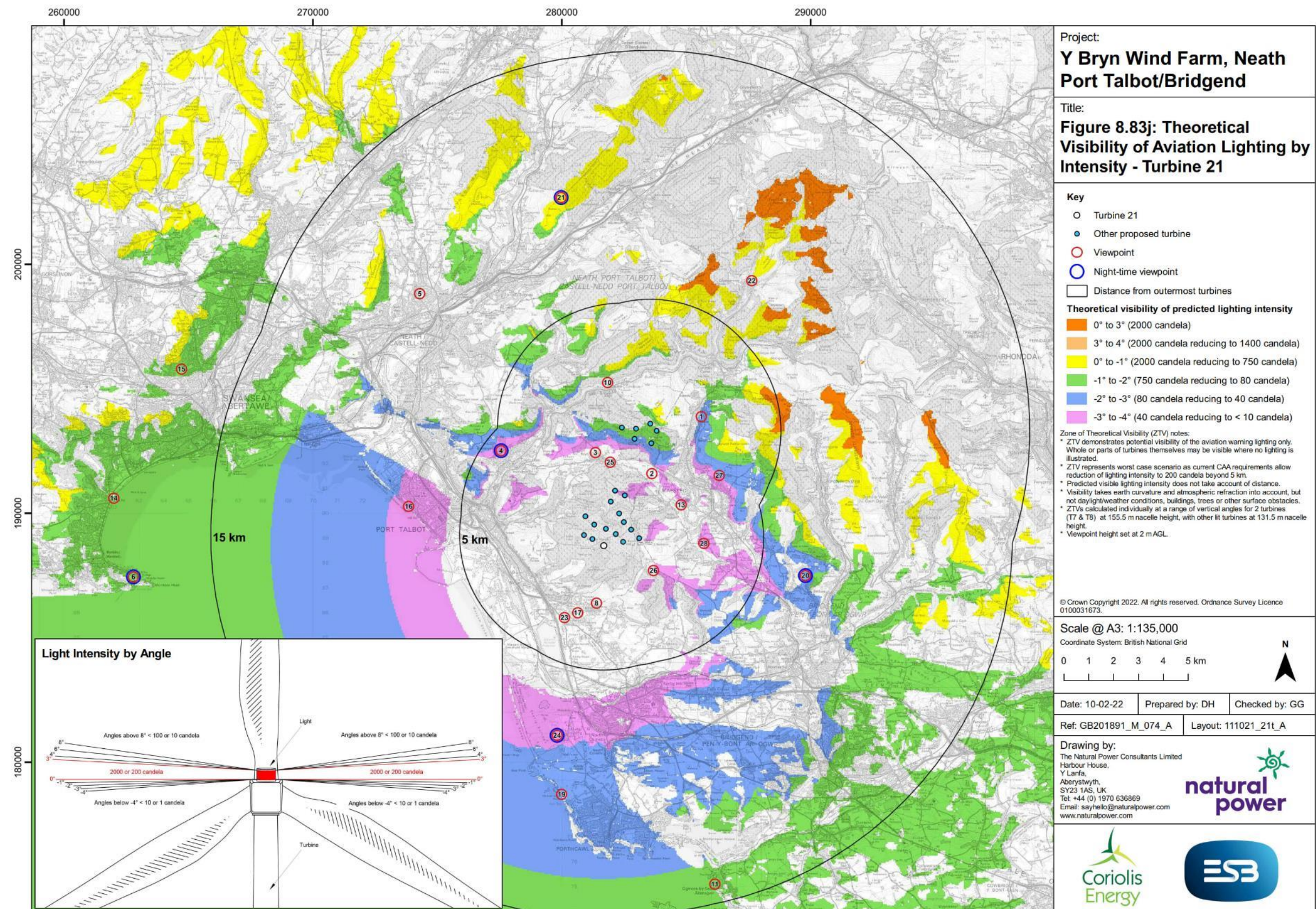




Notes: a) Information on this plan is directly reproduced from digital and other material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the plan itself. b) For the avoidance of doubt and unless otherwise stated: 1. this plan should be used for identification purposes only, unless otherwise stated in accompanying documentation. 2. The Natural Power Consultants Limited accepts no responsibility for the accuracy of data supplied by third parties. 3. The Natural Power Consultants Limited accepts no liability for any use which is made of this plan by a party other than its client. No third party who gains access to this plan shall have any claim against The Natural Power Consultants Limited in respect of its contents.

