South Kyle II Environmental Impact Assessment Report

Technical Appendix 5.6 - Visibility of Aviation Warning Lights

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Visibility of Aviation Warning Lights

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Executive Summary

All wind turbines of height greater than 150m require visible aviation lighting unless dispensation is given by the CAA. In dark rural areas this lighting can be the only light source in particular locations. How bright that light appears to any observer depends on a variety of complex factors, but an estimate can be made for a “typical” person, dependent primarily on distance from the light, angle at which it is viewed, how much ambient light is present, both local and in the view as a whole, and the weather. In poor visibility the aviation lights switch from 200 to 2000 candela but this is found to be of limited importance in their overall appearance given the considerable obscuration between the lights and distant observers. When considering the proposed South Kyle II Wind Farm, the lights appear brightest when seen near the horizontal or just above, such as the night time viewpoints 13 and 14 considered here. A slightly lesser effect is seen from from closer viewpoints which are typically viewing the lights below the horizontal, such as VP7. The brightest apparent lighting is typically seen in good weather in both instances. In these circumstances they appear similar to bright red stars low on the horizon. As a rough rule of thumb, this is no brighter than ordinary car brake lights at a distance of about 6-7km. As a result, the lights typically only become easily visible well into twilight.

1. Preamble

1.1. This background paper has been prepared by Dr Stuart Lumsden. Dr Lumsden has almost 40 years of experience in observational optical and infrared astronomy, and over the past decade has provided advice and evidence regarding the use of aviation warning lights in dark environments. A fuller description of his experience is given in Section 9. This paper provides background information on this topic with specific regard to the proposed South Kyle II Wind Farm.

2. Introduction

2.1. South Kyle II Wind Farm is a proposed development in East Ayrshire, adjacent to the recently constructed South Kyle Wind Farm. It lies approximately 4km from the north eastern corner of the Galloway Forest Dark Sky Park (see Section 0 for a description of the Dark Sky Park and the framework governing the protection of its night-time characteristics). The most north-easterly corner of the Dark Sky Park lies just south of Dalmellington.

2.2. The proposed development consists of 11 turbines, all 200m at tip height. Five of these turbines (T01, T04, T05, T09 and T10) will bear aviation warning lights at hub height (115m), following agreement with the CAA on a reduced lighting plan as set out in their letter dated 22 November 2023, reference Windfarms / South Kyle II attached as Appendix 1. The CAA have further agreed that there is no need for 32 candela mid-tower lighting, which reduces local visibility of lighting considerably.

2.3. The hub lights will operate at 200 candela when the visibility is greater than 5km in any direction, and 2000 candela when it is poorer. The switch-over will be made automatically according to the readings on a local visibility sensor. Unless otherwise noted, the values used in this report are the 10% levels appropriate to good weather.

2.4. The local authorities around the Dark Sky Park have adopted planning guidance in relation to the impact of development on the qualities of the night skies within the Dark Sky Park itself. This report will therefore mainly focus on the night-time environment. This report will identify the factors that impact on night-time vision, the existing night-time characteristics of this region including the different zones that make up and surround the Dark Sky Park, and the impact of the atmosphere on the attenuation of the light as it passes from the wind farm to other locations.

2.5. The agreed nighttime viewpoints are VPs 7, 13 and 14. VPs 13 and 14 were chosen as locations that see the maximum luminous intensity of the lights. VP 7 was requested by consultees and is the previous location of the Scottish Dark Sky Observatory. In addition, consideration will also be given to two other points adjacent and within the Dark Sky Park, using the ZTV of the lit turbines as a guide, Figure 5.4d: Theoretical Visibility of Aviation Lighting by Intensity of the EIAR. One is near the Roundhouse Café on the Loch Doon road (at the northern end of the loch) – a short strip of road along the loch at this point has visibility of the wind farm, but is NOT in the Dark Sky Park; the second is the car park at the southern end of Loch Bradan, which is accessible by the Carrick Forest Drive (when open) from the junction at Stinchar Bridge on the Straiton-Newton Stewart Road, and

which lies just north of the Core region of the Dark Sky Park (see Section 4.2). Both these locations have been visited at night by amateur astronomers, and the Forestry Commission Scotland advertise car parks by Loch Doon and Loch Bradan as good places to view the night sky.

2.6. The selected viewpoints vary in distance from the turbine lights as well as the elevation angle the lights are viewed at. VP7 is closest (5.7-7.9km), but only by less than 1km compared to the Roundhouse Café. Loch Bradan is the most distant (14-16km from the lights), with both VPs 13 and 14 in the range 10-13km. Both VP 7 and the Roundhouse Café location have somewhat negative angles of elevation (-2 degrees or more), whereas VPs 13 and 14, being elevated themselves, view the lights at or above the horizontal. Loch Bradan being more distant has a more modest negative elevation angle (about -0.5 degrees). Both distance and angle of elevation strongly effect how bright the lights appear at any location.

2.7. It should also be noted that Viewpoint 7 was the original site of the Scottish Dark Sky Observatory, which was destroyed by fire. Trustees of the Scottish Dark Sky Observatory have recently announced that they will rebuild on a different location at the former Clatteringshaws Visitor Centre, well away from Dalmellington and the region considered here[1]. VP 7 is still a reasonable match to the expected visibility of the lights on the upper part of the Loch Doon road in the vicinity of the Craigengillan Estate.

2.8. This report will only summarise the principles concerned[2] – the full details can be found in previous inquiry and technical reports by the author (e.g. for the Inquiry regarding the now consented Clash Gour windfarm (Lumsden, 2020a) (Lumsden, 2020b). In particular, Sections 1.3-1.5, and 1.6.1-1.6.5 and 1.7.1-1.7.3 of (Lumsden, 2020a) provide extra general detail; from (Lumsden, 2020b) the parts that provide deeper general background, as opposed to specific material on the Clash Gour proposal, are Section 2 which discusses the units used in measuring light, Section 3 which provides greater detail on human vision, Sections 4 and 5 which discuss the propagation of light through the atmosphere, Sections 6.1-6.4 which discuss properties of the atmosphere and what is meant by visibility, Section 8 which provides a more detailed description of the phases of twilight and Appendix B which outlines the models used to create Error! Reference source not found., Error! Reference source not found. and Figure 7.

2.9. Aviation lighting is an inherent mitigation requirement for air safety due to the turbine measuring greater than 150 m above ground level. This is a legal requirement under Article 222 of the ANO 2016 unless the CAA dictate otherwise. Aviation warning lights of the type required emit only in the red (at 625nm), and their brightness varies with the elevation angle[3] they are viewed at. The old model of Contarnex light used in the analysis here (see Figure 10) has more light overspill than modern variants, so provides a conservative estimate of the visibility expected. It has the advantage of having been seen in-situ by the author, as well

[1] https://www.bbc.co.uk/news/articles/c0mzppkw8pyo

[2] A brief glossary of terms that are likely to be unfamiliar is given in the Appendix.

