



Appendix 15.2

Report on Light Propagation from the Aviation Warning Lights on the Y Bryn Wind Farm

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1. Introduction

- 1.1 The Y Bryn Wind Farm is a proposed development of 18 turbines, all of which reach a tip height of over 150 metres (m).
- 1.2 The Air Navigation Order Article 222 requires turbines exceeding a tip height of 150m to display aviation lighting to indicate their presence. Further guidance is provided in the Civil Aviation Authority (CAA) Policy Statement of 1 June 2017 entitled 'Lighting of onshore wind turbine generators in the United Kingdom with a maximum blade tip height at or in excess of 150m above ground level'. Appropriate visible lighting consists of a 2000 candela red light at the top of the turbine hub, which can be reduced to 200 candela in good visibility conditions, and 32 candela red lighting at intermediate height.
- 1.3 Dispensations for reduced lighting schemes can be agreed with the CAA according to the guidance provided in CAP-764. This generally involves the lighting of cardinal turbines in order to define the perimeter of the wind farm. For the proposed Y Bryn Wind Farm, discussions with local stakeholders have agreed a reduced lighting scheme in which 13 cardinal turbines carry visible lighting at the top of the turbine hub, with no mid-tower lighting. Approval from the CAA is being sought for this lighting scheme. This report adopts this proposed lighting scheme. Discussion is also on-going with the CAA about the use of a radar-activated lighting scheme, whereby the aviation lighting is only switched on when an aircraft is in the vicinity of the wind farm.
- 1.4 This report provides a scientific assessment of the propagation of light from the aviation lighting, during the times that this is activated, taking into account the range of atmospheric conditions typically found in Wales. It further considers how the human eye perceives light.
- 1.5 This enables an assessment of how bright the warning lights for the aviation lighting scheme for Y Bryn Wind Farm will appear to be to observers external to the wind farm. Comparison is made with other sources of light, such as the moon and stars, and man-made sources.
- 1.6 The main body of the report discusses these issues, and summarises the main conclusions, in a non-technical manner, in order to be understandable to a broad audience. Appendices to the report provide a full scientific and technical background, as well as details of the data used.
- 1.7 The author, Philip Best, is Professor of Extragalactic Astrophysics in the School of Physics and Astronomy at the University of Edinburgh, and is a Fellow of the Royal Society of Edinburgh. As an observational astronomer he is familiar with issues related to the propagation of light at night, and issues of light pollution.
- 1.8 Professor Best has had previous involvement in studies of the effects of aviation lighting for wind farm development in the UK, both onshore and offshore, dating back to 2018.

2. Measurement and visual perception of light

2.1 Overview

2.1.1 The apparent brightness of a light, and our perception of it, depends on many factors. These include:

- How intrinsically powerful the light is
- Whether the light is emitted equally in all directions
- The colour of the light
- The distance of the observer from the light
- The nature of the atmosphere through which the light passes
- The background lighting conditions in which the light is viewed
- The response of the human eye

2.1.2 This report will examine all of the issues to assess the perceived impact of the proposed aviation lighting at the proposed Y Bryn Wind Farm.

2.2 Terminology and propagation of light

2.2.1 This section provides a brief overview of the propagation of light, and relevant terminology. For a more detailed technical discussion, see Appendix A.

2.2.2 The regulations on aviation warning lights are expressed in terms of *candela* requirements. Candelas are a measure of the *luminous intensity* of the light. Luminous intensity measures the amount of light, at wavelengths detectable by the human eye, which is emitted in a particular direction.

2.2.3 If a light emits anisotropically (i.e. different amounts of light in different directions) then its candela rating will depend upon direction.

2.2.4 More distant light sources appear fainter, because the light emission spreads out over a larger area. The observability of light depends upon the *illuminance* of the light, which measures the luminous intensity of light that passes through a unit area of surface at that distance. Illuminance is measured in *lumens per square metre*.

2.2.5 It is the illuminance of the light that determines how bright it appears to the observer. This is the key quantity that this report will be deriving for the aviation lighting and comparing to the illuminance of other light sources.

2.2.6 For perfect transmission of light (i.e. no light absorbed or scattered by the medium through which it is passing), the illuminance decreases as the square of the distance between the light source and the observer. Thus, a light observed from a distance of 10km will have an illuminance only 1% of that of the same light observed from a distance of 1km.

2.3 Human perception of light

- 2.3.1 The human eye is composed of two different types of optical sensors, known as *cones* and *rods*, each of which is adapted to function under different light conditions to maximise the overall ability of the eye (see Appendix B for a more detailed technical discussion).
- 2.3.2 Cones cells provide the ability for humans to discern colour. Cones are adapted to work at high ambient light levels; this is known as the *photopic* regime.
- 2.3.3 In contrast, rods have no ability to identify colour, but do have a much higher sensitivity than cones, allowing fainter levels of light to be detected (albeit that in such light levels the eye loses the ability to distinguish colour and objects appear grey). Rods mediate vision at low ambient light levels, known as the *scotopic* regime.
- 2.3.4 At intermediate light levels both cones and rods play a role; this is known as *mesopic* vision. It is not as sensitive as scotopic vision, but does allow for perception of colour.
- 2.3.5 In the photopic regime (daytime vision) the human eye is most sensitive to green light.
- 2.3.6 Luminosity intensity and illuminance are both calculated in a way that weights the colour distribution of the light with the photopic (daytime) wavelength response of the human eye. Thus, in high ambient light conditions, a blue and a red light of the same luminous intensity (candela rating), seen at the same distance, will appear equally bright.
- 2.3.7 In the scotopic regime (night-time vision) the eye is more sensitive to bluer light and has little sensitivity to red light. Therefore, at low ambient light levels (in the mesopic or scotopic regimes), a red light will appear fainter than a blue light of the same candela rating at the same distance.
- 2.3.8 The threshold sensitivity of the eye depends critically on the background ambient light level. It also varies to some extent from observer to observer (e.g. due to deterioration with age).
- 2.3.9 Maximum sensitivity is achieved in the darkest ambient conditions, but only after the eye has become fully dark-adapted. Dark adaptation is associated with chemical changes in the eye and is largely complete after around 30 minutes of darkness. Any (even short) exposure to bright light resets the dark adaptation process. An observer in a partially lit environment (e.g. street lighting), such as would be found from many of the representative viewpoints for the Y Bryn wind farm, never becomes fully dark adapted.

- 2.3.10 Fully dark-adapted eyes in optimal observing conditions (moonless night-time sky, away from sources of light pollution) have a typical sensitivity limit of just below 10^{-8} lumens/m² to a point source of white light. That sensitivity limit is fractionally higher (approximately 2×10^{-8} lumens/m²) for red light, limited by the lower end of the mesopic regime.
- 2.3.11 Infrared lighting, produced to Ministry of Defence standards, emits in the wavelength range 750 to 900nm. The eye has essentially no sensitivity at these wavelengths, and therefore the installation of infrared lights on the proposed wind farm will have no visual impact.

3. Atmospheric attenuation of light

3.1 Atmospheric attenuation in 'clear' conditions

- 3.1.1 As light passes through the atmosphere, it is attenuated (decreased in brightness) by scattering and absorption processes in the atmosphere. A full technical description of this process is presented in Appendix C. Here, an outline summary is provided.
- 3.1.2 The attenuation process is caused both by the molecules of air in the atmosphere and by microscopic solid or liquid particles suspended in the atmosphere, known as aerosols. Aerosols can be natural, such as dust and pollen, or man-made pollutants, such as smoke or vehicle emissions. In maritime environments, sea salt is prevalent. Another common aerosol is liquid water droplets suspended in the air, as is the case for cloud or fog.
- 3.1.3 The total amount of attenuation depends upon amount of material through which the light passes (known as the optical depth, or opacity, of the material). For light travelling horizontally through the atmosphere, the optical depth is proportional to the distance between the light source and the observer.
- 3.1.4 The optical depth is also dependent upon the wavelength of the light. The exact wavelength dependence is determined by the properties of the attenuating material, but in general blue light is more strongly attenuated than red light.
- 3.1.5 Attenuation by air molecules occurs due a process known as Rayleigh Scattering. This is well-quantified, and varies little with time. As outlined in Appendix C, it can be calculated with high accuracy. Rayleigh scattering has a very strong wavelength dependence, with blue light being much more highly scattered (this is the reason that the sky appears blue).
- 3.1.6 The attenuation by aerosols can be estimated (see Appendix C) but, unlike Rayleigh Scattering, this cannot be described by a single number. The quantity and nature of aerosols varies with location and over time (for example, due to the direction that the wind is coming from). This changes the optical depth of the aerosols, the wavelength dependence of the scattering process, and the vertical distribution of aerosols in the atmosphere.