A3.3.33 WHITE CONSULTANTS (REPRESENTING NPTCBC) RESPONSE TO LVIA
CONSULTATION LETTER NOVEMBER 2021 (RECEIVED FROM NPTCBC 8TH
MARCH 2022)

Y BRYN WIND FARM

RESPONSE TO
REVISED SCHEME FOR COMMUNITY CONSULTATION
AND REVISED LANDSCAPE AND VISUAL IMPACT
ASSESSMENT METHOD

Draft Report
for
Neath Port Talbot County Borough Council
Bridgend County Borough Council

November 2021

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Email: sw@whiteconsultants.co.uk
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2. Revised proposals 2

3. Comments on Soltys Brewster response 3

1. Introduction

- 1.1. White Consultants were commissioned by Neath Port Talbot and Bridgend County Boroughs (NPTCBC and BCBC) in January 2021 to review and advise on a scoping response to proposals for Y Bryn wind farm primarily in relation to landscape and visual impact assessment (LVIA) matters.
- 1.2. The proposal is a Development of National Significance (DNS). The developers are Coriolis Energy and ESB. The LVIA related information was prepared by Soltys Brewster Consulting Ltd and the cultural heritage information was prepared by Headland Archaeology (UK) Ltd.
- 1.3. A report was prepared by White Consultants in February 2021 to provide background information and support for the boroughs’ scoping responses to PINS.
- 1.4. This report briefly considers revised proposals put forward for community consultation in October 2021. The bulk of the report responds to a revised method on landscape, seascape and visual impact (SLVIA), cumulative impacts and a residential visual amenity assessment (RVAA). This revised method was submitted by Soltys Brewster Consulting to BCBC on 13 October 2021.
- 1.5. This is the view of Simon White, FLI, not necessarily of NPTCBC and BCBC.

2. Revised proposals

- 2.1. The original scheme consisted of 26 turbines up to 250m to blade tip proposed in two clusters in forest plantation with associated access, battery storage and other infrastructure. No mapped information on the development other than wind turbines has been provided. The southern cluster of turbines is located on Mynydd Margam and Mynydd Bach and the northern cluster lies east of Mynydd Penhydd. The South Wales coalfield plateau scarp lies on the edge of the coastal plain just to the south, the Afan valley lies to the north and west, the Llynfi valley lies to the east and the site is split by Cwm Farteg.
- 2.2. Information obtained from the consultation website virtual exhibition and a plan presented on a PowerPoint slide to stakeholders have been used to review the revised proposals. The amendments include the following:
 - Reduction in number of turbines from 26 to 21, removing turbines T1 and T2 from the northern Penhydd block and T9, T22 and T23 from the southern Margam block.
 - Reduction in height of all remaining 6 turbines in the Penhydd block from 250m to 206m to blade tip ie a 17.6% reduction in height.
 - Reduction in height of the southern and western 6 turbines in the Margam block from 250m to 206m to blade tip ie a 17.6% reduction in height.
 - Reduction in height of 2 northern turbines in the Margam block from 250m to 230m to blade tip ie an 8% reduction in height.
 - Retention of 7 turbines in the Margam block at 250m high.
- 2.3. There are no comments on whether the blade length has changed so the sweep area with associated visual effects may remain the same. This may also mean that the proportion of the rotor to the lower tower heights may appear out of proportion and less elegant.

- 2.4. Future Wales: The National Plan 2040 has now been published and the Margam block still remains outside the National Development Framework Pre-assessed areas for wind energy. This therefore remains a concern.
- 2.5. As this is a community consultation there are no submitted formal assessment documents with mapping, zones of theoretical visibility or measurable visualisations. This means that we cannot arrive at meaningful conclusions on the likely landscape and visual effects as statutory consultees. The effects may have reduced slightly due to the reduced extent of the arrays and slight reduction in height but it is not clear if this would mean a change in the magnitude or significance of effects on landscape, heritage or visual receptors from the previous proposals. The height of most turbines are still substantially larger than any constructed in the UK, let alone South Wales.
- 2.6. As stated in our report in February (4.1), reducing the number and height of turbines from a very large proposed project of arguably unreasonable scale does not in itself mean that the resulting scheme properly minimises effects (as suggested by the community consultation website text). It will have to be looked at on its own merits and it is likely that it will still result in significant effects. Substantial reductions in height and extent would be expected.
- 2.7. One further issue apparent from the website layout provided is that the nearest two proposed Y Bryn turbines (at 205m high) are around 270-280m away from proposed Foel Trawsant turbines which are 145m to blade tip. This compares to 500m + spacing from other Y Bryn turbines. This could lead to an awkward juxtaposition of turbine scales and spacing.