[3] See Section 8 for a definition of elevation angle

as others including the Reporters for the Crystal Rig IV and Windy Standard III Inquiries.

3. Night-time Vision and Light Pollution

3.1. Most people have very similar day-time vision, after appropriate correction with glasses etc. The same is not true at night. It is therefore not possible to give a definitive statement as to how a night-time scene will appear to an individual. The most important factor in driving this variation is age, however. Given this caveat, we can consider some general principles (Lamb, 2016).

3.2. In a truly dark environment, the bulk of our vision relies on the more sensitive, monochrome, rods in the human eye rather than the colour sensitive cones that make up our daytime vision. This slightly limits our ability to see a faint red source, since rods are insensitive to red light. This leads to a gradual "blue-ing" and fading of colour response as the light levels drop, as the cones effectively "switch-off" in the transition. In this case, the faintest red object visible to the human eye is one which just triggers the colour sensitive cones, which is brighter by a factor of 2-3 than the faintest white object we can see.

3.3. The main effect for the areas being considered is not in good weather (the lights are close enough to trigger the colour-sensitive cone response) but in poor conditions when the lights seen at a distance are perceived as being much fainter (see Figure 7). A typical person will not see a red light of illuminance fainter than about 0.01 micro-lux.

3.4. True dark adaptation also takes time (it can be up to 30 minutes for full dark adaptation, though a moderate degree is obtained within the first few minutes). Someone who is in, or emerging from, a lit environment will therefore have limitations on how faint an object they can see. The limits such a person can see will be many times brighter than a dark-adapted comparator. Effectively, individuals in this situation have a residual colour sensitive cone response which slowly gives way to a monochromatic rod response. Where street lighting exists in a settlement full dark adaptation is never possible if the person sees any part of that emission directly, and scattering in the atmosphere and from surfaces can mean that even indirect emission can have a significant impact on dark adaptation.

3.5. In addition, if there is any background light, whether that be natural background light such as twilight, or a moon at or near full, or more distant man-made light pollution, the eye is limited by a contrast effect. The effect varies with the brightness of the background and whether cones or rods are more dominant. In the earliest phase of twilight, the sky will be too bright to see any but the very brightest stars for example.

3.6. As a rough guide, for the situation considered here, it is generally difficult to see a light source that is a few percent brighter than the background, with the exact percentage depending on how bright that background is (the relationship is not linear). In general, a brighter diffuse background means that any light (whether turbine light or star) must itself be brighter than the background to be seen against it. The data used to quantify this effect exactly are based on rather old and limited experimental observations – the main take-away message therefore is simply that

any additional light source will make it “harder” to see the warning lights in the sense that they will appear less “obvious” to the eye than in true darkness.

3.7. This is less true for a camera image, which is one of the reasons why night-time photography may not represent faithfully what the eye can see. Viewing the resulting photograph on a monitor, where you can tweak brightness, or on paper simply adds to the differences between a camera image and human observation.

3.8. Man-made light pollution includes a diverse variety of sources, all of which affect dark adaptation and the contrast issue noted above. Someone leaving a lit house for example will take time to become dark adapted. For an observer in a settlement, local street lighting (even at the level of one light) can reduce their ability to see faint lights because of the contrast between the local lighting and the more distant object. Car headlights have a similar though more transitory effect for an external viewer but limit the ability of the driver to see external faint lights in a similar fashion to street lighting.

3.9. Of greatest impact in much of the relevant region however will be the more distant light pollution arising from “light domes”. This is where lights in larger settlements form visible domes above the horizon. The domes arise both from direct lighting that escapes upwards (e.g. misdirected security lighting, lights in most open plan multi-storey offices) but more typically from light scattered from the ground back upwards, where streetlights are the predominant source. The replacement of older lighting units by modern LED lights has sometimes exacerbated this problem, since LED lights are intrinsically bluer than older types of streetlights, and blue light scatters much more than red, so forms light domes more readily. This is not always represented fully in the satellite images of night-time light pollution (e.g. Figure 1) since the satellite is not sensitive to light of shorter wavelength than mid-green – it misses blue light entirely. Some locations have however improved – Carsphairn is genuinely darker than the pre-LED lighting for example.

3.10. In summary, what is visible at night will vary greatly between individuals, and even more between the settings of those individuals. In what follows it is assumed that the “typical” response lies at the greater sensitivity end of this variance except where noted, and the satellite background light level will be assumed as a guide to the light pollution present.

4. Night-Time Characteristics

4.1. The Galloway Forest Dark Sky Park holds Gold Tier status with the DarkSky International (formerly the IDA) since 2009. Pre-existing lighting is not limited by the award, but over time that has gradually reduced as well. For example, the Loch Bradan water treatment works used to be easily visible in satellite images,

