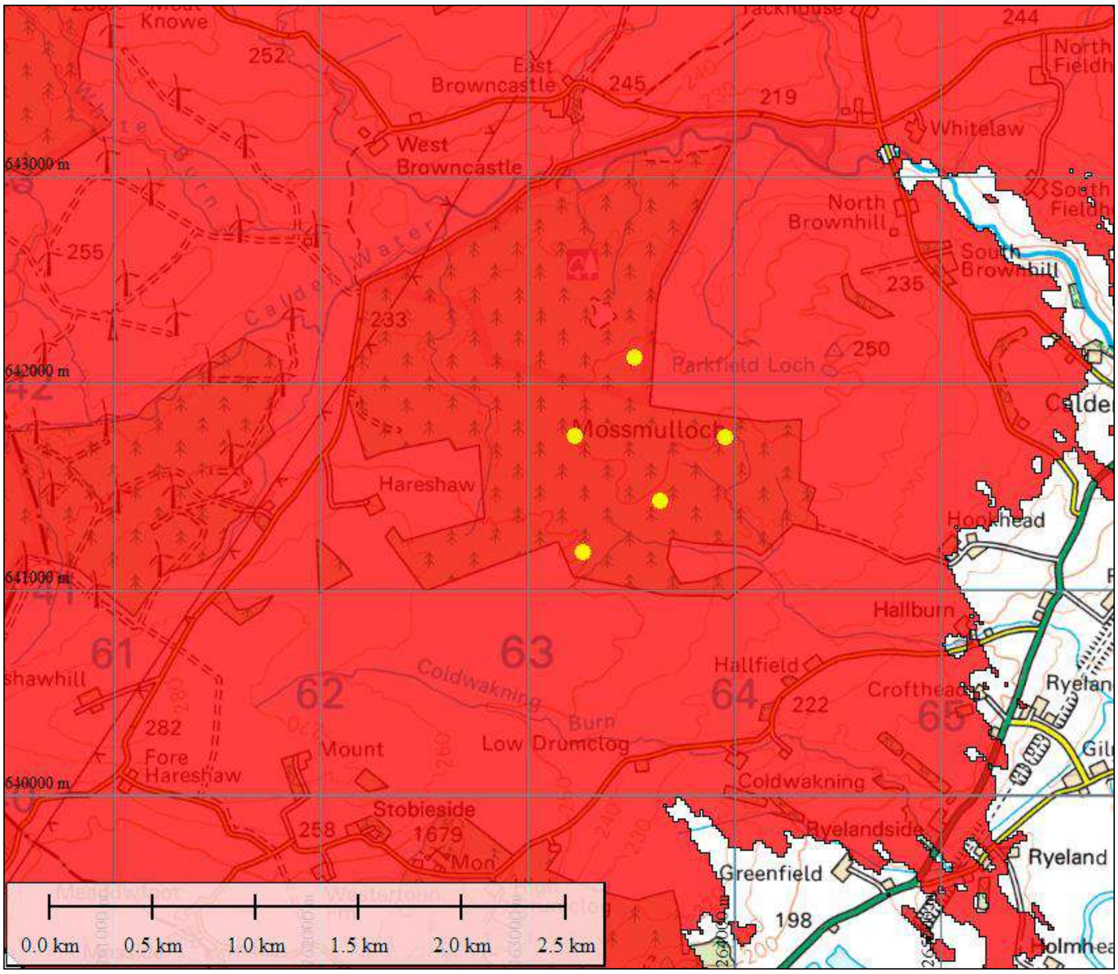

Figure 2: Lowther Hill radar line of sight at 200m agl

NATS Cumbernauld

3.2 Radar line of sight analysis shows that the Cumbernauld PSR will have line of sight to all turbines on the Mossmulloch site (see Figure 3).