3. Comments on Soltys Brewster response

- 3.1. The Soltys Brewster letter dated 13 October 2021 replies to the NPTCBC/BCC responses to the scoping report which are underpinned by the White Consultants response report prepared in February 2021. This is generally a helpful document. The comments below pick up outstanding issues as they appear in the text. However, if there are any omissions, it is incumbent on the LVIA assessor to ensure that all comments made in the original response are addressed in the final SLVIA.

Item/reference	Comment
Contents of letter	
Viewpoints	We note that five of the six proposed additional viewpoints are taken forward, which is appreciated. The one omitted, at Croeserw, Viewpoint G, is not taken forward on the basis that it is close to LVIA Viewpoint 1. The differences between the viewpoints are that G is at a higher level with more expansive views of the valley from the saddle, it represents another settlement and importantly it is intervisible with Llynfi Afan which is valid for assessing cumulative effects. It therefore serves a different function to Viewpoint 1, and as such, it would be helpful to have this considered in the final LVIA. Viewpoint 1 is valid as a representation of views from Caerau and lower valley levels (depending on how it is placed relative to the sports ground related fencing). It is noted that some of the OS coordinates of the

	additional viewpoints differ from those put forward in the scoping response. It would be helpful to have sight of all viewpoints photos in draft form before they can be finally agreed.
Item/reference	Comment
Appendix 1 SLVIA method	
1.2 Guidance	Since our comments in February a further guidance document has been issued by the Landscape Institute, which should be taken into account. This is: Assessing landscape value outside national designations, Technical Guidance Note 02/21, Landscape Institute, 2021.
1.3.2 Seascape/landscape susceptibility factors	In response to our comments seascape/landscape susceptibility factors have been included which is helpful. A few comments arise: - Is not clear what is meant by 'quality' which is an often misunderstood term – does this mean condition? - Various relevant factors such as character of skyline and character of landform appear to be omitted from the list- can the list be reviewed? - The last factor is not clear- can it be rephrased? - It would be helpful to understand what indicators the assessors think are more or less sensitive to wind turbine development. (For a definition/ demonstration of indicators see Natural England guidance on landscape sensitivity). This will then form a transparent yardstick to understand the judgements on susceptibility.
Table 1.1 Susceptibility of seascape/landscape receptors to change	The use of the terms 'frequency and quality of ... characteristics' is unclear- can this be rephrased? Does this relate to key characteristics or susceptible factors/indicators?
Figure 12.1 Significance of effects	We do not consider that effects which are not significant are immaterial. Effects should be considered in the round.
Table 1.6 Susceptibility of visual receptors to change	A variety of residential properties are stated as having high susceptibility where the main views are orientated towards the proposed windfarm. It is considered that all residential properties are high susceptibility but the magnitude of effect on them may change depending on their orientation. Are main views both the front and back of properties? It is not clear what 'cultural heritage based activities' are. Visitors to Margam would be considered high susceptibility, for instance.
1.3.14 Moderate significance	Where effects are determined to have moderate significance the method states that these effects may be

	significant or not significant depending on the professional opinion of the landscape assessor. We consider that, in line with good practice, if any given receptor is subject to a series of moderate effects, such as a long distance path, this could be significant. It would be helpful if this was also noted in the method.
Item/reference	Comment
1.5.1 Cumulative effects landscape baseline	We do not agree that the same landscape baseline is used for cumulative effects. As stated in 5.17 of our scoping response report, combined effects should be assessed against the baseline of no wind turbines on the basis of the temporary nature of the existing development, albeit long-term. If the landscape with existing/consented windfarms baseline is used then the effect of the same existing/consented windfarms on this landscape would mean that only the additional effects of Y Bryn would effectively be assessed which would therefore duplicate the LVIA. We would like this to be reconsidered.
Table 2.1 Magnitude of cumulative seascape/landscape impacts	Whilst we agree that the combined effects should be taken into account, the specific contribution of Y Bryn should also be described in terms of relationship with other windfarms including relative size of turbine.
Table 2.3 Magnitude of cumulative visual impacts	As above, whilst we agree that the combined effects should be taken into account, the specific contribution of Y Bryn should also be described in terms of relationship with other windfarms including relative extent in the view and size of turbine. Also, the effects should be assessed against the baseline of no wind turbines for the same reason as stated in the comment on 1.5.1 above. This properly measures the actual visual experience of the viewer/visual receptor.
1.6.6 Moderate cumulative visual impact	Where effects are determined to have moderate significance the method states that these effects may be significant or not depending on the professional opinion of the landscape assessor. We consider that, in line with good practice, if any given receptor is subject to a series of moderate effects, such as a long distance path, this could be significant. It would be helpful if this was also noted in the method.
Appendix 3 Residential Visual Amenity Assessment method	
Step 2	It is noted that the assessment omits consideration of the residential curtilage of a property, including domestic gardens and access drives, which are mentioned in 4.10 of the RVAA guidance. Whilst it is understood that there are a large number of properties that need to be assessed, the effects on the residential curtilage are highly relevant and will ultimately need to be considered at Step 4. Care will be needed at this stage not to exclude properties which may be affected in