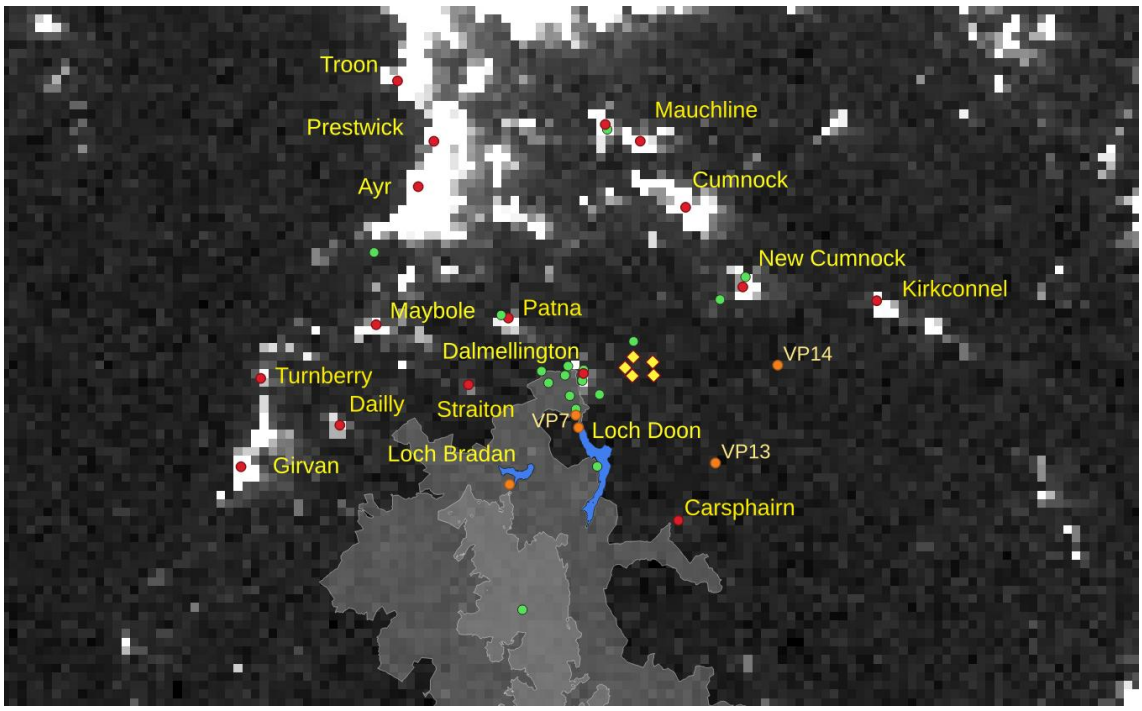

Figure 1: Night-time satellite image of the region around South Kyle. The lit turbines are marked as yellow diamonds. A selection of the settlements in the area are marked in red and named to indicate where existing light pollution arises. Viewpoints for daytime only assessment are shown in green. The three viewpoints for night-time assessment are shown in orange and named, along with two other points within the Dark Sky Park known as previously being used for amateur astronomy. The Dark Sky Park itself is indicated by the grey shaded region. The inner core (light grey) is surrounded by the buffer zone (darker grey). A "transition" zone (not shown on Figure 1) is also defined which extends 10 miles from the boundary of the Park, extending out as far as Cumnock and New Cumnock for example. Finally, the locations of both Loch Doon and Loch Bradan are shown for clarity. The image shown here is a composite of cloud and moon free nights from October 2023 to March 2024.

but is now much less prominent.

4.2. The Dark Sky Park is divided into a Core zone (which entirely encompasses the Merrick Wild Land Area and is shown as light grey in Figure 1) and a Buffer zone (darker grey on the figure). These have stringent lighting conditions (none at all in the Core, shielded and minimal downwards pointing light in the Buffer). A further transition zone, where it is noted that it is "desirable that lighting installed within this zone is dark sky friendly", extends 10 miles beyond the Buffer; the proposed South Kyle II Wind Farm is within the transition zone. For wind farms, the guidance in this transition zone is that it is preferable that a maximum number of infrared lights be used (see the table on page 17 of East Ayrshire Council Dark Sky Park Lighting Supplementary Guidance). The reduced lighting plan for South Kyle II has only five of the eleven hubs lit in the visible, and no mid-tower lighting, so is in line with this strategy. The nearest point of the Core area to the lit turbines is

about 15.5km, and Merrick itself lies 22km distant, reducing the apparent brightness of the lights in those regions.

4.3. The proposed South Kyle II Wind Farm itself is located on a dark site. The nearest significant settlements are Dalmellington and New Cumnock, though some additional lighting will be present on an intermittent basis due to the B741 that links the two. It is clear from Figure 1 that the two towns show a significant degree of lighting for their size.

4.4. Other wind farms either exist, are under construction, or are consented, within 15km of the proposed development. Two of these, the consented Windy Standard III Wind Farm and Overhill Wind Farm, have a need for visible turbine lighting.

4.5. The three agreed nighttime viewpoints, VPs 7, 13 and 14 experience different local environments. Both VPs 13 and 14 are summits of hills in dark areas, and distant from any other lighting. VP 7 is the site of the former Dark Sky Observatory on the Craigengillan Estate, and whilst locally dark, it looks out over Dalmellngton to the north. The additional location at Loch Bradan is very dark. Only two properties lie nearby, and there is no lighting at the southern end of the Loch. The final location on the Loch Doon Road is typically dark, but does lie near the Caravan Park to the south. The terrain shields this stretch of road from the direct effects of street lights in Dalmellington. All locations have indirect light pollution, generally looking towards the northern half of the sky, as discussed in detail at 4.6. Only viewers looking from northwest/east of the lights will see them against a dark background. Mostly this limits such views to very distant observers, where the aviation lights will appear faint anyway. The two obvious locations that exemplify this on the ZTV - Figure 5.4c: Theoretical Visibility of Aviation Lighting by Intensity are near Patna or Cumnock.

4.6. In general, views from south or south-east of the proposed wind farm looking northwards, or north-westwards, including VP13, will see more distant general light pollution from the central belt, or the built-up area around Ayr. This will decrease the contrast of the lights and make them less prominent. From VP13 the lights will be seen in the background to those from Windy Standard III and in the foreground of the lights at Overhill. VP13 looks at all three sites from above, so the primary driver of the apparent brightness to the observer is just the distance. The relative proximity of Windy Standard III means those lights will appear much the brightest. In excellent visibility, they will typically be about 4-5 times brighter than South Kyle II, and more than ten times brighter than Overhill. South Kyle II therefore adds only modestly to the light seen. VP14 by comparison has less background, with only Girvan along the line of sight through South Kyle II. From this viewpoint, Windy Standard III, South Kyle II and Overhill will appear as distinct groups, though Overhill has Ayr as a background. Again the lights are seen from above, so the dominant factor in the brightness at the observer is distance. Again Windy Standard III will be the brightest, though the difference is less prominent than at VP13 (about a factor of two between all three wind farms).

4.7. Both VP7 and the Loch Bradan and Loch Doon locations view the lights against the background of New Cumnock (though the effect is diminished by the high ground that lies between them). However, the two locations differ in their local light pollution (VP7 has a clear view of Dalmellington to the north, the southern end of Loch Bradan has essentially no lighting when forestry operations are not

present). Again, some decrease in contrast is expected if local light pollution impacts on a viewer's vision, even if it is tangential to the line-of-sight. This is not shown clearly by the night-time photography from VP 7 (Figure 5.36 Viewpoint 7: Craigengillan Estate (Dark Sky Observatory), since the camera has a narrower field-of-view than the whole of the human eye (the 50mm lens is designed to match the view of the centre of the field of human vision, which in totality spans more than twice that angle). The lights from the proposed South Kyle II Wind Farm and consented Windy Standard III Wind Farm will again be more obviously distinct clusters of similar brightness when viewed from VP7 though Overhill is not visible from either there or Loch Doon. Loch Bradan may have some visibility of Overhill, in the same general direction as Cumnock, and a full view of both South Kyle II and Windy Standard III. However, the much greater distance to all three, and the fact that the lights are viewed below the horizontal, means the brightness is much less than any other location considered. Again the wind farms will appear as separate clusters of lights.

4.8. Other natural sources of light also need to be considered. The two main ones relevant to dark sites are the presence of a near full moon (produces about 0.1 lux illuminance at maximum), and the presence of twilight sky.

4.9. The presence of a near full moon (roughly full +/- 3 days) is significant because of the contrast issue discussed in 3.5, and because it is above the horizon for much of the night. The sky brightness given by the moon varies by about a factor of 15 between full moon and +/- 7 days of full moon and is not significant outside that period.

