Visibility of Aviation Warning Lights

Dr Stuart Lumsden

Executive Summary

All wind turbines of height greater than 150m require visible aviation lighting. 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 2000cd, but this is found to be of limited importance in their overall appearance given the considerable obscuration between the lights and distant observers. For the proposed Blair Hill Wind Farm, the lights will appear brightest from the viewpoint just north of Newton Stewart. Even there however they will have similar brightness to the bright stars in the sky. The other locations will essentially see rather faint red lights which would require at least a minimum amount of dark adaptation before they become visible to the eye for a typical person.

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 10.

2 Introduction

2.1 Blair Hill Wind Farm is a proposed development that lies adjacent to the southern edge of the Galloway Forest Dark Sky Park (DSP). The DSP has held the highest Gold Tier status with the International Dark Skies Association (now Dark Skies International) since 2009. The lighting plan for the Park and its surroundings now forms part of the Dumfries and Galloway Local Development Plan. The plan assumes a Core region of the DSP in which no new lighting should be permitted, and a Buffer zone in which only fully shielded downwards pointed lighting is allowed. Typically, the buffer zone extends out beyond the core except for the boundary nearest the Blair Hill proposal. The proposed location of the wind farm and the core zone are adjacent at the northern-most boundary near turbine T1. A Transition zone extends beyond the outermost boundary for 10 miles in which the Local Development Plan requests lighting that is "dark sky friendly". The supplementary guidance from Dumfries and Galloway Council indicates that dark sky friendly for a Wind Farm development in the Transition zone should maximise the number of infrared aviation warning lights used.

2.2 The proposed development consists of 14 turbines, all above 150m at tip height. Only six of these (T1, T4, T5, T10, T11 and T14) will bear aviation warning lights at hub height (165m above AOD), following agreement with the CAA on a reduced lighting plan. The CAA also agreed that there is no need for 32 candela mid-tower lighting, which reduces local visibility of lighting considerably. All of the turbines will also carry infrared lights, but these are not visible to the naked eye (or an unmodified camera). This reduced visible lighting scheme is therefore in agreement with the principle laid out in 2.1.

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 This report will identify the factors that impact on night-time vision, the existing night-time characteristics of the region, and the impact of the atmosphere on the attenuation of the light as it passes from the wind farm to other locations. It will conclude by discussing how the proposed wind farm may affect the DSP.

2.5 For brevity consideration will only be given to the agreed nighttime viewpoints (VPs 2, 8, 9 and 10), with a briefer discussion of the nearest areas within the DSP with an agreed viewpoint (VP5) or where visitors are likely to focus night-time activities. These are the car parks by the open visitor centre at Glentrool, the currently closed visitor centre but operating car park at Clatteringshaws Loch, and the open visitor centre at Kirroughtree. It should be noted that neither Clatteringshaws or Kirroughtree have direct visibility of the aviation lights.

2.6 The selected viewpoints vary in distance from the turbine lights as well as the elevation angle the lights are viewed at, and both will be factored into the discussion. Both distance and angle of elevation strongly effect how bright the lights appear at any location.

2.7 This report will only summarise the principles concerned[1] – full details can be found in previous inquiry and technical reports by the author for 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 here.

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, where age, in particular, strongly affects the capability. Given this caveat, we can consider some general principles **(Lamb, 2016)**.

3.2 In a truly dark environment, our eyes rely on the more sensitive, monochrome, rods rather than the colour sensitive cones that make up our daytime vision. This leads to a gradual "blue-ing" (rods have no sensitivity to red light) and fading of colour response as the light levels drop, as the cones gradually "switch-off" in the transition.

3.3 Full dark adaptation takes time (it can be up to 30 minutes for the full switch to "rod-only" vision though a moderate degree is obtained within the first few minutes when both rods and cones are active). Someone who is in, or emerging from, a lit environment (eg a house) will therefore have limitations on how faint an object they can immediately see, and only gradually will fainter objects appear visible to them. Where street lighting exists in a settlement the chance of full dark adaptation is limited. Even indirect emission (such as streetlights scattered back off the ground) can have a significant impact on adaptation.

3.4 In addition, if there is any background light, whether that be streetlights, more distant man-made light pollution, or natural background light such as twilight, or a moon at or near full, the eye is also 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. The main take-away message therefore is simply that any additional light source will make it "harder" to see faint distant lights, whether those be aviation lights or stars.