A3.3.34 NRW RESPONSE TO AVIATION LIGHTING SCHEME AND RATIONALE FOR VPS
LETTER FROM NP MARCH 2022

Revised scheme and LVIA method review – landscape and visual		Y Bryn wind farm	
		this respect (e.g. residents arriving at or leaving their properties) and the method should take this into account.	
Item/reference		Comment	
Step 3		Comments as above for Step 2.	
Step 4		Comments as above for Step 2, the description of effects should include the effects on the users of the residential curtilage of a property/properties, including domestic gardens and access drives. The terms for description of effects and judgements on whether the level reaches the Residential Visual Amenity Threshold (which needs to be defined) should use terminology that is easily understood as indicated in RVAA guidance 4.18 and 4.19. This will necessarily go beyond the visual significance assessed in Step 3. A 90 degree wireline will minimise the apparent visual effects from a property and may not be helpful to the assessor or third parties. Can a larger format wireline be used?	
Criteria for assessment of effects		These criteria and subsequent tables relate only to the Stage 3 assessment and this should be made clear. Disagree that the sensitivity of residents not directly facing the development are medium sensitivity. RVAA guidance considers residents to be of the highest visual sensitivity (4.23). Magnitude of effect should take into account the level of perceived effects which can include consideration of orientation. The main or primary view of a property needs to be defined. This could usually be either the front or the rear of a property, or both.	
Cumulative assessment of RVAA effects		It is not usual for this to be included in RVAA. Is this to cover effects involving Foel Trawsant or all windfarms?	
White Consultants		6	
		Draft/November 2021	



Ein cyf/Our ref: CAS-182192-B6M6
Eich cyf/Your ref: 127606

Maes Newydd,
Llandarcy,
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SA10 6JQ

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The Natural Power Consultants Limited
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ebost/email:
swplanning@cyfoethnaturiolcymru.gov.uk
Ffôn/Phone: 03000 65 3358

11th March 2022

Annwyl / Dear Mr. Glencorse,

BWRIAD / PROPOSAL: Y BRYN WINDFARM, WIND FARM OF UP TO 26 TURBINES (6.6 MW PER TURBINE) AND BATTERY STORAGE

LLEOLIAD / LOCATION: LAND AT BRYN AND PENHYDD FOREST, LOCATED BETWEEN PORT TALBOT AND MAESTEG

Night-time Aviation Lighting Assessment Response

Thank you for your letter dated 17th February 2022 along with the Zone of Theoretical Visibility (ZTV) figures, to Cyfoeth Naturiol Cymru / Natural Resources Wales regarding the above proposal. The letter sets out the proposed night-time aviation lighting scheme and chosen viewpoints, which will support the night-time aviation lighting assessment as an appendix to the Seascape, Landscape and Visual Impact Assessment. We have reviewed the content of the letter and the ZTVs provided and provide our response below.

Lighting Scheme

We welcome the proposals for a reduced lighting scheme as specified in the bullet points within the letter.

We suggest that the following measures are considered:

- Further reducing the number of visible lights, in agreement with the Civil Aviation Authority (CAA), if possible.
- A commitment to the dimming of 2000 candela (cd) to 200cd when visibility exceeds 5km.
- Limiting the highest intensity of visible lights to the horizontal plane or restricting it in other planes – the figures provided indicate that this has been done, however it is unclear if this is a commitment.

Croesewir gohebiaeth yn y Gymraeg a'r Saesneg
Correspondence welcomed in Welsh and English

- Using 'smart' transponder-based demand-controlled aviation lights that only switch on when aircraft are detected within a particular airspace around the windfarm (Aircraft Detection Lighting System – ADLS).