4.10. The importance of twilight depends on which direction you are looking, and whether this is sunset or sunrise. For receptors (people) keen to experience dark skies it is more likely that they will be present during evening twilight, so this is assumed hereafter. It is straightforward to ascertain from the comments below what the likely effect will be during morning twilight by comparison.

4.11. Twilight is most relevant for Viewpoints 13 and 14 at sunset. The bright part of the twilight sky at sunset in summer is sufficiently near the line of sight from these viewpoints to the wind farm as to form a background. Twilight falls into three phases called civil, nautical and astronomical twilight, depending on how far below the horizon the sun is. Civil twilight is bright – even the brightest stars only appear near its end. The aviation lights are turned on 30 minutes after sunset during civil twilight. Nautical twilight is given that name as landforms can still be distinguished against the remaining brightness on the horizon – the lights will be visible during most of this phase from anywhere within 20km. Astronomical twilight is when the full array of stars appears. Full night follows. The main impact of twilight is felt during the summer months. For the three months around mid-summer there is no astronomical twilight, and for six weeks no nautical twilight either.

4.12. Civil twilight at sunset, until around the start of nautical twilight, is the most likely time that walkers will still be present near VPs 13 and 14 given there are no permanent marked paths. The bright twilight sky will make the aviation lights appear less obvious to any such receptor. This is clearly shown by Figure 5.37 Viewpoint 13: Cairnsmore of Carsphairn. The image was acquired just at the end of civil twilight for that July night, and the brightness of the north-western sky is

clearly evident, so that even the lights from the built up areas along the coast such as Ayr are greatly suppressed by comparison. At any time before midnight during the summer months, when the western and north-western sky are still bright, the twilight together with the background man-made light pollution, will make it hard to perceive the lights on clear nights. Cloudier nights are darker as shown by Figure 5.38 Viewpoint 14: Blackcraig Hill, even though this image was actually taken earlier in civil twilight than VP 13.

4.13. By comparison, in evening twilight the car park at Loch Bradan would see the darkest background sky against the wind farm. Although the difference in sky brightness between the point of sunset and its anti-centre is only a factor of a few, that is sufficient to ensure that it is somewhat easier to see the lights looking east at this time. The main difference to looking westwards though will be the lack of persistent twilight during summer in that direction in the evening. The approximate effect of the twilight at this location is shown by Figure 5.36 (VP 7's night-time image), which was taken near the end of civil twilight. There is a very faint brightening at the far left (north-east) edge consistent with the time of night but it is not nearly as noticeable as the image facing east from VP 13.

4.14. The nearest point in the Core area of the Dark Sky Park to the proposed windfarm with visibility of the lights is approximately 15 km away (just south of Loch Bradan, to the west of the Carrick Forest Drive around Shiel Hill) so the same conclusion applies to the northern part of the Core area as well.

4.15. If the twilight is hidden by cloud the contrast between a light and a truly dark background will increase, making it more visible near to, or even at, its switch on time. This does not necessarily reduce the effect of human sources of light pollution however - particularly as such lighting can be reflected back strongly to the viewer from the cloud base if intense enough. The overall conclusion is that looking north or west towards the windfarm will generally tend to have higher background light of all kinds, whilst looking east will tend to show the darkest background.

5. Meteorological Characteristics

5.1. There are no detailed meteorological records for the wind farm site itself. There are four Meteorological Office synoptic weather stations at locations which can be considered representative of the properties of the wider region however. These have modern automatic visibility sensors that measure the particulate concentration in the air along a path of only about 1-2m. The sensor is the same as those used on wind farm sites to trigger the increase in brightness of the aviation warning lights. They are not sensitive to direction, and obviously do not measure what is happening to the visibility further away. The particle concentration is extrapolated to a defined "visibility" according to regulations.

5.2. The nearest of these weather stations to the proposed South Kyle II Wind Farm are at Prestwick (about 30km away). However, Prestwick is renowned for its good weather, which may not be characteristic of other locations, even those only a short distance away inland. For comparison therefore, data was also sought for the meteorological station at West Freugh (also a coastal location near sea-level, about 10km south of Stranraer and 50km from South Kyle II Wind Farm). In addition,

results from both Drumalbin (50km north, at 75m AOD) and Eskdalemuir (70km east at 236m AOD) provide measures of how the weather varies with altitude and inland.

5.3. The Met Office MIDAS Land and Marine Surface Stations Data[4] are publicly available under v3.0 of the Open Government Licence, and provide measures of visibility and cloud base height for all four stations. Hourly data were considered from 2014 onwards, as that period covers full automated measurements at all sites. It should be noted that the data for visibilities and cloud base heights are given as binned ranges rather than discrete data, and these are what have been used here. The cloud base heights are presented as-is, but the visibilities have been rebinned into equal 5km intervals for clarity. The data can be sub-divided by season and time of day. Only the night-time results are shown here as

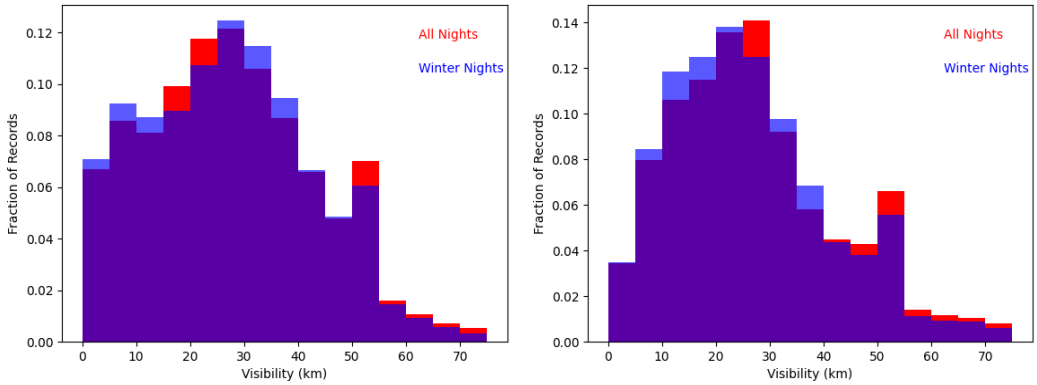

Figure 2: Visibility records for Drumalbin (left) and Prestwick (right).

summarised by Tables 1 and 2.

5.4. There are similar changes of visibility between winter and summer (poorer/better visibility respectively), consistent with these differences largely being due to air temperature. As the air cools, the dew-point becomes closer to the actual temperature, and aerosols start to form larger clumps (nucleation) in the air, largely through the action of the water vapour present.