3.5 This is less true for a camera image, which is a good match for our daytime vision but less so at night. The photomontages which are taken in twilight, as required by guidance, also mask any existing light pollution which becomes more obvious to the eye after longer dark adaptation.

3.6 Man-made light pollution includes a diverse variety of sources, all of which affect dark adaptation and the contrast issue noted above. Some of these are permanent like street

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

lighting, and some transitory, such as car headlights. Drivers are always limited in their ability to see their surroundings because of the brightness of their headlights for example.

3.7 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 Figure 1 shows the night-time light sources in the area around the proposed development. The most significant local feature is Newton Stewart. Although relatively modest, the lighting there will impinge on receptors further to the south such as the other night-time viewpoints (8, 9 and 10). The Council have carried out considerable work in replacing older streetlights with modern LEDs, which has led to a decrease in the overall light pollution in the area, but existing lighting is still obvious.

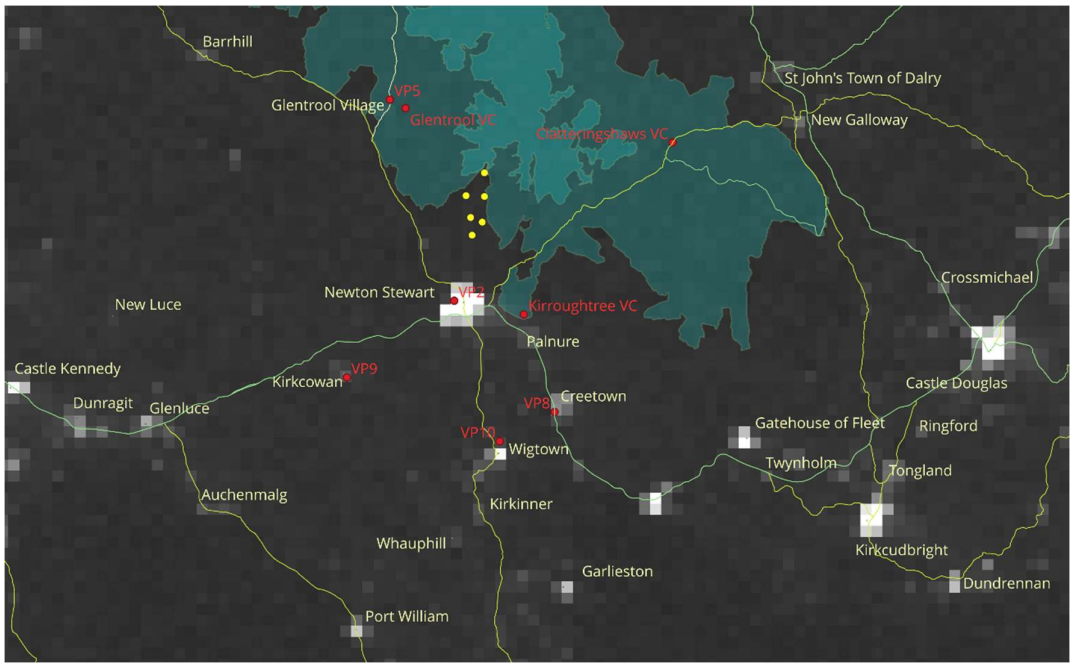

Figure 1: Night-time satellite image of the region around the proposed Blair Hill Wind Farm. The image shown here is a composite of cloud and moon free nights from October 2023 to April 2024. Images are typically acquired between 1 and 3am local time. Note the satellite images are only sensitive to wavelengths of light beyond 500nm, which will capture most of the output of warm white LEDs, but not cool white ones. The extent of the Dark Sky Park is indicated by the turquoise shading. The brighter shading represents the core of the park, where no lighting is permitted. The darker shading represents the buffer zone, where lighting is allowed if it is shielded and emits downwards. The lit turbines are marked as yellow points. A selection of all settlements in the area indicated by name. For context major roads are shown in green. Viewpoints considered are shown in red.