Viewpoints

With regard to the proposed viewpoints for night-time photography and photomontages, Viewpoint 6 Mumbles Hill is appropriate for a viewpoint from the Gower Area of Outstanding Natural Beauty (AONB). We note that there appears to be greater visibility from parts of Clyne Common, however Viewpoint 6 would be easier to access and likely to include a greater number of viewers when lights would be visible.

For completeness, we advise a night-time viewpoint from the Brecon Beacons National Park, which is an International Dark Sky Reserve (e.g. Viewpoint 9 Ogof Ffynnon-Ddu).

If you have any queries on the above, please do not hesitate to contact us.

Yn gywir / Yours sincerely

Hannah Roberts
Cyngorydd - Cynllunio Datblygu / Advisor - Development Planning
Cyfoeth Naturiol Cymru / Natural Resources Wales

A3.3.35 NP RESPONSE TO NRW REGARDING REDUCED LIGHTING SCHEME AND RATIONALE FOR VPS (INCLUDES CAA LETTER APPROVING REDUCED LIGHTING SCHEME) MARCH 2022

24 March 2022

IFS Doc. No. 1276479



Hannah Roberts

Advisor - Development Planning
Natural Resources Wales
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Reg No: SC177881

Y Bryn Wind Farm: Night Time Aviation Lighting Assessment

Dear Hannah

Thank you for your letter of 11th March 2022 concerning the night time aviation lighting assessment for Y Bryn wind farm. Our aviation specialist, Malcolm Spaven of Aviatica, has advised with the response below.

Since our letter to you of 17th February, we have received approval from the CAA for the proposed reduced lighting scheme. A copy of their letter of 17th February 2022 is attached. They have approved the lighting scheme as submitted but with the addition of a visible light on Turbine 11.

Addressing the points in your letter, in turn:

Further reducing the number of visible lights, in agreement with the Civil Aviation Authority (CAA), if possible.

The approved lighting scheme has reduced the number of turbines with 2000 candela lights from 21 to 11, a reduction of 48%. In addition, all mid-tower lights (what would have comprised 3 additional lights per turbine) have been eliminated from the wind farm, thus completely removing a source of lighting that would have been of particular relevance to receptors at close range and at lower angles of elevation from the turbines. The total reduction in number of lights therefore as against CAA standard policy is of the order of 87% (11 lights versus 84).

The applicant intends to propose a planning condition which will commit to carrying out a review of the lighting scheme prior to construction, with the aim of minimising the number of lights, their intensity and the frequency and duration of their illumination.

A commitment to the dimming of 2000 candela (cd) to 200cd when visibility exceeds 5km.

This is a standard element of the CAA's policy since 2017 on the lighting of onshore wind turbines of height 150 metres or more above ground level and is a confirmed component of the approved lighting scheme for Y Bryn.

24 March 2022

IFS Doc. No. 1276479



Limiting the highest intensity of visible lights to the horizontal plane or restricting it in other planes – the figures provided indicate that this has been done, however it is unclear if this is a commitment.

The specification of the lighting, including its intensity at different elevation angles, is required to meet aviation safety standards set out in ICAO Annex 14. These standards do not specify any minimum intensity requirement at horizontal elevation angles below -1° but do require lighting to meet minimum intensity specifications at angles higher than that. The night time aviation lighting assessment uses one manufacturer's data as a basis for the visibility of the lights at different viewpoints.

As part of the commitment to reviewing the lighting scheme prior to construction, the applicant will review the performance of different manufacturers' lighting products and select the light that best achieves the aims of the review.

Using 'smart' transponder-based demand-controlled aviation lights that only switch on when aircraft are detected within a particular airspace around the windfarm (Aircraft Detection Lighting System – ADLS).

The CAA has acknowledged the applicant's intention to install an ADLS on Y Bryn wind farm. The CAA has yet to publish its policy for the specification and approval process for such systems. The CAA's Airspace Modernisation Strategy commits to introducing the technical and regulatory change that would underpin the introduction of ADLS by 2024. This is within the timeframe of the consent process for Y Bryn. The applicant will address the detail of the specification and approval process for an ADLS when the CAA published its policy on these systems.

For completeness, we advise a night-time viewpoint from the Brecon Beacons National Park, which is an International Dark Sky Reserve (e.g. Viewpoint 9 Ogof Ffynnon-Ddu).