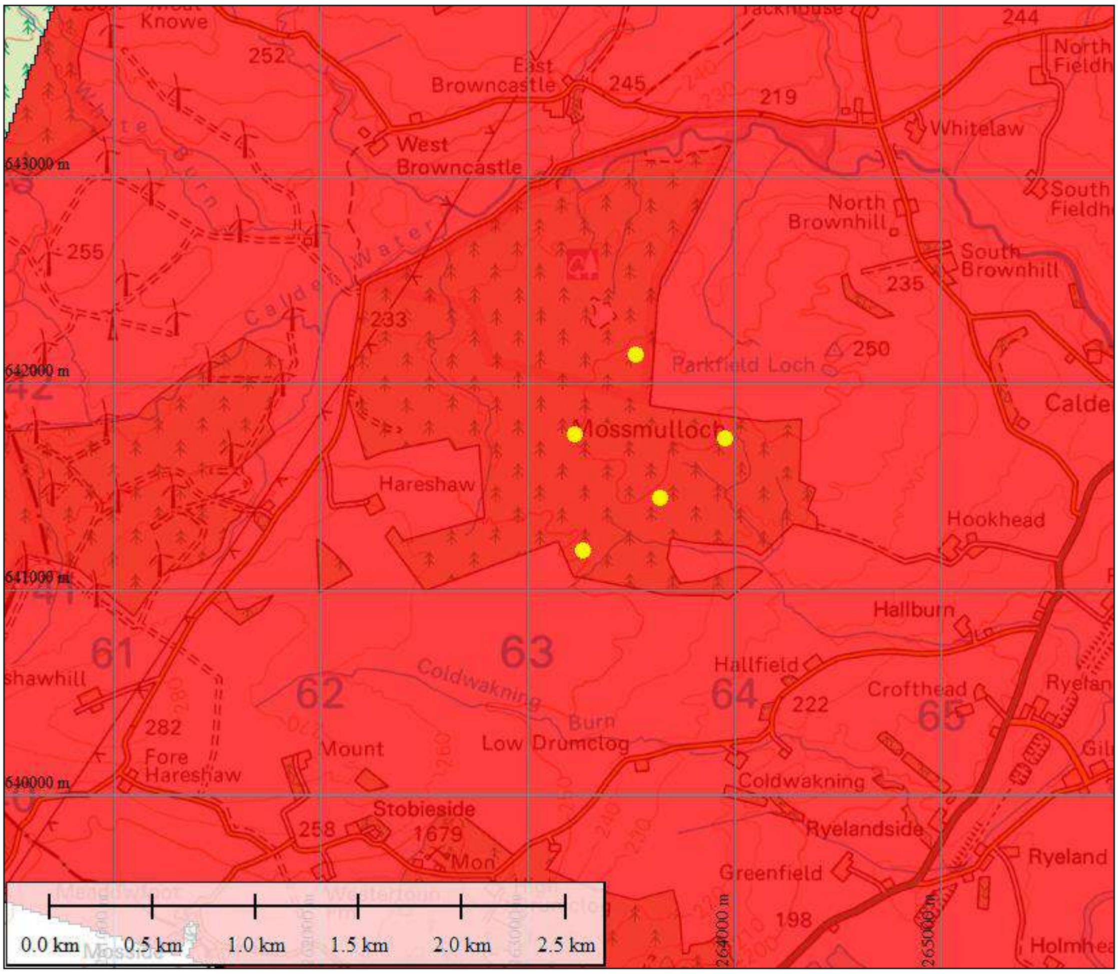

Figure 3: Cumbernauld radar line of sight at 200m agl

3.3 Consultation with NATS En Route has confirmed that the only radars with line of sight to the Proposed Development are Lowther Hill and Cumbernauld.

Glasgow Airport

3.4 Radar line of sight analysis shows that the Glasgow Airport NASR-10 PSR will have no line of sight to 200m turbines on the Mossmulloch site (see Figure 4).