4.2 The viewpoints for which night-time photomontages are available, VPs 2, 8, 9 and 10, all lie near settlements (Newton Stewart, Creetown, Kirkcowan and Wigtown respectively), and hence the effects described in Sections 3.3 and 3.4 are relevant in those general areas. VP 2 lies to the north of the bulk of Newton Stewart so will have the least intervening light pollution in the direction of the wind farm. As noted in 4.1, the other night-time VPs will have any light pollution from Newton Stewart in the same field of view as the wind farm.

Anyone closer to these settlements will be affected more by the local lighting in addition. The visitor centres and their car parks are in dark locations, but only Glentrool has any potential visibility, of two lights, and this is close enough to the horizon that it is masked by local trees. Glentrool Village itself also has street lights which are visible in the satellite image. Neither Clatteringshaws or Kirroughtree have direct visibility of the aviation lighting. The viewpoint near Glentrool, VP5, on the road north towards Straiton has slightly greater visibility. A short stretch of road (about 0.5km) will present three of the lights clearly, and one just above the horizon when driving south.

4.3 Since the car parks at all three visitor centres are where casual visitors may tend towards at night it is worth considering whether any of the lights will affect the view, even though not directly visible.

4.4 Distant light pollution can also give rise to "light domes" (or skyglow). 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. "bad" street lighting, misdirected security lighting, lights in most open plan multi-storey offices) but also light scattered back upwards from the ground back upwards. These are reflected on the satellite image. Nearby skyglow mostly comes from light emitted just above the horizontal plane which then scatters back down to the viewer. Replacement of older streetlights by LEDs has led to improvements in Dumfries and Galloway. However LED lights (even "warm" ones) intrinsically have more blue light output than the typical older sodium or high pressure sodium lights. Blue light scatters more efficiently than red light (by a factor of about 6), and there is even some evidence that LEDs have led to an increase in skyglow in other parts of the world. Where streetlights are not fully shielded they will dominate the local skyglow simply due to their number, colour and brightness. It is possible to calculate the magnitude of the effect from red aviation lights as well to determine if they contribute to local skyglow, especially where the lights themselves lie just below a dark horizon, as would be the case at Clatteringshaws. The result is basically below detectable level for the human eye – perhaps not surprising given the actual small amount of light they give out when running at 10% level.

4.5 Natural sources of light also need to be considered in assessing the visibility of the turbine lights. 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.

4.6 The presence of a near full moon (roughly full +/- 5 days) is significant because of the contrast issue discussed in 3.4. The sky brightness given by the moon varies by about a factor of 15 between full and +/- 7days and is not significant outside that period.

4.7 The importance of twilight depends on which direction you are looking, and whether this is sunset or sunrise. For receptors keen to experience dark skies it is more likely that they will be present during evening twilight, so this is assumed. It is straightforward to ascertain what the likely effect will be during morning twilight by comparison. For most of the year the specified viewpoints are not affected. However, in summer VPs 2, 8, 9 and 10 and Kirroughtree would see the bright northern horizon caused by the fact that full night never actually happens at all for the 6 weeks around mid-summer. Clatteringshaws looks towards the bright sky near to sunset for much of the year when viewing the direction of the wind farm. Glentrool by comparison looks towards sunrise.

4.8 Overall then it can be seen that the naturally darkest locations where visitors might be expected currently have no visibility of the aviation lights, and the other night-time viewpoints apart from VP2 are distant and all others may be partly compromised by their local lighting. The effect of the lights at VP5 is of very short duration for road users.

5 Meteorological Characteristics

5.1 There are no detailed meteorological records for the wind farm site itself. There is a Meteorological Office synoptic weather station at West Freugh however, which is 30km south-west of the development. The station lies at 17m AOD so is a reasonable match to the night-time viewpoints. This station has 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. These automated sites also 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 wind farm is within cloud.