The applicant has procured a 'Lighting Propagation Physics' report authored by Philip Best, Professor of Extragalactic Astrophysics, from the School of Physics and Astronomy at the University of Edinburgh, such as has been produced and accepted on a number of similar wind farm projects now, and will form an appendix to the LVIA. VP 9 is 23.01km from the nearest lit turbine – Turbine 5. Professor Best's report calculates that the illuminance of a 200 candela light (the intensity of the light in clear weather) at that distance would be 0.15 x 10⁻⁶ lumens per m². That level is somewhere between the "visible limit for full dark-adapted eyes" of 0.02 x 10⁻⁶, and the "faintest light visible from street-lit area" of 0.4 x 10⁻⁶ lumens/m². Therefore, the lights will be, in the worst case, only barely detectable from VP9. Additionally there are likely to be brighter lights visible at closer ranges to VP9 such as road traffic along the A4109 and A465 roads and street/industrial site lighting in the Dyffryn Cellwen/Onllwyn area. We therefore suggest that an additional night time viewpoint at VP9 would serve little or no purpose.

Please let me know if you have any further comments on the above.

Yours Sincerely

Rafe Osborne
Project Manager
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A3.3.36 CIVIL AVIATION AUTHORITY (CAA) CONSULTATION ON REDUCED LIGHTING
SCHEME – FEBRUARY 2022

Safety and Airspace Regulation Group
Safety and Business Delivery



Malcolm Spaven
Director, Aviatika Ltd.
Reservoir House
Gladhouse
Midlothian
EH23 4TA

17 February 2022
Ref Windfarms/Y Bryn

Dear Malcolm,

Proposed Obstacle Lighting Scheme for Y Bryn Wind Farm, South Wales

Reference: Aviatika Report No. 21/972/NPC/1, e-mailed 17 December 2021

1. Thank you for the e-mail at reference. The attached report discusses the proposed obstacle lighting plan for the Y Bryn wind farm.
2. The proposed Y Bryn wind farm consists of 21 turbines, with tip heights up to between 206 and 250m. This brings the wind farm within scope of the Air Navigation Order (ANO) Article 222.
3. We have considered the report carefully and take note of the intent to address concerns relating to the night-time visual impact of such aviation lighting while ensuring that the lighting installed on the turbines meets air safety requirements.
4. You have conducted an aviation study that considers the type of aviation operations who might be expected to fly in this area and set out the rationale for a reduced lighting scheme.
5. We note the local terrain aspects and additional mitigation provided by the provision of infra-red lighting for those operators who carry Night Vision Device capability.
6. Noting potential operations at night, below minimum heights required by the rules of the air under permissions issued by the CAA, we consider that an additional visible light on the eastern edge of the southern cluster would be beneficial to safety by better delineating the perimeter. As a result, we have inserted a requirement for a combined visible/IR light on turbine 11. We agree to the request not to install mid-tower lighting as there are sufficient lights on a group of structures to provide a suitable horizontal reference.

Design 5: Design Chill – April 2022

7. As a result, the CAA agrees a variation to the lighting requirements specified in the ANO Article for the Y Bryn wind farm, under provisions given in the Air Navigation Order (ANO) Article 222 section 6, as per the following:

- medium intensity steady red (2000 candela) lights on the nacelles of turbines T01, T04, T05, T06, T07, T08, T11, T13, T14, T19, and T21;
- a second 2000 candela light on the nacelles of the above turbines to act as alternates in the event of a failure of the main light;
- the lights on these turbines to be capable of being dimmed to 10% of peak intensity when the lowest visibility as measured at suitable points around the wind farm by visibility measuring devices exceeds 5km;
- infra-red lights to MoD specification installed on the nacelles of turbines T01, T02, T03, T04, T05, T06, T07, T08, T09, T10, T11, T12, T13, T14, T17, T18, T19, T20, T21.

8. Intermediate level 32 candela lights are not required to be fitted on the turbine towers.

9. The proposed intent to install an aircraft detection lighting system (ADLS) to the Y Bryn wind farm in the future is noted.