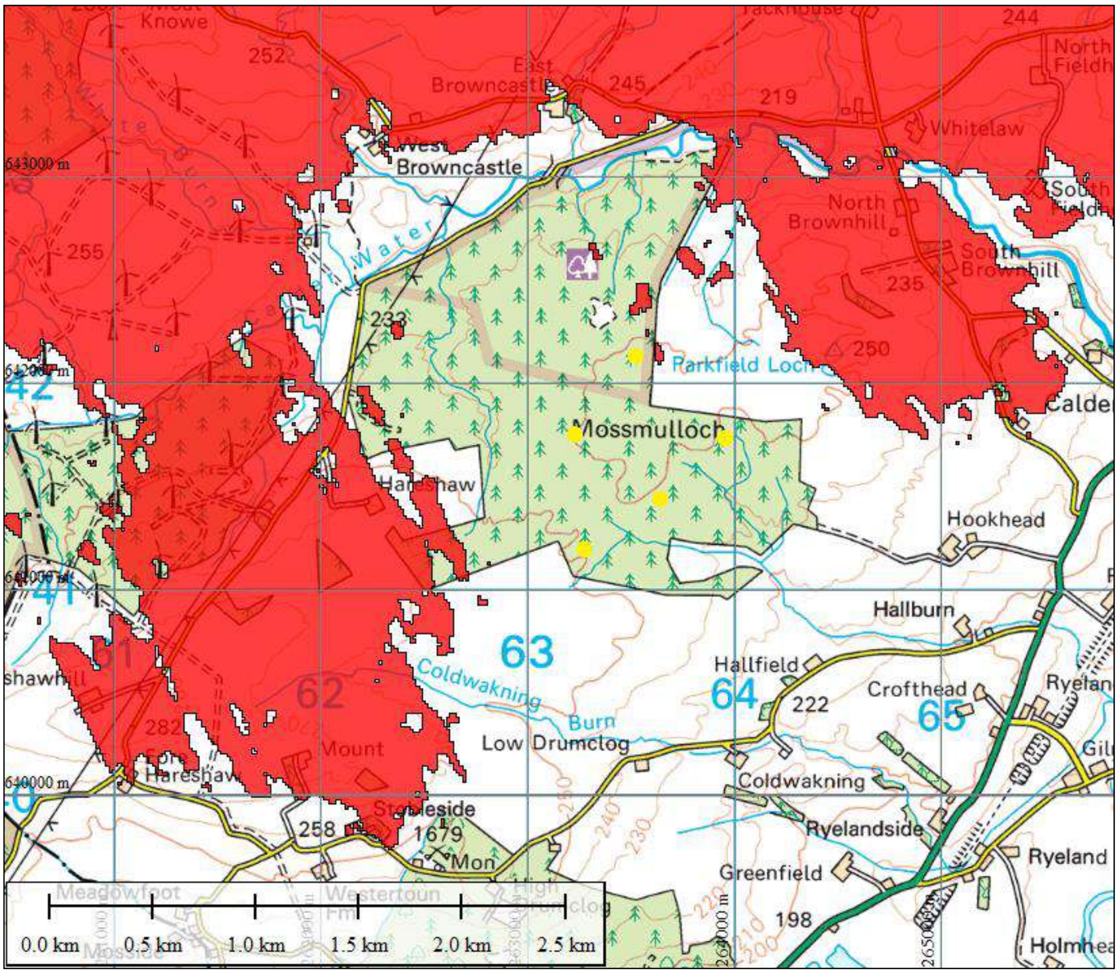

Figure 4: Glasgow Airport NASR-10 radar line of sight at 200m agl

Prestwick Airport

3.5 Radar line of sight analysis shows that the Prestwick Airport EN-4000 PSR will have no line of sight to 200m turbines on the Mossmulloch site.

4. Radar mitigation options

NATS En Route

4.1 Visibility of the Mossmulloch turbines from the Lowther Hill and Cumbernauld radars is inevitable. Technical mitigation will be required to address the effects on NATS En Route radars. The Glasgow Airport NASR-10 radar, which provides data to NATS En Route as well as to Glasgow Airport, will have no line of sight to the turbines and may therefore be usable as an in-fill radar to mitigate the effects on the Lowther Hill and Cumbernauld radars. Alternatively, mitigation could be provided by an extension of the boundary of the Kincardine radar mitigation area which has been in place since 2009 to mitigate the effects of the Whitelee wind farm on the Lowther Hill and Glasgow Airport radars.

4.2 The Applicant will secure appropriate mitigation for the effects of the Proposed Development on the NATS En Route Lowther Hill and Cumbernauld radars through a commercial agreement.

Glasgow and Prestwick Airports

4.3 The Proposed Development will not be within line of sight of the radars at Glasgow or Prestwick Airports therefore no mitigation will be required.

5. Instrument flight procedures

5.1 Instrument flight procedures (IFPs) set out minimum altitudes for aircraft to fly on departure from and approach to an airport in order to ensure 300m (984 ft) vertical separation (less in the approach phases) from all terrain and obstacles. IFP assessment areas extend to 25 nautical miles (nm) (plus a 5nm buffer) from all Initial Approach Fixes (IAFs) in a published procedure. Where a new obstacle would require any of the procedure minima to be raised, the procedure has to be re-designed and new charts approved by the CAA and re-issued.