- 3.1.7 Extensive ground-based measurements of the distribution of properties of aerosols exist in different UK environments, and these are complemented by satellite observations. Based upon these, predictions can be made for the range of levels of attenuation of light by aerosols (see Appendix C), as a function of distance, for typical 'clear' conditions.
- 3.1.8 Considering this range, the calculations in Appendix C of the atmospheric attenuation of red light show that between 50% and 75% of the light remains, when viewed horizontally from a distance of 10km, at an altitude of 450m (this is the average hub height of the 18 turbines in the Y Bryn Wind Farm: hub heights of these turbines vary from around 400m to around 490m).
- 3.1.9 The geometric dilution of light with distance (see 2.2.6) is then scaled by this attenuation factor to determine the final observed illuminance of the light. Given the strong geometric dilution effects compared to the relatively mild atmospheric attenuation at distances below 10-15km, the choice of adopted aerosol parameters (for 'clear' conditions) does not qualitatively change the conclusions.

3.2 Visibility

- 3.2.1 The Air Navigation Order regulations (Article 222) and the CAA Policy Statement of 1 June 2017 ('Lighting of onshore wind turbine generators in the United Kingdom with a maximum blade tip height at or in excess of 150m above ground level') require relevant turbines to be lit with a 2000 candela light, but this may be reduced to 200 candela if the visibility is better than 5km.
- 3.2.2 Visibility is defined by the World Meteorological Organisation as the distance at which the intrinsic brightness of a light is reduced to 5% of its initial value due to light attenuation. It is thus directly related to optical depth.
- 3.2.3 In poor visibility conditions, the opacity is generally associated with larger particles such as liquid water droplets (cloud or fog).
- 3.2.4 The illuminance of a light can be accurately calculated as a function of distance, at the threshold visibility value. This represents a worst-case scenario for 2000 candela lighting: in better conditions the luminous intensity of the lighting can be reduced, while in poorer conditions atmospheric attenuation effects will be increased.
- 3.2.5 The fraction of time for which the visibility is below 5km would ideally be determined using on-site measurements. However, estimates can be made by considering publicly-available datasets from other locations within the UK.
- 3.2.6 Met Office data from Cardiff Airport (about 33km from the Y Bryn Wind Farm) provides information on the historic visibility. The 5km visibility threshold for requirement of the 2000 candela lights is met at Cardiff Airport for about 10% of

the time, averaged over the year. Data from other nearby airports provide similar values.

- 3.2.7 An extensive dataset is also available from the Met Office measurement site at St Athan, about 28km from the Y Bryn wind farm. At St Athan, the 5km visibility threshold is met for 9.5% of the time over the last 20 years.
- 3.2.8 Many of these datasets are obtained close to the coast, and some of the measured periods of poor visibility are likely to be due to coastal fog which would not extend as far inland as the proposed Y Bryn Wind Farm. Furthermore, the airports are typically located close to large population centres, where they are subject to higher aerosol pollutants. Aerosol density also decreases with increasing altitude. On the other hand, higher altitude sites like that of the proposed Y Bryn Wind Farm will be more susceptible to periods of low cloud and mist. These different effects may largely counter-balance each other. These results suggest that the Y Bryn Wind Farm may be affected by poor visibility (and hence require the use of 2000 candela lighting) for about 10% of the time.

4. Illuminance of aviation lighting

- 4.1 Following the detailed calculations of Appendix C, the illuminance of individual turbine lights, as a function of distance, is shown in Figure 1. These are calculated for 'clear' atmospheric conditions for a luminous intensity of 200 candela. Results are shown for average assumptions of the aerosol attenuation.
- 4.2 Also shown on Figure 1 are the results for 2000 candela lights as observed at the threshold visibility limit of 5km (i.e. the worst-case scenario for these lights). In the poor visibility conditions when they are required, these 2000 candela lights have lower illuminance than the 200 candela lights seen in typical clear conditions, for all distances beyond 5km.
- 4.3 For comparison with these calculations, Figure 1 also shows the illuminance of the brightest star in the northern sky, and of typical bright stars such as those in the constellation of Orion. The latter provide a good approximation of the limiting illuminance that can be observed from street-lit locations. Also shown is the approximate visible limit under optimal conditions: fully dark-adapted eyes away from any light pollution. Table 1 provides numerical values for these illuminances, and also the illuminance of car brake lights at different distances, which provide a natural comparison.
- 4.4 Figure 1 and Table 1 make clear that from a distance of 5km, both the 200 candela light in clear conditions and the 2000 candela light in poor visibility have illuminances below that of the brightest star, and comparable to car brake lights seen from distances of a few km. At larger distances from the turbines, the 2000 candela light (in poor visibility) quickly becomes unobservable. The illuminance of the 200 candela light is comparable to that of typical bright stars at distances of 10-15km, reaching the observable threshold from street-lit areas by a distance of

about 15km. For observers with dark-adapted eyes, the 200 candela lights will remain visible (with decreasing prominence) out to distances of 30-40km.

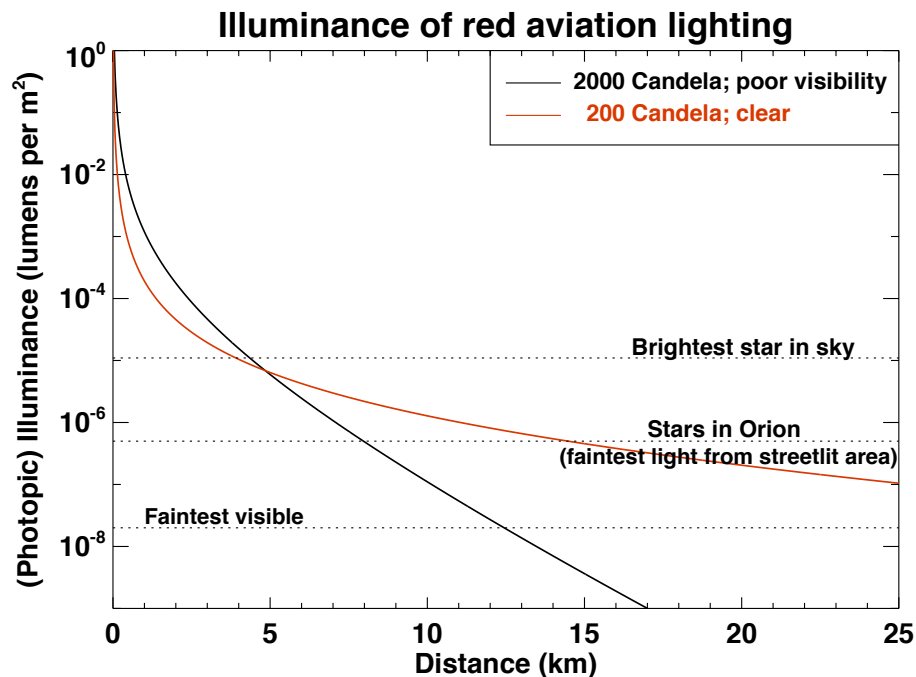


Figure 1: The illuminance of a single red light (633nm) as a function of distance, viewed horizontally at an altitude of 450m. The results are shown for a light with a luminous intensity of 200 candela for typical 'clear' atmospheric conditions. Also shown are the results for 2000 candela lights, at the threshold visibility (visibility=5km) that these are required. For comparison, the illuminance provided by the brightest star in the northern sky is shown, along with those of typical bright stars such as those in the constellation of Orion. The latter also represent the approximate visual limit of the eye from street-lit areas (see Appendix B). Also indicated is the approximate visible limit to red light under perfect conditions (away from street lighting and other light pollution; new moon; dark-adapted eyes).

Comparison object	Approx. Illuminance (Lumens per m²)
Car brake lights at 1km distance	100×10^{-6}
Brightest star in the sky	13×10^{-6}
Car brake lights at 10km distance	1×10^{-6}
Typical bright stars (e.g. in Orion)	0.5×10^{-6}
Faintest light visible from street-lit area	0.4×10^{-6}
Visible limit for fully dark-adapted eyes	0.02×10^{-6}

Table 1: Illuminances of typical comparison objects.

- 4.5 It is important to note that Figure 1 assumes that the aviation lighting is seen horizontally. The regulations in the International Civil Aviation Organization Annex 14 to the Convention on International Civil Aviation relate to the luminous intensity emitted in the horizontal plane. At angles below the horizontal plane, the luminous intensity of modern aviation lighting (2000 or 200 candela) is strongly suppressed, resulting in significantly lower illuminance. This is shown in Figure 2 which presents technical data from an aviation LED currently on the market.