10. Please let me know if you have any further queries.

Yours sincerely,

Andy Wells

Andy Wells
Manager Rulemaking and Safety Publications

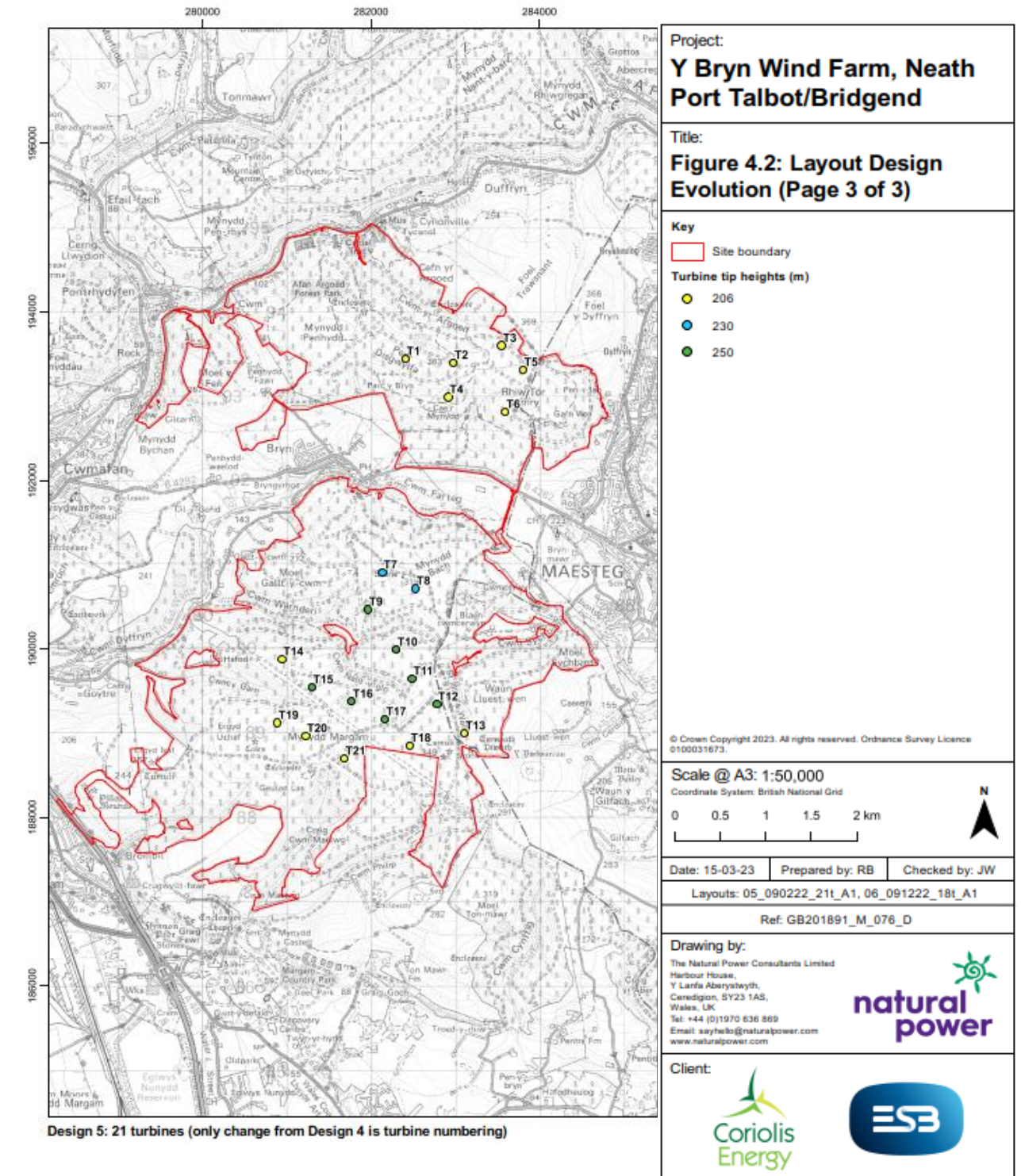


Figure A3.3.4: Design Chill layout for Y Bryn Wind Farm

Continued (2 of 2 pages)

A3.3.37 AIRBOURNE SOLUTIONS – MAY 2022

Rafe Osborne

To: Malcolm Spaven
Subject: RE: RE: Aerial firefighting South Wales

[illegible]

>
>I have attached a map excerpt showing the wind farm and the reservoir. My
>understanding is that any use of that reservoir would involve approaching
>from the west up the Cwm Wernderi valley, and departing by the same route,
>due to the narrowness and steep sides of the valley - is that correct?
>Presumably if that is the case, there would be no hazard from the turbines,
>all of which are located on terrain at least 300ft above the valley floor?
>
>I would welcome a chat with your Chief Pilot to talk through the issues. I
>can be contacted on [REDACTED]
>
>Many thanks
>
>Malcolm Spaven