5.5. Visibility data for these sites are summarised in Tables 1 and 2. The actual histograms for Drumalbin and Prestwick are shown in Figure 2. The key difference in terms of median visibility clearly related to the altitude of the site, with Eskdalemuir showing much lower values, especially in winter, as might be expected. Prestwick's reputation as a fog-free site is reflected by the low fraction of nights with less than 5km visibility. The fractional similarity of number of records with visibility less than 5km for Drumalbin and West Freugh suggests these are a better estimate for the general region at lower altitudes. However, since the turbine hubs are actually at a greater altitude than Eskdalemuir, these should be treated as a lower limit on the fraction of times when the lights may operate at 2000cd. The reason for this is best seen by looking at the altitude of the lowest cloud base height for each site.

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[4] Met Office (2019): Met Office MIDAS Open: UK Land Surface Stations Data (1853-current). Centre for Environmental Data Analysis [online]. Available at: http://catalogue.ceda.ac.uk/uuid/dbd451271eb04662beade68da43546e1

Station	Median (km) all nights	Median (km) summer nights	Median (km) winter nights
Drumalbin	27	28	27
Eskdalemuir	17	20	14
Prestwick	25	25	24
W. Freugh	20	18	20

Table 1: Median night-time visibilities for the four selected Met Office stations.

Station	Percentage of nights with less than 5km visibility	Percentage of summer nights with less than 5km visibility	Percentage of winter nights with less than 5km visibility
Drumalbin	6.7	5.8	7.1
Eskdalemuir	16.3	12.6	19.9
Prestwick	3.4	2.8	3.5
W. Freugh	7.5	7.5	6.8

Table 2: Fraction of nights when the visibility is measured as less than 5km.

5.6. These automated sites measure the altitude of the lowest level of the cloud base using LIDAR. The cloud base height informs the likelihood that elevated land such as at the windfarm is within cloud.

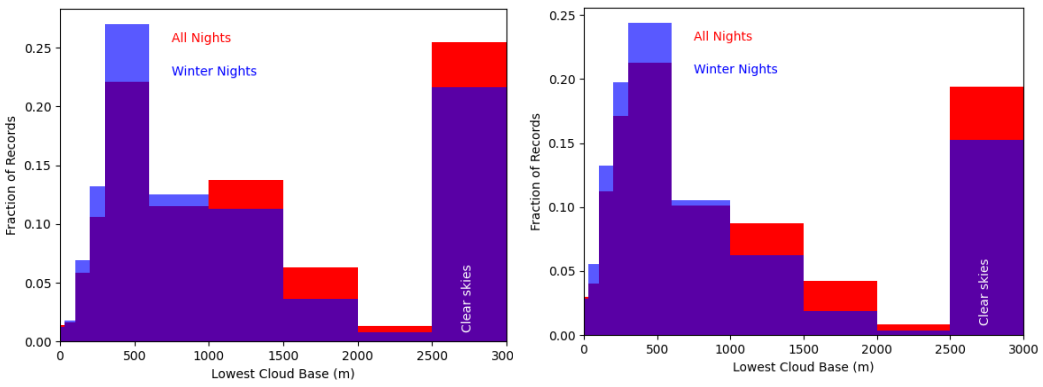

Figure 3: Cloud base records for Drumalbin (left) and Eskdalemuir (right). The differences are consistent with the higher altitude of the Eskdalemuir site.

5.7. The results for all nights, with winter nights highlighted separately, are shown in Error! Reference source not found. for Drumalbin and Eskdalemuir. The difference in the histograms for altitudes below 500m can largely be accounted for by the higher elevation of the Eskdalemuir site. The same is true when comparing

these to West Freugh and Prestwick. Essentially, as a reasonable first approximation, the cloud base is at a similar altitude above sea level for all sites, with the expectation that it will rise slowly as clouds pass over more elevated ground. This reflects the fact that, at its most basic, the cloud base is the height in the atmosphere where the temperature drops below the dew point, and temperature is a function of altitude.

5.8. The turbine hubs at the proposed South Kyle II Wind Farm are 475-575m above sea level. Cloud base data are only recorded in bins at 50, 100, 200, 300 and 600m. The best match to the turbine hub height is therefore the <600m records for Prestwick or West Freugh or the <300m record for Eskdalemuir. Prestwick and West Freugh night-time records are similar as might be expected with 42-46% having a lowest cloud base below 600m. The Eskdalemuir record is slightly poorer with 56% of all records having a cloud base height below 300m.

5.9. It should be emphasised that if the turbine hubs are above the cloud base they will essentially be equivalent to being viewed through thick fog at ground level. The effective visibility in this case is much less than 5km. Therefore, although the lights may be operating at 2000cd, they will largely be invisible to most receptors (see also Figure 7).

5.10. A better estimate of the time when the lights may be visible below the cloud base whilst operating at 2000cd is to examine the number of records which have cloud base above hub height, but visibility below 5km. This is a small number, 0.5% for Prestwick and clouds above 600m, and 1.3% for Eskdalemuir and clouds above 300m

5.11. Overall then it seems likely that most of the time when the lights will operate at 2000 candela will be in conditions where they will not be seen beyond 5km, as will also be demonstrated in Error! Reference source not found., Error! Reference source not found. and Figure 7. Further consideration requires the use of numerical models to quantify the extent of any attenuation.

6. Attenuation of Light

6.1. Any aerosol present attenuates light as it propagates through the atmosphere, by a combination of scattering and absorption. In a vacuum, the light would diminish only through geometry as it spreads out, diminishing by 1/(distance^2). Adding aerosols can make this reduction much more extreme (think of thick fog for example), since their effect is an exponential reduction dependent on the aerosol density.

6.2. Modelling this process requires a knowledge of how bright the light is initially, its distance to the observer, and the density of aerosols present in the air. Visibility is intrinsically linked to the density of aerosols – higher density, poorer visibility and vice versa. We can therefore use the meteorological data to estimate the likely aerosol density, and hence how bright the lights appear to the observer.

6.3. The dramatic effect of aerosols can be demonstrated by looking at how much attenuation is expected at a given distance and altitude as the visibility changes (see Error! Reference source not found.). In this case the aerosol density is allowed to

vary along the line of sight since the turbines typically lie at a different altitude than the observer (see Lumsden 2020b for details). Typical values appropriate for the hub height and altitude for the turbines at South Kyle II of 500m, and for the observer at the lower altitude viewpoints (250m) were used. The exact choice of these parameters does not significantly affect the result. In order to be conservative, free-air aerosol densities as a function of altitude are used. In practice the aerosol density may be higher, making the visibility worse. Winds push material upslope, so even at altitude the aerosol density at ground level will be higher than naïve free-air prediction suggests.