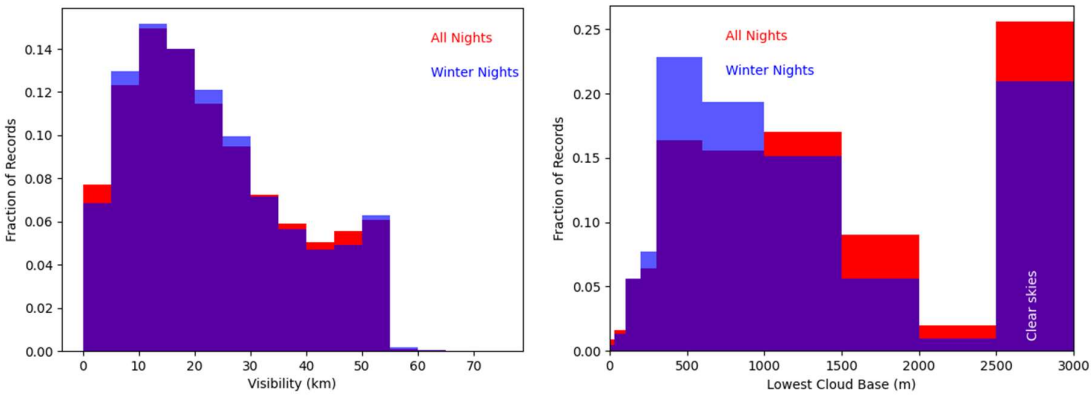

Figure 2: Visibility records (left) and lowest cloud base height (right) for West Freugh.

5.2 The Met Office MIDAS Land and Marine Surface Stations Data[2] are publicly available under v3.0 of the Open Government Licence, and provide measures of visibility and cloud base height. Hourly data were considered from 2014 onwards, as that period covers full automated measurements. 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 relevant night-time results are shown here.

5.3 West Freugh shows little difference between winter and all year records for visibility. However the cloud base does lower (as expected given cooler air) in winter.

5.4 The cloud base data show that 38% of records have a cloud base below 300m in winter nights and 29% in summer nights. For a 600m threshold (the next bin in the data) this rises to 57 and 39% respectively. This corresponds to the range of turbine hub heights for the wind farm, so will reflect the fraction of time that the turbine lights are above the base.

5.5 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 4).

[2] 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

5.6 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 - 1.7% of all records for West Freugh have a cloud base above 300m but visibility below 5km.

5.7 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 much beyond 5km, as will also be demonstrated in Figure 3 and Figure 4. 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. In a vacuum, the light would diminish only through geometry as it spreads out, diminishing by 1/(distance^2). Adding aerosols will reduce this further. Examples of this effect are shown in Figure 3. For simplicity, the aerosol density is assumed to vary with altitude only in accordance with the expected atmospheric scale height.

6.2 Even good visibility can lead to notable reduction in the observed brightness as shown by Figure 3 and Figure 4. In practice the aerosol density may be higher, making the visibility worse. Winds push material upslope, so even at 200-400m altitude (typical of the base of the turbines) the aerosol density at ground level may be higher than naïve free-air prediction used in the calculation. This would make the lights appear fainter.

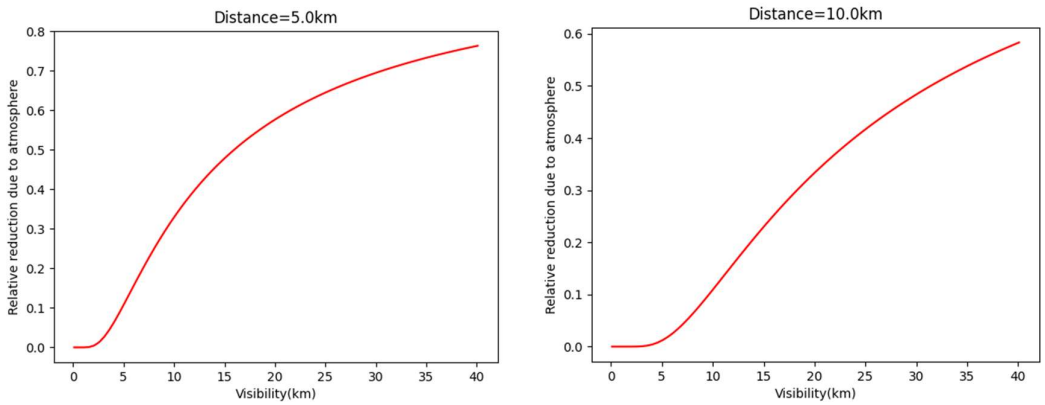

Figure 3: the panels show how much the light is attenuated for an observer as a function visibility. Only the attenuation due to the atmosphere is shown – the reduction due to distance is not included. In both cases it is assumed that the hub height is 450m and the observer at 20m, typical of values for both the turbines and VPs 2, 8, 9 and 10. The curves change little for modest changes in these values. The attenuation is exponential, so drops rapidly at poorer visibilities, which is difficult to see on the linear y-axis shown. Very poor visibility (less than 1km as might be expected when the hubs are above the cloud base) reduces the apparent brightness significantly.