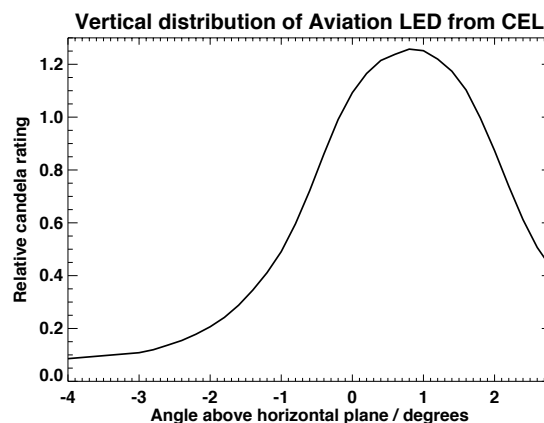


Figure 2: The attenuation of the illuminance of aviation lighting away from the horizontal plane. The figure shows technical data for an aviation LED from CEL, currently on the market. At an angle of 3 degrees below the horizontal plane, the brightness of the lights is suppressed by a factor of 10.

- 4.6 This vertical suppression will be relevant both for observers close to the turbines (who will typically be viewing them from below) and for population centres located at lower altitude.
- 4.7 Table 2 provides the calculated illuminance of the brightest turbine light that will be visible from each of the 37 designated viewpoints, also taking into account the topology of the land between the turbine and the viewpoint (note that the topology means that none of the turbine lights are visible from Viewpoint 32). The calculation of these values takes into account both the propagation of light (Figure 1) and the suppression of light relative to the horizontal plane (Figure 2). Values are given for average 'clear' conditions (with a 200 candela light), for the limit of 'poor visibility' conditions (with a 2000 candela light). Table 1 provides every-day visual comparators to the calculated illuminances.
- 4.8 For the proposed Y Bryn Wind Farm, receptors in nearby population centres (for example: Bryn, viewpoints 3,25; Maesteg, viewpoints 2,13,27; Caerau, viewpoint 1; Llangynwyd, viewpoint 28; Cynonville, viewpoint 10; Cwmafan, viewpoint 4) will observe the aviation lights from angles of at least 4 degrees below the horizontal plane, and thus observe the 200 candela lights to be suppressed by a factor of at least 10 relative to the illuminances calculated in Figure 1.

Viewpoint	Brightest Turbine				Illuminance (lumens per square metre)	
	Number	Distance (km)	Angle below horizontal (degrees)	Vertical suppression factor	200 cd average conditions	2000 cd poor visibility
1	4	1.88	8.4	0.09	4.4×10^{-6}	18.2×10^{-6}
2	5	1.22	10.4	0.09	10.8×10^{-6}	60.9×10^{-6}
3	3	1.67	9.1	0.09	5.7×10^{-6}	26.0×10^{-6}
4	12	4.29	4.1	0.09	0.75×10^{-6}	1.00×10^{-6}
5	12	11.15	1.8	0.25	0.24×10^{-6}	0.01×10^{-6}
6	12	18.32	1.1	0.45	0.12×10^{-6}	$<0.01 \times 10^{-6}$
7	12	31.53	0.4	0.83	0.04×10^{-6}	$<0.01 \times 10^{-6}$
8	18	2.59	5.9	0.09	2.3×10^{-6}	6.7×10^{-6}
9	2	22.77	-0.25	1.18	0.15×10^{-6}	$<0.01 \times 10^{-6}$
10	1	2.18	7.6	0.09	3.3×10^{-6}	11.7×10^{-6}
11	11	14.23	1.8	0.24	0.12×10^{-6}	$<0.01 \times 10^{-6}$
12	11	41.24	0.0	1.07	0.02×10^{-6}	$<0.01 \times 10^{-6}$
13	11	2.15	7.0	0.09	3.3×10^{-6}	12.1×10^{-6}
14	12	18.96	1.2	0.41	0.09×10^{-6}	$<0.01 \times 10^{-6}$
15	12	17.27	-0.9	0.52	0.15×10^{-6}	$<0.01 \times 10^{-6}$
16	12	7.12	3.2	0.10	0.29×10^{-6}	0.10×10^{-6}
17	18	3.02	7.1	0.09	1.6×10^{-6}	3.9×10^{-6}
18	2	33.10	-0.7	1.25	0.05×10^{-6}	$<0.01 \times 10^{-6}$
19	17	10.45	2.3	0.17	0.19×10^{-6}	0.01×10^{-6}
20	11	6.84	2.6	0.14	0.43×10^{-6}	0.17×10^{-6}
21	3	10.13	0.6	0.74	0.88×10^{-6}	0.07×10^{-6}
22	2	7.04	1.6	0.28	0.80×10^{-6}	0.29×10^{-6}
23	18	3.35	7.0	0.09	1.3×10^{-6}	2.7×10^{-6}
24	17	8.12	2.9	0.12	0.24×10^{-6}	0.05×10^{-6}
25	3	1.36	11.7	0.09	8.7×10^{-6}	46.1×10^{-6}
26	11	1.42	6.7	0.09	8.0×10^{-6}	40.9×10^{-6}
27	5	3.02	5.4	0.09	1.6×10^{-6}	3.9×10^{-6}
28	11	2.61	5.7	0.09	2.2×10^{-6}	6.5×10^{-6}
29	12	30.18	0.7	0.65	0.03×10^{-6}	$<0.01 \times 10^{-6}$
30	11	21.31	1.1	0.44	0.07×10^{-6}	$<0.01 \times 10^{-6}$
31	2	27.31	-0.4	1.22	0.09×10^{-6}	$<0.01 \times 10^{-6}$
32	-	-	-	-	-	-
33	12	17.96	1.3	0.39	0.10×10^{-6}	$<0.01 \times 10^{-6}$
34	17	15.16	1.6	0.29	0.12×10^{-6}	$<0.01 \times 10^{-6}$
35	17	26.68	0.9	0.54	0.04×10^{-6}	$<0.01 \times 10^{-6}$
36	12	10.48	2.2	0.18	0.20×10^{-6}	0.01×10^{-6}
37	17	30.22	0.8	0.60	0.03×10^{-6}	$<0.01 \times 10^{-6}$

Table 2: Calculated illuminances of the brightest turbine aviation light visible from the 37 viewpoints (note that none are visible from viewpoint 32). Table 1 provides every-day comparisons to the illuminances quoted. Calculations are provided for both a 200 cd light under average 'clear' atmospheric conditions and a 2000 cd light at the limit of the poor visibility conditions (visibility=5km) when such a light is required. Calculations take into account the vertical suppression of light away from the horizontal plane, assuming the LED specifications of a commercially-available aviation light from CEL (see Figure 2).

- 4.9 The aviation lighting viewed from these nearby population centres will appear to be similar in brightness to the very brightest stars in the sky. They will appear comparable to viewing car brake lights from distances of around 5km.
- 4.10 On the rare occasions when the visibility is sufficiently poor as to require 2000cd lighting, the aviation lighting from these nearby population centres will appear up to a factor of about 5 brighter than the typical 200 candela lights, appearing slightly brighter than the brightest star in the sky, or comparable to car brake lights at a distance of around 2km.
- 4.11 Receptors for the Y Bryn Wind Farm located in moderately distant population centres such as Port Talbot (e.g. viewpoint 16) will observe the aviation lights from around 3 degrees below the horizontal plane, corresponding to a suppression of the illuminance by almost a factor of 10. From these locations, the turbine lighting will be comparable in brightness to typical bright stars such as those in Orion. These lights will be close to the limit of observability from street-lit locations. On the occasions when visibility is poor and the 2000 candela lights are required, these will appear even fainter than the 200 candela lights in typical condition.
- 4.12 For receptors located at viewpoints even more distant from the Y Bryn wind farm (for example: Swansea, viewpoints 6, 14, 15; Ogmore-by-sea, viewpoint 11; Neath, viewpoint 5), the lights will be too faint to be observable from heavily street-lit areas, but will be visible with a degree of dark adaptation of the eyes.
- 4.13 A common concern is that, during the hours of darkness, when turbine blades pass in front of the aviation lights they will appear to flicker. Although this is true, it should be noted that lights in the night sky naturally flicker (stars 'twinkle') due to atmospheric refraction effects. When seen from viewpoints at which the illuminances of the turbine lights are comparable to those of stars, any such flickering will therefore be consistent with other similar brightness lights in the night sky, and so is unlikely to be any cause of concern.