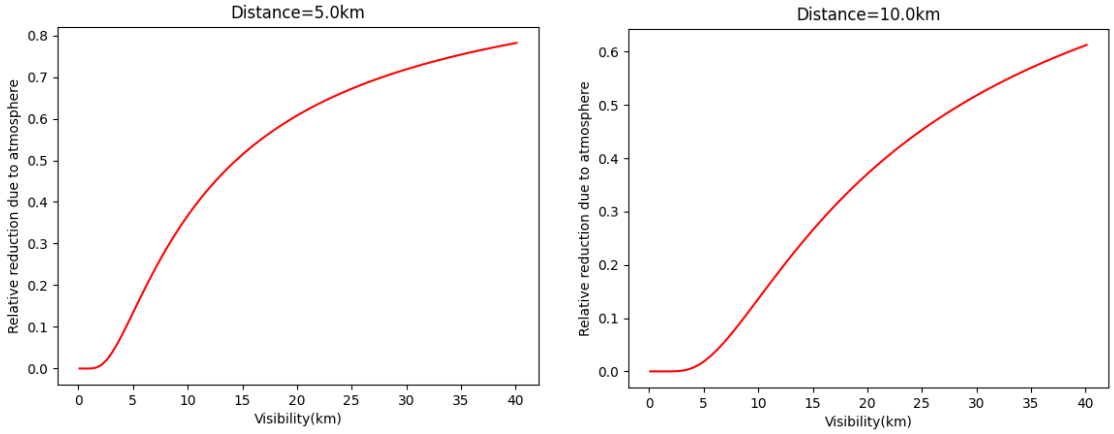

Figure 5: the panels show how much the light is attenuated for an observer as a function of distance and visibility. The left panel represents a distance and altitude typical of locations near the wind farm such as VP7, the right approximates the effect near VPs 13 and 14. The attenuation is exponential, so drops rapidly at poorer visibilities, which is difficult to see on the linear y-axis shown. Only the attenuation due to the atmosphere is shown in these panels – the reduction due to distance is not included. It can be seen that very poor visibility (less than 1km as might be expected when the hubs are above the cloud base) reduces the apparent brightness significantly.

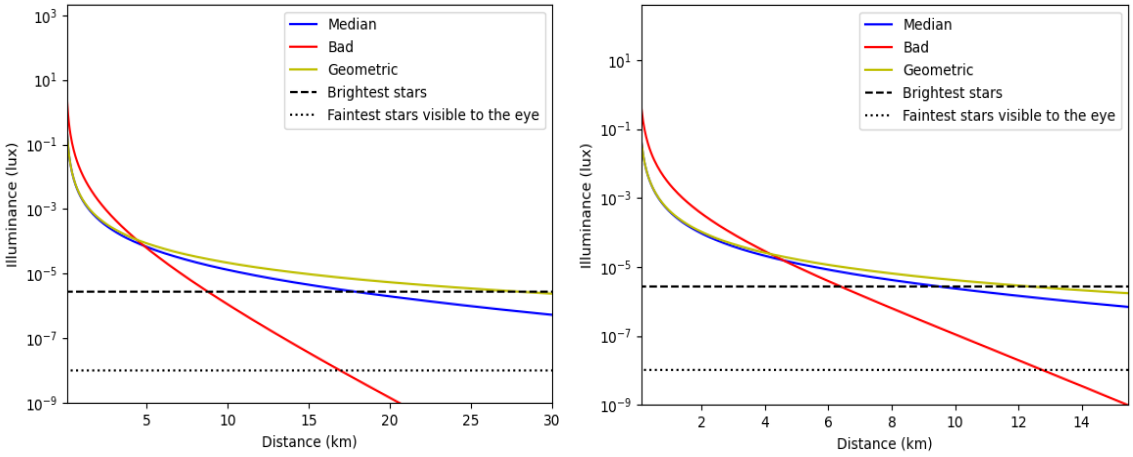

Figure 4: The light as seen by an observer at varying distances according to geometric attenuation only, the median visibility of 25km, consistent with the night-time results for the region, and the visibility corresponding to the point at which the light switches from 200 to 2000 candela. The y-axis is logarithmic. The plots are for the light seen horizontally (left: corresponding roughly to VPs 13 and 14) and at an angle of -2 degrees (right: VP7). At 10km, even with the very good 25km visibility curve, the light is attenuated by a factor of two compared to the geometric, 1/(distance^2), dilution. The model used to predict this is described in detail in previous reports (Lumsden, 2020a). It allows for the decrease in atmospheric density with altitude, though to be conservative in this case it is assumed the aerosol density all along the line of sight is set here for approximately the average value of the lit hub heights. Changes of height of +/-50m make little difference to the results.

6.4. Combining both geometric dilution and aerosol attenuation gives the results shown in Figures 5 and 6. Figure 5 shows how the apparent brightness to the observer of the light varies with distance. For simplicity, the median night-time visibility for Prestwick is assumed. The yellow curve shows the decrease due purely to geometry, whilst the blue curve shows how that changes when the aerosols are

added in. The small change seen is because the plot is logarithmic on the y-axis. Even good visibility reduces the brightness of light seen. In addition, as noted before it is likely that the visibility at the wind farm will be less than at Prestwick, which will also reduce the brightness of the observed light at all distances.

6.5. An alternative way to consider the models is to considering how the apparent brightness at the observer changes for specific locations and turbines as a function of visibility. Combining the attenuation due to the atmosphere with that due to geometric dilution for the three examples given in Error! Reference source not found. gives the actual illuminances shown in Figure 7 for four specific locations. The most notable feature in these plots is the change when the light is switched up to 2000 candela. This is almost not visible as a change at larger distance, but when the distance roughly matches the visibility, as in the upper left panel, the effect is dramatic. However, even then, once allowance is made for attenuation the predicted brightness of the 2000 candela light is typically similar to