5.2 Glasgow Airport has advised that objects with heights less than 300m agl on the Mossmulloch site will have no effect on their IFPs.

5.3 Prestwick Airport has advised that the Proposed Development will have no effect on their IFPs.

6. Strathaven airfield

6.1 Strathaven airfield applies a policy of objecting to any wind turbine proposal where a 2km radius circle around the airfield is infringed by a circle of radius 20 rotor diameters (RD) around the wind turbine, on grounds of potentially hazardous downwind turbulence effects on aircraft using the airfield.

CAA policy and guidance

6.2 The current (2016) edition of CAA guidance CAP 764 notes that while there is a significant body of research in the area of downwind turbulence, verification and validation of model outputs is still ongoing. CAP 764 also notes that:

> There are currently no Mandatory Occurrence Reports (MOR) or aircraft accident reports related to wind turbines in the UK. However, the CAA has received anecdotal reports of aircraft encounters with wind turbine wakes representing a wide variety of views as to the significance of the turbulence. Although research on wind turbine wakes has been carried out, the effects of these wakes on aircraft are

> not yet known. Furthermore, the CAA is not aware of any formal flight trials to investigate wake effects behind operating wind turbines.[1]

6.3 A revised edition of CAP 764 is in preparation and expected to be published in 2024. On downwind turbulence, the draft of the new edition advises that:

> Published research suggests a distance of 8-12 rotor diameters downstream of the wind turbine is a distance at which the turbulence effects are not expected to affect conventional aircraft flying.[2]

6.4 Two research publications are referenced for those distances downstream. The 12 rotor diameter figure comes from a 2003 literature survey of research on the characteristics of turbulence, but which had no connection with the effects of such turbulence on aircraft. 12 rotor diameters relates to the maximum distance downstream at which turbulence was scientifically measurable in that study. The figure of eight rotor diameters downstream is from a paper by the Dutch aerospace research organisation NLR.[3] While the paper is focused on the effects on helicopters, the eight rotor diameter figure itself is derived from a lateral gust speed criterion – or "velocity deficit" - for fixed wing aircraft of 6 knots. NLR found that velocity deficits of 6kts could be found at "*almost six wind turbine rotor diameters in the wake*" behind a single turbine and advised that "*it is concluded that the safe distance of eight rotor diameters for a wind farm can be regarded as a 'worst case' scenario*."

6.5 From the above it is concluded that, while academic studies have been able to measure turbulence at up to twelve rotor diameters behind a wind turbine, no inference can be drawn that turbulence can affect the safety of aircraft at that distance downstream; and turbulence effects on aircraft are unlikely to occur further downstream from a wind farm than eight rotor diameters.

6.6 The CAA has also commissioned its own research into wind turbine turbulence effects on light aircraft, using wake modelling, field measurements and piloted flight simulations. This concluded that:

> The current results show that for the small-size WTN250 wind turbine the wake is not strong enough to cause any significant upset to the aircraft at distances of 5 wind turbine diameters and longer.[4]

6.7 The 20 RD turbulence zone adopted by Strathaven airfield is not supported by the evidence from published research and CAA policy. It is understood that the airfield considers that the published research and policy

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[1] CAA SARG, *CAA Policy and Guidelines on Wind Turbines*, CAP 764, 6th Edition, February 2016, paragraph 2.54.

[2] CAA SARG, *CAA Policy and Guidelines on Wind Turbines*, CAP 764, Draft 7th Edition, June 2020, paragraph 2.51.

[3] NLR, *Determining a safe-distance guideline for helicopters near a wind turbine and wind park*, NLR-TP-2019-083, 2019.

[4] University of Liverpool, Wind Turbine Wake Encounter Study, Version 1.0, 27 March 2015, p.60. The study was unable to extrapolate the findings to larger turbines. There is no evidence to suggest that the five rotor diameter figure does not also apply to turbines with a larger rotor diameter. Equally, however, there is no evidence that it does apply.

does not take account of the greater vulnerability of microlight aircraft – the main users of Strathaven airfield – to turbulence and that, consequently, a more conservative approach is required.