5. Summary

- 5.1 This report has considered the observability of the aviation lighting for proposed Y Bryn Wind Farm. The report takes into account the brightness of the lights, geometric dilution of light, atmospheric attenuation, and the response of the human eye.
- 5.2 At distances of 5-15 km, 200 candela lights, which will be lit on the turbines under typical atmospheric conditions, will have an apparent brightness comparable to that of bright stars in the night sky, or to car brake lights at a distance of 3-10km. They will thus be visible to observers with a degree of dark adaptation, but will not be prominent. The lights will remain visible to fully dark-adapted eyes out to distances of 30-40km, but their prominence falls further still.
- 5.3 When the visibility is sufficiently poor as to require 2000 candela lighting, then the visual impact of these beyond 5km distance will be less than that of the 200 candela lights, and these lights will be invisible beyond about 10km distances.
- 5.4 The reduction of light intensity below the horizontal plane for aviation lighting means that, in reality, from most nearby locations any impact would be even further reduced, by up to a factor of 10.
- 5.5 The impact of the aviation lighting is illustrated through consideration of the illuminance of the brightest turbine light from each of the designated viewpoints. Under typical atmospheric conditions where the 200 candela lights can be used, in all cases the illuminance of the aviation lighting is calculated to be fainter than that of the brightest star in the sky.
- 5.6 For the estimated $\approx 10\%$ of the time when the visibility is poor and the 2000 candela lights are required, from locations more than 5km from the wind farm these lights are observed to be fainter than the 200 candela lights under typical conditions. However, for the closest viewpoints considered, they can appear brighter than the 200 candela lights by up to a factor of about 5.
- 5.7 The calculations provided here are based on the aviation lighting being switched on. A radar-activated lighting scheme for the Y Bryn Wind Farm, whereby the lights are only switched on when aircraft are in the vicinity, would greatly reduce any impact of the lighting.

Appendix A: Terminology and propagation of light

- A.1 The measure of how intrinsically powerful a light source is (its *power*, or *radiant flux*) is the amount of energy that it emits each second. This is measured in *Watts*. A familiar example will be a standard domestic light bulb (e.g. a 60 Watt light bulb).
- A.2 This energy emitted by a light can be spread across a wide range of wavelengths (colours); some of these are not detectable by the human eye (see Appendix B for a technical discussion of the eye's sensitivity). The amount of energy per second emitted, weighted by the (daytime) sensitivity of the human eye at different wavelengths, is known as *luminous flux* and is measured in *lumens*.
- A.3 Another commonly used measure of the intrinsic brightness of a light source is the *luminous intensity*. This is defined as the luminous flux emitted per unit solid angle in a given direction. Solid angle is a measure of angular area, measured in *steradians*. The solid angle of the full surface of a sphere is 4π steradians (thus 1 steradian is approximately 3283 square degrees).
- A.4 For an isotropic light source (i.e. one that emits light equally in all directions) the luminous intensity is simply the luminous flux scaled down by the factor of 4π . If a light emits anisotropically (i.e. different amounts of light in different directions) then the luminous intensity will vary with direction.
- A.5 Luminous intensity is measured in *candelas*. Aviation warning light regulations are expressed in terms of candela requirements.
- A.6 More distant light sources appear fainter, because the light emission spreads out over a larger area. The observability of light depends upon the *illuminance* of the light, which measures the luminous intensity of light that passes through a unit area of surface at that distance. Illuminance is measured in *lumens per square metre* (also known as *lux*). It is the illuminance of the light that determines how bright it appears to the observer.
- A.7 For perfect transmission of light (i.e. no light absorbed or scattered by the medium through which it is passing), the illuminance (*I*) is related to the luminous intensity (*L*) by:

$$I = \frac{L}{D^2}$$

where *D* is the distance between the light source and the observer in metres.

- A.8 Figure A1 shows examples of illuminance as a function of distance for lights of 200 and 2000 candela luminous intensities, in the absence of any attenuation effects (see Appendix C).

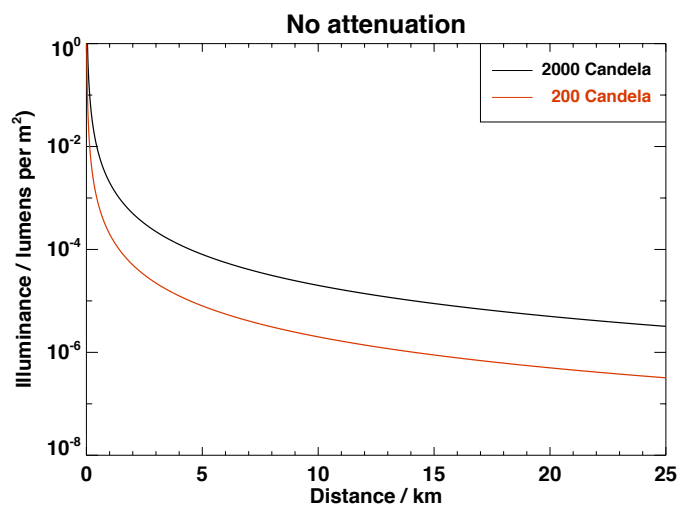


Figure A1: The illuminance of 2000 candela and 200 candela luminous intensity lights as a function of distance, in the absence of any atmospheric attenuation (i.e. considering geometric effects only).

Appendix B: The response of the human eye to light

B.1 Optical sensors in the eye

- B1.1 The human eye is composed of two different types of optical sensors, known as *cones* and *rods*.
- B1.2 Cones are concentrated in the central portion of the retina, and provide the sharpest vision. Cones come in three types adapted to detect different wavelengths of light (approximately, blue, green and red light respectively). The combination of light detected by these three types of cone cells provides the ability for humans to discern colour. Cones are adapted to work at high ambient light levels, (above a few candela/m²), which is known as the *photopic* regime.
- B1.3 Rods are more distributed around retina. Rods have a much higher sensitivity than cones, allowing fainter levels of light to be detected. Rods mediate vision in the *scotopic* regime, corresponding to ambient light levels below about 0.003 candela/m². Rods have no colour response, and so in these low light levels the eye loses the ability to distinguish colour and objects appear grey.
- B1.4 Because rods are spread across the eye, and largely absent from the (cone-dominated) central region, this gives rise to the well-known effect that in low ambient light levels, faint light sources appear clearer in peripheral vision than when looked at directly.
- B1.5 The eye's sensitivity function has been formalised by the International Commission on Illumination (CIE). In the photopic regime, the widely used standard is the CIE 1978 $V(\lambda)$ function, based on data by Judd (1951) and Vos (1979): this is shown in Figure B1 and has maximum sensitivity at a wavelength of 555nm (green).
- B1.6 Figure B1 also shows the CIE 1951 $V'(\lambda)$ sensitivity function of the eye in the scotopic regime, which is based on measurements by Wald (1945) and Crawford (1949). Here it can be seen that the peak sensitivity is at significantly shorter wavelength than the photopic curve (507nm), and that the sensitivity at longer (redder) wavelengths is dramatically lower in the scotopic regime. In particular, at the wavelength of standard red aviation LEDs (633nm) it is nearly a factor 100 lower.
- B1.7 At intermediate light levels both cones and rods are activated; this is known as *mesopic* vision. It is not as sensitive as scotopic vision, but does allow perception of colour. The eye sensitivity in mesopic vision depends upon the relative stimulation of the cones and rods. As indicated on Figure B1 there is a gradual change of the sensitivity function as we move down the mesopic regime. At all points, the sensitivity to red LEDs will be dominated by whatever component of photopic vision remains.

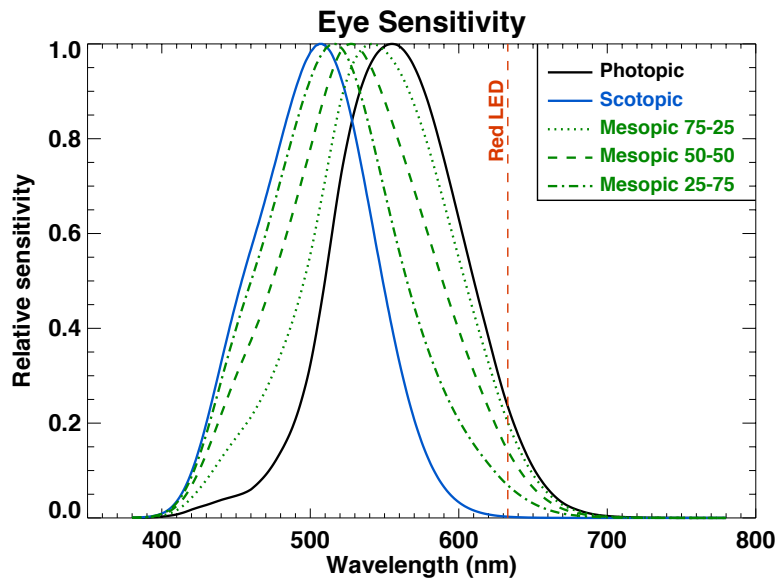


Figure B1: The relative sensitivity of the eye as a function of wavelength, in the photopic regime (black line; vision mediated by cones, at high light levels) and the scotopic regime (blue line; vision mediated by rods, at low light levels). The data are the accepted CIE 1978 and CIE 1951 standard values (see text for details). At low light levels the eye sensitivity function shifts towards bluer wavelengths, with significantly lower relative sensitivity to red light. Also shown in green lines are intermediate stages of mesopic vision, where both cones and rods are activated (dotted, dashed and dot-dashed lines show respectively a 75%-25% split, a 50%-50% split, and a 25%-75% split between photopic and scotopic vision).