6.3 Combining the attenuation due to the atmosphere with that due to geometric dilution gives the actual illuminances shown in Figure 4 for six 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. This only occurs for locations within about 5km however – the lights basically appear brighter than when in 10% setting when the distance is less than the visibility. Locations outside 5km see the lights attenuated rapidly.

6.4 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. 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.

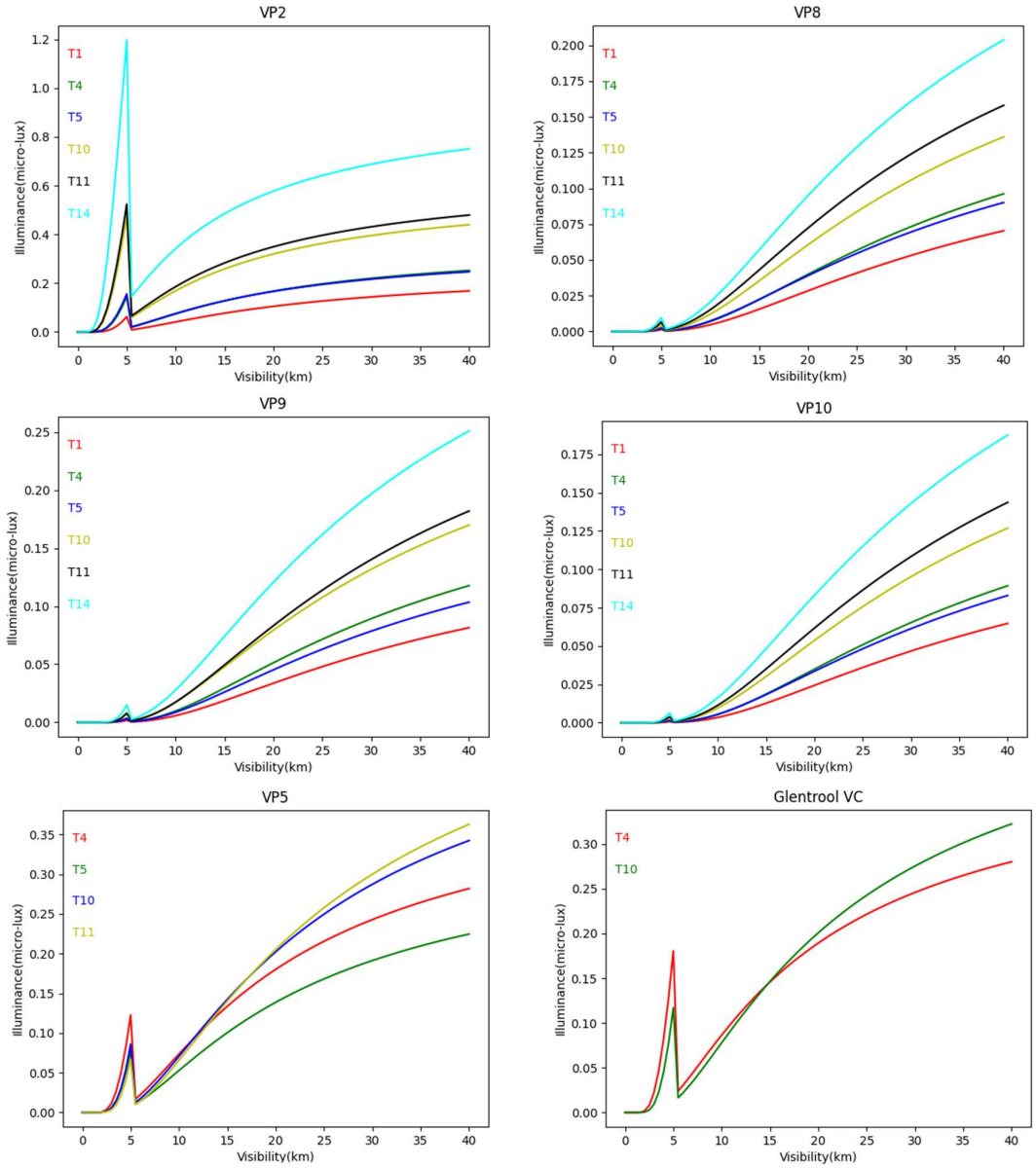

Figure 4: The figures show the actual observed illuminance for the four night-time viewpoints (upper four panels) and for two location within the Dark Sky Park, VP5 and the Glentrool Visitor Centre. These plots include both the attenuation due to the atmosphere and the reduction due to distance. The 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 lights switch to full intensity when the visibility is at 5km. Only viewpoints nearer than about 5km see the lights as notably brighter when in “high-mode” than in good weather (compare VP 2 and 10 for extreme examples). 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 visible stars to the human eye due to the colour).

7 Individual Viewpoints

7.1 VP 2: The lit turbines visible from this viewpoint range from 4.5 to 8.8km. They are all at significantly negative viewing angles relative to the horizontal plane at the turbine hub, ranging between -3.5 degrees and -3.2 degrees. For the adopted Contarnex light this would give an expected luminous intensity as emitted of about 20 candela at 10% output. Newer lights should be capable of improving on this (less emission at large negative angles). This is the one location where a switch to 100% intensity lights in poorer than 5km visibility results in the lights potentially appearing brighter since T14 is closer than 5km, and T10 and T11 are only just beyond that distance. Even at their brightest however they are only comparable to the brightest stars in Orion (Figure 4).

7.2 VP 5: This location lies between 8 and 10.6km from the lights. The corresponding viewing angles range from -3.1 degrees to -1.1 degrees. This would give an expected luminous intensity 21 and 90 candela at 10%. Despite a brighter part of the light being seen, the greater distance means that in median visibility the lights are only comparable to the belt stars in Orion. For a typical person driving south along the road here this would make the lights difficult to perceive compared to the glow of their own headlights.