6.8 A search for published data on the effects of downwind turbulence from wind turbines specifically on microlight or ultralight aircraft found three papers.[5]

6.9 Stoevesandt carried out simulations of turbulence effects on ultralight aircraft operating from the Linnich-Boslar ultralight airfield in Germany, where a large wind farm was proposed nearby. The research found that "*at the Linnich-Boslar landing field, the turbulence generated by the wind turbines is lower than the ordinary turbulence of the surrounding environment*" but cautioned that the findings may have limited application to airfields with different surrounding environments in terms of terrain profile and forestry.

6.10 Glabeke, whose analysis relates to the regulatory provisions for ultralight aerodromes in Belgium, concludes:

> *"In order to formulate an answer to the original question (i.e. what must be the minimum separation between aircraft and wind turbines?) one could state that, at the light of the results of our analysis, a safety zone of approximate 400m will be enough to avoid dangerous flight conditions. But few remarks can be stated because the effect on the ultralight aircraft is type and flying condition related. In this case the Cheetah Rotax 582, in cruise regime, flying level at hub height of the E82-2MW wind turbine.*
> *Furthermore different assumptions like uniform inlet conditions, no tip loss corrections, axisymmetry, actuator disk principle,… were used, making these results a good indication rather than an exact solution. Keeping in mind the above approximations, reducing the safety zone of approximately 3000m specified in CIRCULAR GDF-04U [1] to 400m is dangerous. With the introduction of an extra safety factor, to take into account the above remarks, one can state that a safety zone of at least 1200m should be sufficient*."

6.10 Glabeke's analysis was based on an Enercon E-82 turbine with a rotor diameter of 82m. Therefore, the recommended safety zone of 1200m equates to a distance 14.63 RDs downstream from the turbine. It should be noted that this incorporates a safety factor of three times the distance at which 'dangerous flight conditions' would be avoided.

6.11 Varriale et al found that changes in aircraft load factor generated by downwind turbulence occurred at 1 to 3 diameters downstream in low wind speeds and 1 to 7 diameters downstream in high wind speeds, but that none of the investigated cases involved load factors approaching the limits of the aircraft's structural strength or the flight envelope diagram. The paper proposes further study including flight or simulator tests.

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[5] Stoevesandt, B., Wind farms: A danger to ultra-light aircraft? Fraunhofer Research News, August 2012; Glabeke, G. et al, The influence of wind turbine induced turbulence on ultralight aircraft, a CFD analysis, von Karman Institute, presentation to European Wind Energy Association conference, Copenhagen, 2012; Varriale, C. et al, Flight Load Assessment for Light Aircraft Landing Trajectories in Windy Atmosphere and Near Wind Farms, *Aerospace* Vol.5 No.42, 2018.

6.12 In the context of Glabeke et al's suggested 14.63 RD safety zone, the distances of each of the Mossmulloch turbines from a 2km radius circle around Strathaven airfield have been calculated and are shown in Table 2. It can be seen that all of the turbines will be located further than 14.63 RDs from the 2km radius circle around the airfield.

Table 2: Turbine distances from Strathaven airfield

Turbine no.	*Easting*	*Northing*	*Distance from 2km radius circle round airfield (m)*	*Distance from 2km radius circle round airfield (RDs)*
1	263230	641753	3069	18.9
2	263520	642134	2603	16.1
3	263265	641188	3425	21.1
4	263640	641439	2983	18.4
5	263957	641739	2547	15.7

Accident and incident data

6.13 A search of the Air Accidents Investigation Branch (AAIB) website for accident/incident reports since 2005 in which the word 'turbulence' occurred was conducted on 10 January 2024. The search found 127 cases. Following elimination of duplicates the total reduced to 125 cases. Of these, only one report made reference to wind turbines. This was a landing accident at Beverley airfield in East Yorkshire involving a Piper Tri-Pacer, registration G-ARDS, in August 2021.[6] The accident report states:

> *"In reviewing the accident, the pilot reported that he believed that both the turbulence during final approach and the loss of control during the flare may have been associated with wake turbulence downstream of a wind turbine installation to the south of the airfield."*

6.14 The AAIB inspectors reviewed the possibility that the turbulence experienced by the pilot could have been caused by the wind farm. The accident report states:

> *"The AAIB contacted the airfield management enquiring whether there had been any reports of aircraft experiencing turbulence on approach and landing when with a southerly wind direction. They were not aware of any occurrences but did suggest that there can be some shadowing from the trees to the west of the clubhouse.*
>
> *The available literature would suggest that the possibility of encountering wake turbulence from the windfarm at this airfield is remote. However, it cannot be entirely ruled out. The accident aircraft flew an approach that crossed downwind of the wind turbines but the distance from the closest turbine to the location that the aircraft encountered the upset was further than 16 rotor diameters identified in CAP 764 as the furthest distance that turbulence would be*

[6] AAIB reference AAIB-27575.

encountered.[7] It was also well outside that of the most recent estimates of eight rotor diameters downwind of windfarms."