- B1.8 The conversion of radiant flux to luminous flux is normally derived by weighting the radiant flux by the photopic sensitivity function. Thus, in the photopic regime, a light of given luminous intensity viewed from a given distance will appear to deliver the same illuminance irrespective of its colour: in other words, from a given distance, a blue light and a red light emitting the same candela of light would appear equally bright.
- B1.9 However, if the light level is sufficiently low that the eye enters the mesopic or scotopic regime, then the shift of the eye's sensitivity function towards shorter wavelengths would result in a redder light appearing fainter than a bluer one.

B.2 Eye detection thresholds

- B2.1 Studies of the detection threshold of the eye (that is, the faintest detectable illuminance for a single fixed light) have a long history; for example, it is of wide interest in astronomy to understand the faintest star visible under different light pollution conditions, and that analysis is directly relevant here.
- B2.2 The most authoritative and extensive data samples were taken by Blackwell (1946), supplemented by the work of Knoll et al. (1946), who studied the detectability of point sources of light by the eye in different ambient lighting

conditions. Specifically, they considered background illumination levels (B), and tested the ability of observers to detect point source lights of incremental illuminance (ΔI) above this background. The primary results are shown in Figure B2 and have largely been supported by later studies.

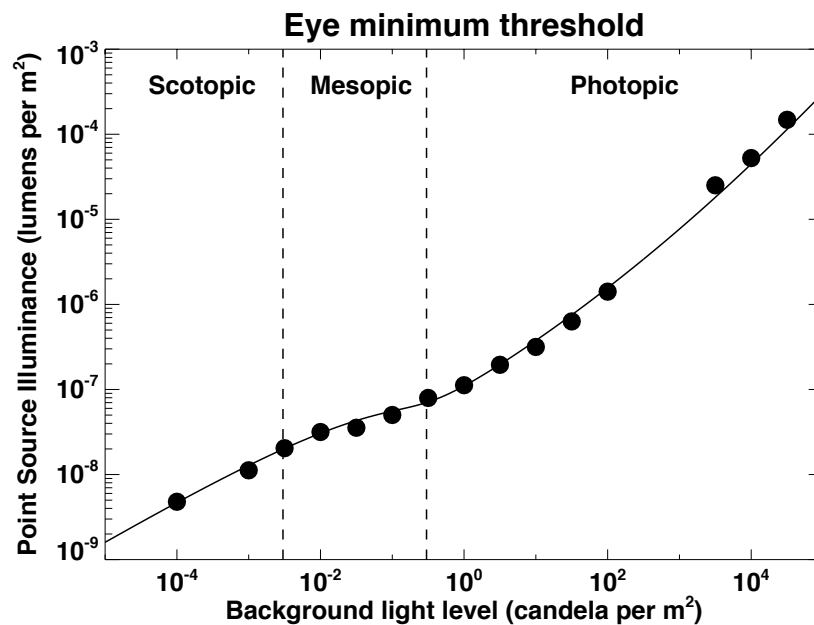


Figure B2: The minimum point source illuminance, which is detectable by the eye, as a function of the background ambient light level. Plotted data points are from Knoll et al. (1946), and the fitting function comes from Crumey (2014).

- B2.3 There have been many attempts to provide functional fits to these data. The best of these consider separate functional forms in the photopic and scotopic regimes, as it is clear from Figure B2 that the detectability of light is non-linear due to the changes between the different vision regimes. The fit shown in Figure B2 comes from Crumey (2014), and is the one adopted for the current analysis.
- B2.4 These results are based on a white light source (i.e. one that emits across a very wide range of wavelengths); the colour temperature of the white light (that is, the exact distribution of radiant flux across wavelength) will have an effect on the derived threshold in the mesopic and scotopic regime, but this will typically be well below a factor of 2.
- B2.5 Note that these data are based on the average results from young adults (less than 30 years old) in fully dark-adapted conditions. Those who have not taken the time to dark-adapt their eye in low lighting conditions, will have significantly higher detectable limits.

- B2.6 Dark adaptation is a relatively slow process associated with chemical changes in the eye. Dark adaptation of the cones to lower light levels takes between 5 and 10 minutes. Rods are nearly fully activated after about 30 minutes, although the sensitivity of rods to low light levels continues to improve marginally even after hours of darkness. Even a short exposure to bright light resets this process. An observer in a partially lit environment (e.g. street lighting), such as would be found from many of the representative viewpoints for the Y Bryn wind farm, never becomes fully dark adapted.
- B2.7 Older people typically take longer to dark-adapt, and generally have significantly higher detectable limits. Blackwell & Blackwell (1971) estimate a factor approximately 3 higher threshold on average at age 65.

B.3 Ambient background lighting levels and limiting sensitivities

- B3.1 Figure B2 indicates that the detectable limit of light depends strongly on the background ambient light level. This can vary considerably, depending on location and on moon phase.
- B3.2 In a street-lit area, the ambient light level is about 10 candela/m². From Figure B2, this gives a faintest detectable illuminance of a (white) point-source light of around 5×10^{-7} lumens/m². To put this value into context, this is about the same apparent brightness as typical bright stars in the night sky, such as the main stars in the constellation of Orion, or of a car brake light seen from a distance of about 10 km.
- B3.3 The darkest night-time conditions are found for a new moon, and away from any source of light pollution. For this, the ambient light level due to starlight from all of the stars in the sky is around 2×10^{-4} candela/m². The corresponding faintest detectable illuminance is around 6×10^{-9} lumens/m².
- B3.4 Falchi et al. (2016) studied the sky brightness as a function of location in Europe; their data indicate that the background light level away from towns in the region of the Y Bryn Wind Farm is a factor of at least 3 times higher than the dark sky background. Cinzano et al. (2001) found a similar result for the increased sky brightness due to airglow. Their limiting brightness in that region of Wales corresponds to an illuminance of around 2×10^{-8} lumens/m². This value provides a more realistic estimate of the limit of the detectability of a white light source in optimal new moon conditions.
- B3.5 For red LED aviation lighting at 633nm, the sensitivity of rods is a factor approximately 100 below that of the cones (see Figure B1). Thus, if the ambient light level were to be sufficiently low as to be fully in the scotopic regime, then faint red lights become largely undetectable. The bottom of the mesopic regime occurs at an illuminance of around 2×10^{-8} lumens/m², and so this also represents a realistic detectable limit for faint red lights.

Appendix C: Attenuation of light

C.1 Overview

- C1.1 Light is attenuated by scattering and absorption processes as it travels through the atmosphere. The attenuation is described by the *optical depth* of the attenuating medium, τ , such that the un-attenuated fraction of light (f) is given by:

$$f = \exp(-\tau)$$

where $\exp$ is the exponential function.

- C1.2 The optical depth depends upon the amount of attenuating material that the light passes through. This can be written as

$$\tau = \sigma \int n \, dl$$

where σ is the cross-section of the absorber or scatterer, n is the number density of the scatters, and the integral over dl is an integral along the path from the source to the observer.

- C1.3 In the case of light travelling horizontally through the atmosphere near the surface of the Earth, the number density of scatterers can be estimated to be constant along the line of sight, and so the optical depth scales proportionally to the distance (D). This can be written as

$$\tau = \tau_0 \left(\frac{D}{1\text{km}} \right)$$

where τ_0 is the optical depth for a characteristic distance of 1km.

- C1.4 The value of τ_0 depends on the properties of the atmosphere, and also depends on the wavelength of the light that is being observed.
- C1.5 The value of τ_0 is also dependent upon altitude, since the density of scatterers depends upon altitude.
- C1.6 If the observer and the light source are at different altitudes then a full integral of the equation in C1.2 is formally required, rather than the simplification in C1.3. However, differences in calculated illuminance are small. Furthermore, where different altitudes are involved, the suppression of the beam of the aviation light away from the horizontal plane has a far more significant effect on the resultant illuminance of the light, meaning that a more detailed calculation is unwarranted.
- C1.7 Atmospheric optical depth has been widely studied, by measuring the attenuation of light as it passes vertically through the atmosphere from the edge of space to the surface of the planet (i.e. the attenuation of incoming light from the Sun or stars, or equivalently of out-going light from Earth as measured by satellites).