7.3 VP 8: The lit turbines visible from this viewpoint lie between about 13 and 17km. The corresponding viewing angles flatten as a result of the distance, showing a narrow range from -1.8 degrees to -1.3 degrees. This would give an expected luminous intensity between 48 and 75 candela. The distance however ensures that the lights appear fainter than the belt stars in Orion.

7.4 VP9: This viewpoint is actually very similar to VP 8, with the lights appearing about 10% brighter on average, so the same conclusions apply.

7.5 VP10: This is the most distant nighttime viewpoint, ranging from about 14 to 18km. As a result the angles are similar to viewpoints 8 and 9, and the greater distance means the lights appear faintest of all, about 10% fainter than VP8.

7.6 The Visitor Centres: The lights are completely blocked at Kirroughtree since it lies to the south of the higher ground containing Kirroughtree Forest. Clatteringshaws lies in a bowl surrounding the loch. The lights are hidden by the surrounding higher ground, so again are not directly visible (they lie at least 0.6 degrees below the bare horizon). Glentrool does have potential visibility of two lights – they lie at 7.2 and 8.5km distance – which are currently screened by forestry. The lights are at negative angles of -3.0 and -2.1 degrees. This limits the brightness to being similar to Orion belt stars should the screening be removed at any time.

7.7 Looking at the Dark Sky Park as a whole, the main areas with notable visibility of the lights are high ground near the south of the park. In particular the higher ground around VP21 and VP22 will see the lights at maximum intensity. However, this area is unlikely to have significant night-time visitors. The Southern Upland Way, which may have night-time travellers, is shielded by this higher ground to the south at VP21/22 so has no visibility.

7.8 Finally, it is worth stressing again that VPs 8, 9 and 10 will have the faint but noticeable light pollution from Newton Stewart in view at the same time as the warning lights.

8 Discussion

8.1 Another way to compare the lights is to compare the emitted candela as seen at each location with other known sources of lighting that are typically visible at night. Although

care must be taken with this approach it can help people understand the effect the colour may have. The simplest of these examples 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. 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. This is especially true of 2000 candela lights fitted to construction cranes, which appear to clearly exceed the ICAO recommendations. Similarly, flashing red lights (eg Beinn an Tuirc wind farm) are not an equivalent metric as they are intrinsically more noticeable to the eye even if of lower candela.