6.15 The wind farm to the south of Beverley airfield is known as Hall Farm. It consists of twelve turbines with tip heights of 100m and rotor diameter of 80m. The closest turbine is 1230m (15.375 rotor diameters) from the threshold of runway 30 and 1390m (17.375 rotor diameters) from the threshold of runway 12. The wind farm has been operational since May 2013.

6.16 None of the other 124 AAIB accident/incident reports in which the word 'turbulence' occurred make any reference to wind farms or wind turbines. However, all 124 reports were analysed to determine whether the incident occurred in an area where there are operational wind turbines in the vicinity. Four were found to have occurred within 2km of an operational wind turbine. In all cases these were single wind turbines. In each of these cases it is considered highly unlikely that downwind turbulence from the wind turbine was a factor in the accident since:

- in the first example, in Lincolnshire in June 2013, the turbine is estimated to be in excess of 30 rotor diameters away from the location of the accident;
- in the second case, in South Wales in March 2018, the turbine is approximately 17 rotor diameters away from the location of the accident;
- in the third case, in County Tyrone in April 2019, the turbine is 1400 metres away from the location of the accident;
- in the fourth case, in East Lothian in July 2020, the turbine is located south of the runway but the accident occurred during a northerly wind in which any turbulence would be blown away from the runway not towards it; and
- in none of these cases were wind turbines mentioned as a possible source of the turbulence encountered.

6.17 The CAA guidance on wind turbine turbulence also notes that, having interrogated twenty years of incident data,

"There have been no occurrence reports or aircraft accident reports related to wind turbines in the UK. However, the CAA has received anecdotal reports of aircraft encounters with wind turbine wakes representing a wide variety of views as to the significance of the turbulence.[8]"

6.18 It is concluded from the results of research studies and accident and incident data that the Mossmulloch turbines will not pose a downwind turbulence hazard to aircraft operating to or from Strathaven airfield.

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[7] The 2020 draft revised version of CAP 764 amended this advice to "Published research suggests a distance of 8-12 rotor diameters downstream of the wind turbine is a distance at which the turbulence effects are not expected to affect conventional aircraft flying". It should be noted, however, that the research referred to was not conducted to assess the potential for turbulence effects on aircraft; it assessed only whether turbulence was measurable by scientific instruments at those distances downwind.

[8] CAP 764, Draft 7th Edition, paragraph 2.52.

7. Lighting

7.1 All turbines with blade tip heights of 150m or more are required by law to be fitted with aviation obstruction lighting. The CAA has the authority to approve derogations from the requirements to light every turbine and has granted numerous such approvals for wind farm proposals where the applicant seeks to minimise the visual impact of lighting on non-aviation receptors. In addition, the visual impact of aviation lighting can be reduced through the use of lighting designs that minimise the intensity of light generated at negative angles of elevation and by the dimming of the lights in periods of good meteorological visibility. Further, aircraft detection lighting systems (ADLS) can limit the time periods when lights are switched on.

7.2 The Applicant will implement measures to minimise the extent and intensity of the visual impact of lighting on non-aviation receptors while maintaining aviation safety.

8. Conclusions

8.1 All turbines in the Proposed Development will be visible to the NATS En Route radars at Lowther Hill and Cumbernauld.

8.2 There will be no line of sight to the Mossmulloch turbines from the radars at Glasgow or Prestwick Airports.

8.3 The Applicant will secure appropriate mitigation for the effects of the Proposed Development on the NATS En Route Lowther Hill and Cumbernauld radars through a commercial agreement.

8.4 There will be no effect on Glasgow Airport or Prestwick Airport instrument flight procedures.

8.5 It is concluded from the results of research studies and accident and incident data that the Mossmulloch turbines will not pose a downwind turbulence hazard to aircraft operating to or from Strathaven airfield.

8.6 Turbines over 150m must be lit. The Applicant will implement measures to minimise the visual impact of aviation lighting on non-aviation receptors..