- C1.8 The attenuation is made up of two¹ primary components. These are: (i) Rayleigh scattering by air molecules; and (ii) scattering and absorption by microscopic solid or liquid particles suspended in the atmosphere (aerosols). These are discussed in the next two sections.

C.2 Rayleigh scattering

- C2.1 Scattering by particles whose size is much smaller than the wavelength of the light, such as air molecules in the atmosphere, is known as Rayleigh scattering. Rayleigh scattering has a characteristic wavelength dependence as roughly

$$\tau \propto \lambda^{-4}$$

where λ is the wavelength of the light (e.g. Penndorf 1957). Thus, bluer wavelengths are more strongly scattered (this is why the sky appears blue).

- C2.2 The total optical depth for Rayleigh scattering vertically through the atmosphere has been well-established. It is given by (e.g. Hayes & Latham 1975; Buton et al. 2013):

$$\tau_{Rayleigh,atmos} \approx 0.14 \left(\frac{\lambda}{500 \text{ nm}} \right)^{-4} e^{(-h/h_0)}$$

where the numerical value corresponds to a wavelength λ of 500nm (5×10^{-7} m) which is appropriate for white light detected by the eye at low light levels (see Appendix B). In this equation, h is the height of the observer above sea-level, and h_0 is the scale-height of the atmosphere, set by the rate at which atmospheric pressure falls off with altitude.

- C2.3 The atmospheric scale-height depends upon temperature, but for a temperature of 280K (around 7°C) it is typically $h_0 \approx 8$ km.

- C2.4 Optical depth is proportional to the number of scattering molecules, and therefore to the density of the air. Atmospheric density (ρ) largely follows pressure (apart from small effects of temperature variations with altitude) in falling off exponentially with altitude, $\rho \propto \exp(-h/h_0)$. Since

$$\int_0^\infty \exp\left(\frac{-h}{h_0}\right) dh = h_0$$

the optical depth of the atmosphere, viewed vertically to space from sea level, is equivalent to looking through a distance h_0 of atmosphere horizontally at sea-level.

- C2.5 Given the large scale-height of the atmosphere, the density at an altitude of 450m above sea-level (the average hub altitude of the turbines in the Y Bryn Wind Farm) is around 95% of that at sea-level. Thus, when looking horizontally at any altitude close to the Earth's surface, the optical depth due to Rayleigh scattering can be

¹ A third component of atmospheric attenuation, due to Ozone, is small ($\tau_{ozone} \approx 0.016$ along a vertical path from Earth to space) and in any case it can be ignored for the current analysis of horizontal attenuation near the Earth's surface, as the ozone is located at high altitude.

treated as a constant, depending only on the distance (D) between the light source and the observer,

$$\tau_{Rayleigh} \approx 0.14 \frac{D}{h_0} \left(\frac{\lambda}{500 \text{ nm}} \right)^{-4}$$

Thus the optical depth produced by air molecules in 1 km of atmosphere close to sea level is

$$\tau_{0,Rayleigh} \approx 0.018 \left(\frac{\lambda}{500 \text{ nm}} \right)^{-4}$$

C.3 Scattering by aerosols

C3.1 In addition to the normal molecular composition of air, air can contain additional components which restrict the passage of light. Common examples include dust and pollen, or man-made pollutants such as smoke or vehicle emissions. In maritime environments, sea salt is prevalent. Another common aerosol is liquid water droplets suspended in the air, as is the case for cloud or fog.

C3.2 It is common experience that under foggy conditions lights are visible for considerably shorter distances. For other aerosols, at typically much lower concentrations, the effect is less stark than for fog, but these still attenuate light, through scattering processes.

C3.3 For most aerosols the dominant scattering process is known as Mie scattering. The wavelength dependence of Mie scattering depends upon the nature of the scattering aerosol. Mie scattering is often expressed as a power law,

$$\tau \propto \lambda^{-\alpha}$$

where α is known as the Ångström exponent. Broadly speaking, the smaller the particle, the larger the value of α . For very small particles, Mie scattering tends towards Rayleigh scattering ($\alpha \sim 4$). For large particles such as water droplets, which are very much larger than the wavelength of the light, the scattering become geometric, with no wavelength dependence ($\alpha = 0$).

C3.4 Since for typical aerosols α is significantly below 4, the importance of Mie scattering compared to Rayleigh scattering increases for redder light. Mie scattering also differs from Rayleigh scattering in its directionality: Mie scattering tends to deflect light by relatively small angles.

C3.5 To model the attenuation due to aerosols, both the Ångström exponent and the density of aerosols are required. Like Rayleigh Scattering, the aerosol optical depth is generally measured along a vertical path between the surface of the Earth and space, either by ground-based instruments such as a LIDAR (Light Detection and Ranging) or from space, for example by MODIS (the Moderate Resolution Imaging Spectroradiometer) on NASA's Terra satellite. The total optical depth for aerosol scattering vertically through the atmosphere can be written as

$$\tau_{aerosol,atmos} \approx A_0 \left(\frac{\lambda}{500 \text{ nm}} \right)^{-\alpha} e^{(-h/h_{aerosol})}$$

where A_0 is the aerosol optical depth from sea-level to space at 500 nm, h is the height of the observer above sea-level, and $h_{aerosol}$ is the scale-height of aerosols in the atmosphere.

- C3.6 The scale-height of aerosols is significantly smaller than that of the molecular content of the atmosphere. The precise value depends upon local conditions – both topology and weather. Hayes & Latham (1975) draw on data from many sets of measurements and argue for a typical scale-height of 1.5 km, while noting that it can vary by a factor of two from day to day. This value is widely adopted by many researchers. Matthias et al. (2004) analyse a significant dataset obtained from the European Aerosol Research Lidar Network in Aberystwyth and derive a typical scale height of 1.2km, again with significant variations. Other UK locations can be expected to be similar. In this report, a conservative value of $h_{aerosol} = 1.5\text{km}$ is adopted.
- C3.7 The aerosol optical depth is found to vary considerably with location on the Earth, being particularly high in polluted areas. In any given location, it also varies significantly with time.
- C3.8 Estellés et al. (2002) measured A_0 over an 8-year period at a coastal location of the UK (Plymouth) and determined that it varied around a mean of 0.18 (median 0.19), with an (asymmetric) standard deviation of 0.08. The lowest observed value of the observed aerosol optical depth over this period was about 0.08. Matthias et al. (2004) found a median A_0 of 0.14 (after converting their data from 350 to 500nm), with a lower limit of around 0.06. Data available from the Aerosol Robotic Network (AERONET; see <https://aeronet.gsfc.nasa.gov>) suggests a median A_0 of 0.11 for Exeter and 0.12 for Rhyl, which span the location of the Y Bryn wind farm.
- C3.9 The proposed Y Bryn Wind Farm is located relatively close to numerous sources of man-made pollutants (such as the M4 motorway and Port Talbot steelworks), and so hence the aerosol density might be expected to be moderately high (see National Atmospheric Emissions Inventory; <https://naei.beis.gov.uk/emissionsapp/>). For the analysis in this report, the effect of a range of different A_0 values from 0.06 to 0.16 is considered. This is a conservative approach: if the value of A_0 is higher then at larger distances the aviation lighting will appear slightly fainter than the values calculated
- C3.10 Observed values of the Ångström exponent are typically in the range 0 to 1.5 (see discussion in Hayes & Latham 1975). Smirnov et al. (2002) argue that the exponent in maritime environments is $\alpha = 0.3\text{--}0.7$, while Estellés et al. (2012) found $\alpha = 1.03 \pm 0.21$ for their data taken at Plymouth. The Exeter and Rhyl AERONET data also both find a median $\alpha \approx 1.0$. Larger values of α lead to lower values of attenuation for red lights, and so here a conservative value of $\alpha = 1.2$ is adopted. It should be stressed that the adoption of other reasonable values of α would not have a significant influence on the results (the effect of varying α is smaller than the effect of the range of A_0 values considered above).

C3.11 As for Rayleigh scattering (C2.4), the aerosol optical depth as viewed vertically to space from sea level, is equivalent to looking through a distance of $h_{aerosol}$ of atmosphere horizontally at sea-level.

C3.12 Unlike Rayleigh scattering, the aerosol scale-height is low, and so the altitude above sea-level needs to be taken into account when considering the attenuation. For an altitude of 450m, and a scale-height of 1.5km, the aerosol density is around 74% of that at sea-level.