8.2 The emitted candela seen by an observer is discussed in Section 7. Only good visibility values will be considered for brevity. For all apart from VP 2, the emitted luminous intensity is about the same as a car brake light. But this is a car brake light seen at 10+km distance.

8.3 VP 2 shows a lower emitted intensity of about 20 candela. In perfect visibility a 20 candela light appears like a 80 candela at half the distance. So a 20 candela light at 4.5km is like a car brake light at 9km in perfect visibility.

8.4 The author previously observed the Contarnex light used in the modelling in this report in-situ during preparation for the Inquiry for the consented Crystal Rig IV extension. The light was observed at a distance of 15km, similar to VPs 8, 9 and 10, 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, on this occasion. The Reporters to the Inquiry noted the same.[3] It was seen to be similar to the Orion belt stars, as expected.

8.5 In summary then, the lights appear similar to bright stars (albeit obviously red). As a result they will not impact on night sky measurements made in future in the locale, which is the key measure of sustainability for the DSP. The plan for the DSP as adopted by Dumfries and Galloway Council asks simply that any wind farm development near but outside the park minimise its lighting. As a result of the aviation study conducted this has been achieved. Notably, other consented developments such as Windy Standard III did not raise lighting issues from Dumfries and Galloway Council, despite lying within the Transition zone around the Galloway Forest Dark Sky Park, and being in a wholly dark environment.

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

9 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.
AOD	Above Ordnance Datum – basically altitude above sea level
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. The switch over "zone" is known as mesopic vision.
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. See Figure 5 below. An observer below the height of lights is at a negative elevation angle.
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. Measured in lumens.
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. Measured in candela.
lux	SI unit of illuminance. Equivalent to lumens/m^2
nm	nanometres, or 10^{-9} m.
opacity	The attenuation of light due to intervening material
optical depth	The opacity along a given line-of-sight.
photopic	The term denoting human vision in daytime. This is dominated by the colour sensitive cones, which also give us the best acuity in our vision. The cones become inactive at low light levels.
resolution	For an optical system, the angular separation of two objects before they appear to merge into one.
scale height	The height in the atmosphere below which most of a given material exists. For example, most of the aerosol component in the atmosphere is under the aerosol scale height of approximately 1.5km.
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. This is dominated by the monochromatic rods. The rods are more sensitive to blue than red light. The rods "switch-off" in daytime.
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 π square degrees.
steradians	1 square radian, or 3282.9 square degrees.
subtends	An object at a distance from a viewer is seen to be a certain angular size – that is it subtends that angle. Also used to describe angular areas.
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). Human vision operates approximately between 400 and 750 nanometres.

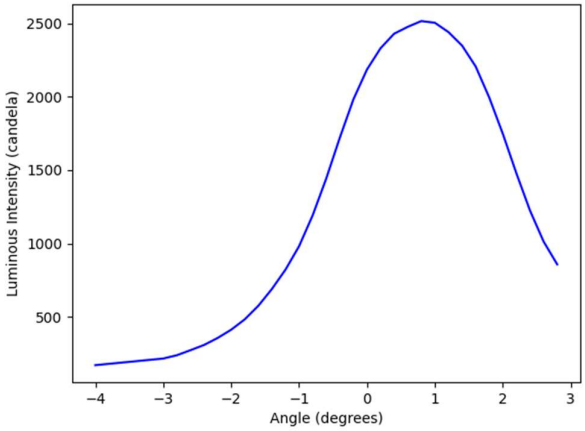

Figure 5: Intensity versus elevation angle for the Contarnex light used in the modelling.

10 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.

11 References

Lamb, T., 2016. Why Rods and Cones?. *Eye,* Volume 30, pp. 179-185.

Lumsden, S., 2020a. *CD014.006 - Inquiry Report of Dr Stuart Lumsden in relation to Scientific Elements of Visible Aviation Lighting.* [Online]
Available at: https://www.dpea.scotland.gov.uk/Document.aspx?id=701431

Lumsden, S., 2020b. *CD014.007 - Technical Report of Dr Stuart Lumsden Propagation of Light from the Proposed Aviation Warning Lights.* [Online]
Available at: https://www.dpea.scotland.gov.uk/Document.aspx?id=701433