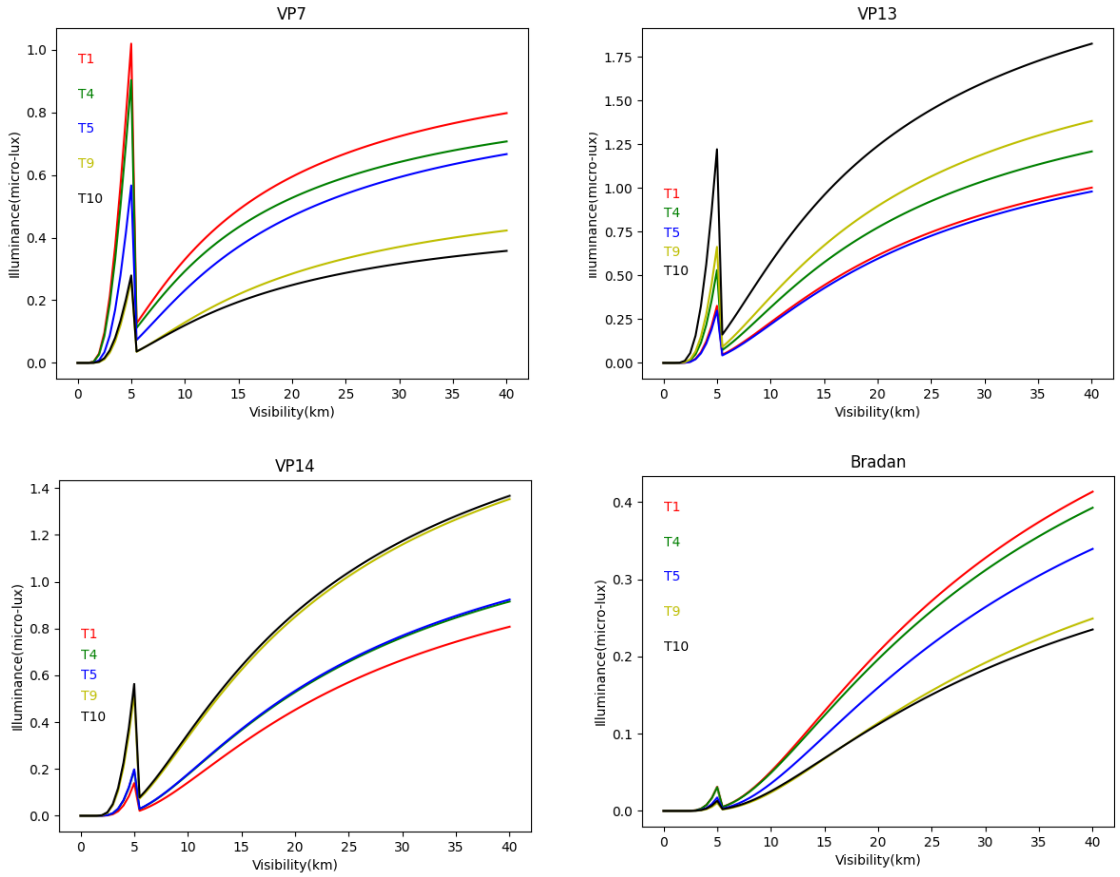

Figure 6: The figures show the actual observed illuminance for the three night-time viewpoints as well as the car park at the southern end of Loch Bradan. These plots include both the attenuation due to the atmosphere and the reduction due to distance. The intrinsic brightness of the warning light as a function of angle and distance has been accounted for appropriately for each case, and the individual turbine hubs are shown separately. The differences are mostly due to the different elevation angles that they are viewed at. The lights switch to full intensity when the visibility is at 5km. Note that even at full intensity, the light remains dimmer to the observer than when the visibility is 10km with the 10% light unless the observer is close to the wind farm (eg as for VP7). Even in this case the drop-off as the visibility decreases is rapid. The faintest red light that can be detected by a "typical" person is about 0.01 micro-lux (twice the brightness of the faintest stars).

the 200 candela light in very good visibility.

6.6. We can compare these predictions with astronomical sources. Orion is the most prominent winter constellation, sitting about 30 degrees above the southern horizon, shaped approximately like an H. The upper left and lower right stars in this pattern are amongst the brightest in the sky, with an illuminance between 1.5 and 2 micro-lux, comparable to the dashed line drawn in Error! Reference source not found.. The three stars that form Orion's belt, i.e. the bar of the H, are typical middling stars. These would appear as approximately 0.3 micro-lux. Such stars are relatively easy to see but not particularly prominent.

6.7. All the examples shown in Figure 7 lie between the range shown in Orion. The aviation warning lights at most then are similar to bright stars, as seen from the more distant VPs 13 and 14 (which view close to the maximum luminous intensity given the VPs are the peaks of local hills) or the closer VP7 (which views the lights at a more negative elevation and hence lower intrinsic intensity), with correspondingly fainter lights apparent from more typical distant regions such as Loch Bradan. The Roundhouse Café is not shown here but the results are about 75% of the brightness of VP 7. Only Turbines 1 and 4 are visible here. The same conclusion would apply for most of the stretch of Loch Doon Road between the Roundhouse and Beoch, where there is any ability to see the lights.

7. Discussion

7.1. Another way to compare the lights is to examine the emitted candela as seen at each location. This can then be compared to other known sources of lighting that are typically visible at night. The simplest of these are car rear brake lights, which on average are about 80cd. The colour is similar to the aviation warning lights as well, making the comparison easier. This should be taken as a qualitative guide only.

7.2. The emitted candela seen by an observer from the turbine lights is defined purely by the elevation angle between the hub of the turbine and the observer. The actual values for any locations are shown on the ZTV - Figure 5.4d: Theoretical Visibility of Aviation Lighting by Intensity. Only good visibility values will be considered. Two effects are seen from this. For nearby receptors, the altitude of their location relative to the turbine hubs is the dominant effect in determining how bright the lights are. For more distant receptors the angles "flatten out" reducing this effect somewhat.

7.3. The comparison of VP7 with VPs 13 and 14 is illustrative of the former case. The latter viewpoints essentially view the lights near horizontally, whereas VP7 views them from below. Therefore, even though VP7 is closer, the lights appear fainter. VPs13 and 14 will see the full intensity.

7.4. As also shown by the ZTV - Figure 5.4d: Theoretical Visibility of Aviation Lighting by Intensity, most of the locations near the proposed wind farm which are more likely to have receptors at night also see faint lights because they view the turbines at steep elevation angles. This is true for the A713 east of Dalmellington for example. The effect for these locations as well as VP7 is roughly equivalent to seeing a car brake light at the distance they are from the wind-farm.

7.5. More distant locations can see both more turbines and an intrinsically brighter light even at modest altitude because of the flattening effect of elevation angle with distance. Towards the north and the west, in the region around 15-20km, there will be locations which will see a ~100 candela light. However, at this distance this will be hard to see (paragraph 7.8 below) even though looking south towards the wind farm is the direction with least background light.

7.6. The intrinsically brightest lights are seen from the high points nearby such as VPs 13 and 14, as well as along the ridge near Merrick in the core of the Dark Sky Park. These locations therefore will see lights at approximately 200 candela. In perfect visibility a 200cd light appears like a 80cd one at 60% of the distance. For VPs 13 and 14 this as if they were 80cd lights at 6-7km. This is why the illuminances from the detailed model appear so similar for VPs 7 and 13 and 14. Merrick is further away again diminishing the effect even more.