C3.13 Thus, following the arguments in C2.5, when looking horizontally at an altitude h , the optical depth due to aerosol scattering depends on the distance (D) between the light source and the observer as

$$\tau_{aerosol} = A_0 \frac{D}{h_0} \left(\frac{\lambda}{500 \text{ nm}} \right)^{-\alpha} \exp \left(\frac{-h}{h_0} \right)$$

Thus for typical conditions, using our best estimate parameters and assuming 450m altitude, we find an optical depth for 1 km distances of

$$\tau_{0,aerosol} = [0.03 \text{ to } 0.08] \left(\frac{\lambda}{500 \text{ nm}} \right)^{-1.2}$$

where the term in square brackets represents the range, due to the range of values to be adopted for A_0 .

C.4 Resultant total attenuation under typical conditions

C4.1 Combining the optical depth for Rayleigh scattering with that from aerosols gives the total optical depth:

$$\tau = \tau_{Rayleigh} + \tau_{aerosol}$$

C4.2 At distance D , this is thus:

$$\tau \approx \left(0.017 \left(\frac{\lambda}{500 \text{ nm}} \right)^{-4} + [0.03 \text{ to } 0.08] \left(\frac{\lambda}{500 \text{ nm}} \right)^{-1.2} \right) \left(\frac{D}{1 \text{ km}} \right)$$

C4.3 From C1.1, the un-attenuated fraction of light is then $f = \exp(-\tau)$. Figure C1 shows this attenuation both for white light (500nm) and for red light (633nm). The solid and dashed lines show, respectively, the fractions of remaining light given by the equation in C4.2, for the upper and lower ends of the range of A_0 values. The dotted lines show the contribution from Rayleigh scattering only.

C4.4 It can be seen that atmospheric attenuation has a significant effect, reducing light levels by factor of approximately 2 at 10km distance (depending on colour) in poorer aerosol conditions, with shorter (bluer) wavelengths of light being more strongly attenuated than longer (redder) wavelengths.

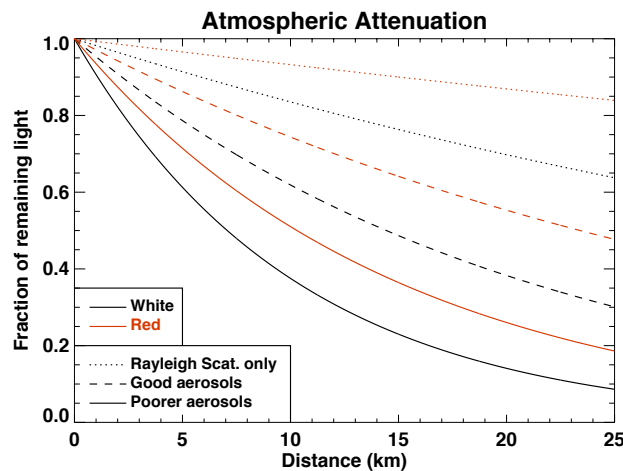


Figure C1: The attenuation of light as it passes horizontally through the atmosphere at an altitude of 450m. Results are shown for both white light (500nm) and red light (633nm). The dotted lines show the contribution from Rayleigh scattering by air molecules, in the absence of aerosols. The dashed and solid lines include aerosol attenuation under a range of realistic 'clear sky' condition. It can be seen that atmospheric attenuation has a significant effect, particularly at larger distances. There is a dependence on colour, with redder light being less strongly attenuated.

- C4.5 Combining this atmospheric attenuation with the geometric dilation of light discussed in Appendix A (Figure A1) then allows the total illuminance of a light as a function of distance to be derived, by multiplying the geometrically-calculated illuminance by the un-attenuated fraction. This is shown for a 200 candela light in Figure C2.
- C4.6 Figure C2 also compares the derived illuminance against other objects in the night sky, in particular the brightest star in the northern hemisphere, and typical bright stars in the constellation of Orion. It can be seen that at a distance of around 10km, the illuminance of a 200 candela red light is comparable to those of bright stars in the night sky.
- C4.7 Figure C2 further shows that the choice of aerosol attenuation factor makes little qualitative difference to the perceived brightness of the lights, at least out to distances of 10km.

C.5 Reduction of illuminance of aviation lighting below the horizontal plane

- C5.1 It is important to note that the calculations of Figure C2 assume the quoted candela value for the lights. Turbine lighting is highly directional, with the CAA candela requirements relating to the horizontal plane. At angles well below the horizontal plane, the luminous intensity of the aviation lighting is strongly suppressed, resulting in significantly lower illuminance. This will be relevant both for observers close to the turbines (who will typically be viewing them from below) and for population centres located at lower altitude.

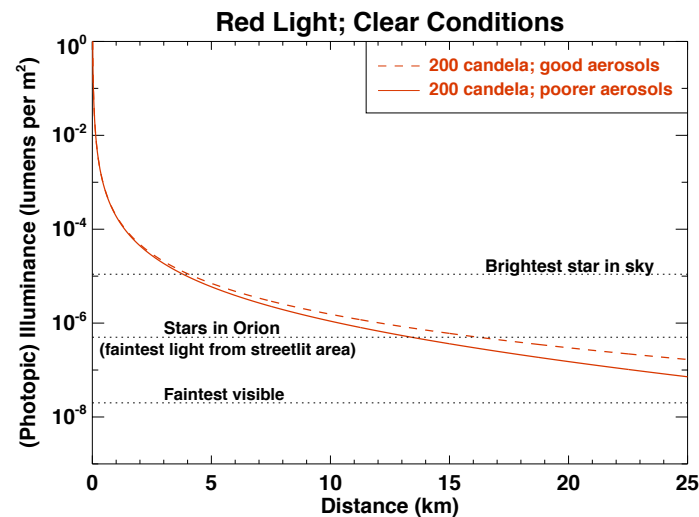


Figure C2: The illuminance of a single 200 candela red light (633nm) as a function of distance, viewed horizontally at an altitude of 450m. The results are shown considering the upper (solid line) and lower (dashed line) end of the realistic range of aerosol optical depth for typical clear conditions. For comparison, the illuminance provided by the brightest star in the northern sky is shown, along with those of typical bright stars such as those in the constellation of Orion. The latter also represent the approximate visual limit of the eye from street-lit areas (see Appendix B). Also indicated is the approximate visible limit to red light under perfect conditions (away from street lighting and other light pollution; new moon; dark-adapted eyes).

- C5.2 To illustrate this effect, Figure 2 in the main report shows the vertical distribution of light using the technical specifications of a 2000 candela or 200 candela aviation LED currently available on the market, supplied by Contarnax Europe Ltd (CEL). This shows the strong suppression below the horizontal plane.
- C5.3 If an aviation light is installed at a hub height of around 120m (the lowest turbines being considered for Y Bryn) then an observer at a distance of 2.3 km, at the same altitude as the base of the wind turbine, will be at an angle of -3 degrees relative to the light's horizontal plane. For an aviation LED with CEL's specifications, this corresponds to a factor 10 suppression in candela rating, thus effectively converting a 200 candela light into a 20 candela light. At 4.6km the observer will be at an angle of -1.5 degrees, with about a factor of 3 suppression of light. Where the observer is on lower ground than the turbines, or turbines are even taller, these suppression factors will be even greater.

C.6 Visibility

- C6.1 An important factor for aviation lighting on wind turbines is the *visibility*. According to The Air Navigation Order regulations (Article 222) and the guidance in the Civil Aviation Authority Policy Statement of 1 June 2017 ('Lighting of onshore wind turbine generators in the United Kingdom with a maximum blade tip height at or in excess of 150m above ground level'), when the visibility is better than 5km

the luminous intensity of the aviation warning lights may be reduced from 2000 to 200 candela.

C6.2 Visibility relates to the attenuation of light. It is defined by the World Meteorological Organisation as the distance at which the intrinsic brightness of a light is reduced to 5% of its initial value due to light attenuation (i.e. excluding the $1/D^2$ geometric dilution discussed in Appendix A). It is usually defined at 550nm.

C6.3 Visibility and optical depth are directly related. At the 5% visibility threshold,

$$\exp(-\tau) = 0.05.$$

This corresponds to $\tau=3.0$.

C6.4 As discussed in C2.5, the contribution of Rayleigh scattering at 550nm to the optical depth at a distance of 5km is only $\tau_{\text{Rayleigh}} = 0.06$, and thus aerosol scattering completely dominates the opacity in poor visibility conditions.

C6.5 In such poor visibility conditions, the opacity is generally associated with larger particles such as liquid water droplets (cloud or fog), and hence a lower value of the Ångström exponent is appropriate. Here a value of $\alpha=0.6$ is assumed, but again the results are not critically dependent upon the choice. For $\alpha=0.6$, the opacity at 633nm at the visibility threshold is $\tau = 2.6$ at 5km, corresponding to an optical depth per km of $\tau_0 = 0.52$.