7.7. One comparison that should be avoided is to view a random full 2000 candela aviation warning light in-situ on buildings etc and assume that those views can be extrapolated. Only the view as seen at -1 degree is likely to be at all well constrained by the ICAO regulations, and even then the lights are allowed to be brighter than 2000 candela. The same applies for lights of other luminous intensities where the beam profile is not well known. For example, 32 candela mid-tower lighting of the kind not required at the proposed South Kyle II Wind Farm can be as bright as 60 candela in mid-beam. Similarly, flashing red lights are not an equivalent metric as they are intrinsically more noticeable.

7.8. The author previously observed the Contarnex light used in the modelling in-situ during preparation for the Inquiry for the consented Crystal Rig IV extension. The light was observed at a distance of 15km and an output of approximately 65 candelas given the elevation angle, and that it was operating at 10% of maximum intensity. The light was visible, but not prominent, in this occasion. The Reporters to the Inquiry noted the same.[5]

7.9. In summary then, the lights appear similar to bright stars (albeit obviously red) from the selected night-time viewpoints, with background light pollution reducing the contrast we see them at from many locations. The main effect is from high ground such as VPs 13 and 14, though whether these are visited in true night is unclear. In twilight, they are sufficiently distant that the brightness of the lights against the sky is limited somewhat by contrast with the background. More distant locations in the Core zone of the Dark Sky Park, such as the Merrick Wild Land Area are far enough away that even though the lights are largely viewed horizontally, they appear faint purely because of the effect of distance. Although more visited nighttime areas such as the Loch Doon Road are closer, the effect of viewing angle means the apparent brightness of the lights is less than VPs 13 and 14, and this time looking more towards the background light pollution from the central belt, further reducing the apparent effect.

[5] Paragraph 4.139 of CD 008.3 https://www.dpea.scotland.gov.uk/Document.aspx?id=732056

8. Glossary of Terms

absorption	In the context of atmospheric physics, light that is completely removed when interacting with a molecule or particle is said to be absorbed.
aerosol	Any particle, man-made or natural, in suspension in the atmosphere.
aerosol optical thickness	The attenuation of light when looking directly upwards, measures the total aerosol content. This is less than the attenuation that would be seen horizontally given the rapid decrease of atmospheric and aerosol density with altitude.
candela	SI unit of luminous intensity – see below.
contrast	In the context of atmospheric physics and vision, generally defined as the difference in brightness of two objects divided by the average of the two brightnesses.
dark adaptation	The process by which our eyes switch from photopic (cone mediated) vision to scotopic (rod mediated) vision after moving from a lit area to a dark one.
elevation angle	The warning lights appear as different brightness according to the angle of elevation they are viewed at. Here, the horizontal plane is defined as 0 degrees, and below the plane is negative. At increasingly negative values, the lights are correspondingly fainter. Figure 5.4d of the EIAR provides a schematic illustrating this. See also Figure 10 below.
illuminance	How bright a light appears per unit area to a distant observer. Typically defined in terms of lumens/m^2 which is also denoted as lux. For a distant observer looking up at the aviation warning lights, the illuminance they see in the case is set by the angle of elevation (which is negative because although they are looking up the light is propagating downwards from the horizontal), the distance and the atmospheric clarity.

lumens	SI unit of luminous flux – see below
luminance	Like luminous intensity, but for a source that is extended as far as the observer is concerned. It is defined in terms of brightness per unit area (e.g. as the light output from a TV screen is defined in terms of its luminance). This is not typically used for warning lights except very close to the source, but is relevant for factors such as the brightness of the twilight sky.
luminous flux	Again, this is how bright a light is at the source, but summed up over all the angles it emits at, so different from the luminous intensity (candela) value. For a uniform source this is equivalent to multiplying the candela value by 4π, the angular area of the surface of a sphere. A standard domestic light-bulb, which typically emits across a wide angular spread, is usually defined in terms of its luminous flux.
luminous intensity	This is the brightness of a light as a function of the viewing angle at the light source itself. For a uniform angular illumination this is easily related to the luminous flux. For the aviation lights this is not true.
lux	SI unit of illuminance. Equivalent to lumens/m^2
nm	nanometres, or 10^{-9} m.
optical depth	The opacity along a given line-of-sight.
photopic	The term denoting human vision in daytime.
resolution	For an optical system, the angular separation of two objects before they appear to merge into one.
scattering	In the context of atmospheric physics, light that is scattered is reflected from a molecule or particle, at an angle that depends on the process. Back-scatter is reflected back to the source, and forward-scatter

	is actually light that largely tracks its original path for example.
scotopic	The term denoting human vision in night-time.
solid angle	The angular area of a surface. For example a circle seen as having an angular extent of 1 degree in radius has an angular area of 1 square degrees.
visibility	How far away an object can be seen and still have a distinctive 5% contrast with its surroundings. For example, in hazy conditions you might see a distant building but not the individual windows on its facade, when in clear conditions you can. The 5% contrast is defined by regulation.
wavelength	The wavelength of light is the physical unit that defines its colour. For visible light, given in units of nanometres (1 billionth of a metre).
ZTV	Zone of theoretical visibility. Where the turbines may be visible from based purely on the shape of the landforms, and excluding any other intervening obstructions.

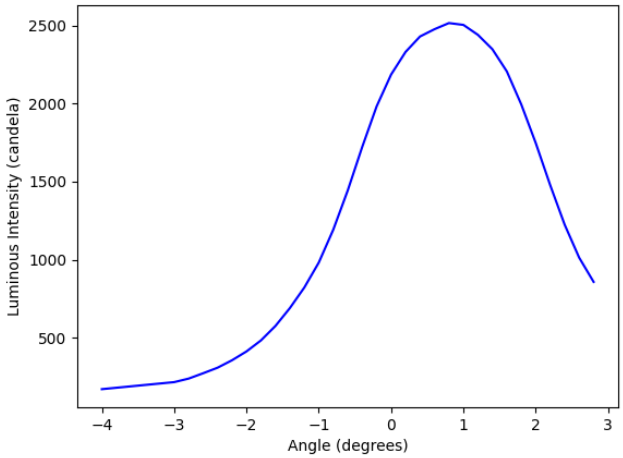

Figure 7: Intensity versus elevation angle for the Contarnex light used in the modelling.

9. Dr Stuart Lumsden is an Associate Professor in the School of Physics and Astronomy at the University of Leeds. He worked for the professional optical observatory based near Coonabarabran, NSW, the (then) Anglo-Australian Observatory for 6 years, working on optical and infrared instrumentation for astronomy, and is therefore familiar with issues related to light pollution, and the propagation of light, at night. He has acted as an expert on such matters for wind farm developments in Scotland over the past 10 years, with particular regard to the use of infrared lighting on turbines with tip height of less than 150m near the Dark Sky Park in Galloway, and visible red aviation lighting for the turbines exceeding 150 m at developments across Scotland, including the public inquiries for Crystal Rig IV, and Clash Gour. He is a member of the Scottish Government Aviation Lighting Guidance Working Group.

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