C6.6 In such poor visibility conditions, a 2000 candela light is required. Figure C3 shows the illuminance of such a light as a function of distance, accounting for atmospheric attenuation at the threshold value. This is a worst-case scenario for 2000 candela lighting: in better conditions the luminous intensity of the lighting can be reduced, while in poorer conditions the atmospheric attenuation effects will be increased.

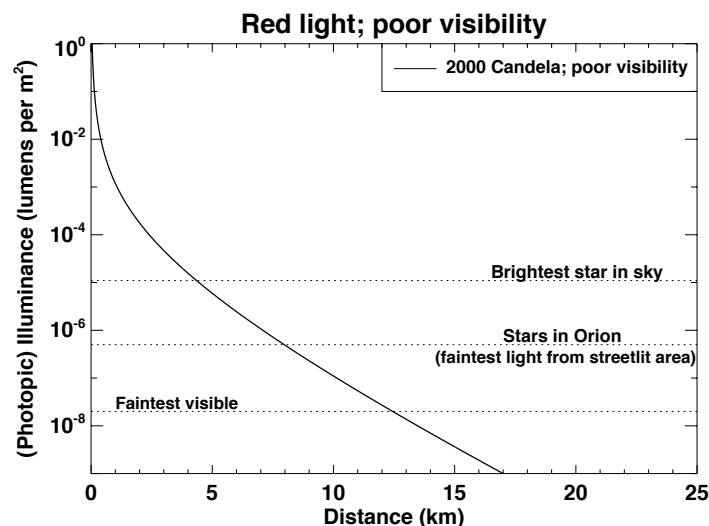


Figure C3: The illuminance of a 2000 candela light as a function of distance, as observed when the visibility conditions for the wind farm are at the threshold limit for requirement of such lights (visibility = 5%). This is compared against the illuminance provided by bright stars in the night sky.

- C6.7 Figure C3 shows that, beyond about 5km from the wind turbine, the illuminance of this light drops below that of the brightest stars in the night sky.
- C6.8 Zhang et al. (2020) give an overview of different techniques for measuring visibility. As locally-derived data are not available for the distribution of visibilities on the proposed Y Bryn Wind Farm site, an estimate can be made using the public data on visibility measurements available in other locations around Wales.
- C6.9 Data on visibilities published by the Met Office for Cardiff Airport (about 33km from the Y Bryn Wind Farm) is shown in the upper panel of Figure C4. This shows that visibility drops below 5km for about 10% of the time (average across the year). Similar data from other nearby airports provide similar poor visibility fractions. It should be noted that these airports tend to be located closer to large population centres, where man-made pollutants will be higher.

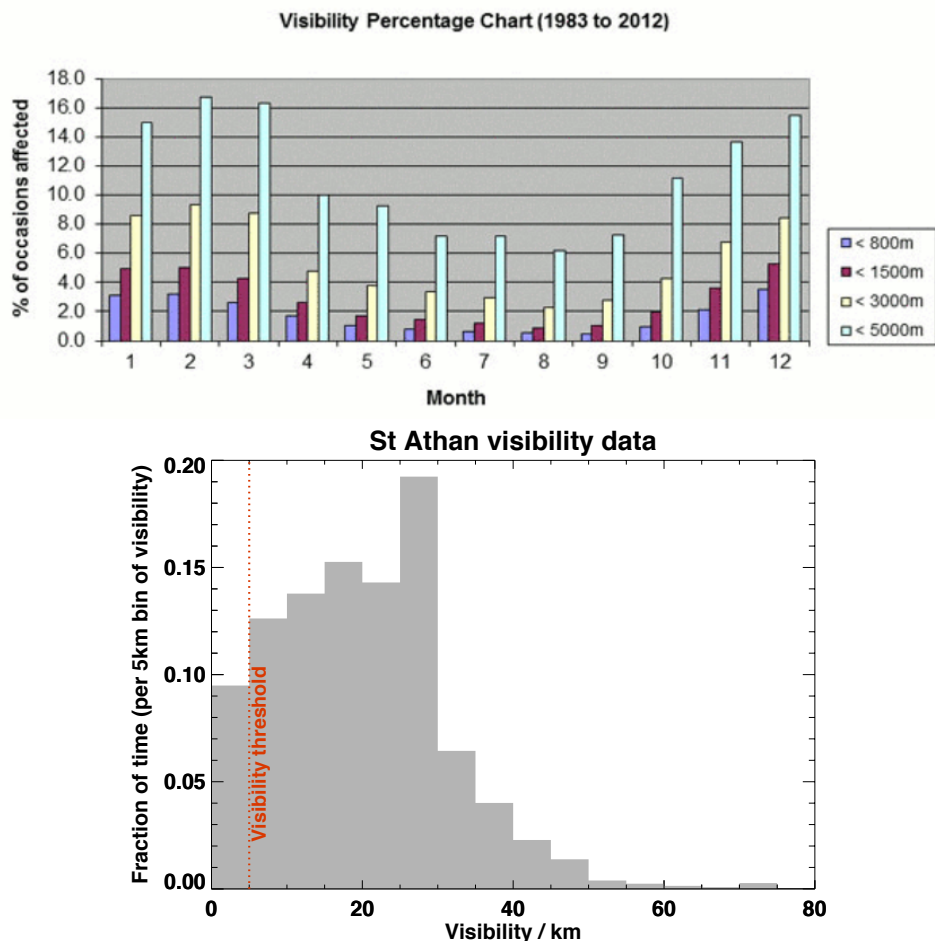


Figure C4: Top: the distribution of visibilities measured at the St Athan meteorological station over the past two decades (data from the MIDAS Open database). Bottom: the published visibility chart for Cardiff Airport (credit: Met Office).

- C6.10 A dataset is available from the Met Office station in St Athan, 28km from the Y Bryn Wind Farm, that stretches back more the 2 decades (available through the MIDAS Open database). The visibility distribution for St Athan is shown in the lower panel of Figure C4. Based on these data, the visibility at St Athan drops below 5km for 9.5% of the time.
- C6.11 St Athan and Cardiff Airport are both subject to broadly the same weather conditions and prevailing wind direction as Y Bryn. They are, however, both located close to sea level, and may be more affected by coastal fog than more inland sites. Furthermore, aerosol densities decrease with increasing altitude. On the other hand, higher altitude sites like the Y Bryn Wind Farm are more likely to be affected by cloud or hill mist. The balance between these two effects cannot be determined without on-site visibility data, but it is likely that the Y Bryn Wind Farm will be affected by poor visibility for about 10% of the time.

References

- Blackwell H.R., 1946, Journal of the Optical Society of America, Vol. 36, Issue 11, p624
- Blackwell O.M. & Blackwell H.R., 1971, Journal Illuminating Engineering Society, 1, 3.
- Buton C. et al., 2013, Astronomy & Astrophysics, 549, A8.
- CEL Technical Specifications for 2000 candela ANO light
- Cinzano P., Falchi F., Elvidge C.D., 2001, Monthly Notices of Royal Astronomical Society, 323, 34.
- Crawford B.H., 1949, Proceedings of the Physical Society, B62, 321.
- Crumey A., 2014, Monthly Notices of Royal Astronomical Society, 442, 2600.
- Estellés V., Smyth T., Campanelli M., 2012, Atmos. Environment, 61, 180.
- Falchi F. et al., 2016, Science Advances, 2, e1600377.
- Hayes D.S. & Latham D.W., 1975, Astrophysical Journal, 197, 593.
- Judd D.B., 1951, 'Report of U.S. Secretariat Committee on Colorimetry and Artificial Daylight.', Proceedings of the Twelfth Session of the CIE, Stockholm, Vol.1, p11.
- Knoll H.A, Tousey R., Hulburt E.O., 1946, Journal of the Optical Society of America, Vol. 36, Issue. 8, p480.
- Matthias et al 2004, Journal Geophysical Research, 109, D18201.
- Met Office airport climate statistics;
<https://www.metoffice.gov.uk/services/transport/aviation/regulated/airfield-climate-stats>
- Met Office - MIDAS Open: UK hourly weather observation data. Centre for Environmental Data Analysis,
<http://dx.doi.org/10.5285/c58c1af69b9745fda4cdf487a9547185>
- National Atmospheric Emissions Inventory; <https://naei.beis.gov.uk/emissionsapp/>
- Penndorf R., 1957, J. Opt. Soc. Amer.,47, 176–182.
- Smirnov et al 2002, Journal of Atmospheric Science, 59, 501.
- Vos J.J., 1978, Color Research & Application, 3, 125.
- Wald G., 1945, Science, 101, 653.
- Zhang S., 2020, Earth Science Review, 200, 102986