Aviatica
Reservoir House
Gladhouse
Midlothian EH23 4TA
Tel: [REDACTED]

A3.3.38 NRW RESPONSE TO NP LETTER REGARDING REDUCED LIGHTING SCHEME AND RATIONALE FOR VPS APRIL 2022



Ein cyf/Our ref: CAS-185184-Z1V5
Eich cyf/Your ref: 127606

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1st April 2022

Annwyl / Dear Mr. Osborne,

BWRIAD / PROPOSAL: Y BRYN WINDFARM, WIND FARM OF UP TO 26 TURBINES (6.6 MW PER TURBINE) AND BATTERY STORAGE

LLEOLIAD / LOCATION: LAND AT BRYN AND PENHYDD FOREST, LOCATED BETWEEN PORT TALBOT AND MAESTEG

Night-time Aviation Lighting Assessment – Follow Up Response

Thank you for your response dated 24th March 2022 to our comments made in our letter of 11th March 2022 (our reference: CAS-182192-B6M6) on the Night-time Aviation Lighting Assessment.

We advise that if the proposed scheme acquires the necessary planning consent, we would support the Applicant's intention to propose a planning condition which will commit to carrying out a review of the lighting scheme prior to construction, with the aim of minimising the number of lights, intensity and frequency and duration of their illuminance, as detailed within your letter.

We note that the Applicant will address the detail of the specification and approval process for an Aircraft Detection Lighting System (ADLS) when the Civil Aviation Authority (CAA) publishes its policy on these systems.

Finally, we note the comments regarding Viewpoint 9 in the Brecon Beacons National Park and await the 'Lighting Propagation Physics' report Appendix to the LVIA.

If you have any queries on the above, please do not hesitate to contact us.

Yn gywir / Yours sincerely

Hannah Roberts
Cynghorydd - Cynllunio Datblygu / Advisor - Development Planning
Cyfoeth Naturiol Cymru / Natural Resources Wales

Croesewir gohebiaeth yn y Gymraeg a'r Saesneg
Correspondence welcomed in Welsh and English

A3.3.39 NP RESPONSE TO NRW LETTER REGARDING LIGHT PROPAGATION REPORT - APRIL 2022

6th April 2022
IFS Doc No.1278070



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Y Bryn Wind Farm: Night Time Aviation Lighting Assessment

Dear Hannah

As requested in your response dated 1st April 2022, and to give further context to our position on whether to include Viewpoint 9 - Brecon Beacon National Park in the Aviation Lighting Assessment, please find attached the current draft copy of the "Report on Light Propagation for the Aviation Warning Lights on the Y Bryn Wind Farm". The overall report is fairly technical, but reading sections 1 to 5, and looking at Tables 1 and 2 together, should give you a clear picture. If you'd like any further explanation, we can try and arrange a call with the author of the report, Professor Philip Best of the Institute for Astronomy, University of Edinburgh. The proposed Y Bryn Wind Farm is probably the first scheme in Wales considering turbines taller than 150m, but there are several others in this category in scoping/ pre-application stage, so if you think NRW would benefit from this discussion we would be happy to set this up. You may also find it worth speaking with NatureScot, who have experience in this area from numerous 150m+ projects in Scotland.

Please note that the draft report is based on an aviation lighting scheme with 10 lights lit, whereas the CAA have approved a scheme with 11 lights. The final submitted report will be updated to reflect this change. Since the additional light is located in the southern cluster of turbines, and is therefore located further away from Viewpoint 9, it will not affect the results detailed in Table 2.

If you have any queries on the above, or wish to schedule a conversation with Professor Best, please let me know.

Yours sincerely

Rafe Osborne
Project Manager
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Encl. Report on Light Propagation for the Aviation Warning Lights on the Y Bryn Wind Farm

Y Bryn Wind Farm: Night Time Aviation Lighting Assessment

Page 1 of 1





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

Professor Philip Best, FRSE
Institute for Astronomy
University of Edinburgh

29/01/2022

Report prepared on behalf of Edinburgh Innovations Ltd, a wholly-owned subsidiary
company of the University of Edinburgh

1. Introduction

- 1.1 The Y Bryn Wind Farm is a proposed development of 21 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. 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 Civil Aviation Authority (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 10 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. He is Head of the University's Institute for Astronomy, and 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 21 turbines in the Y Bryn Wind Farm: hub heights of these turbines vary from around 410m to around 475m).
- 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 CAA CAP-764 guidance 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.

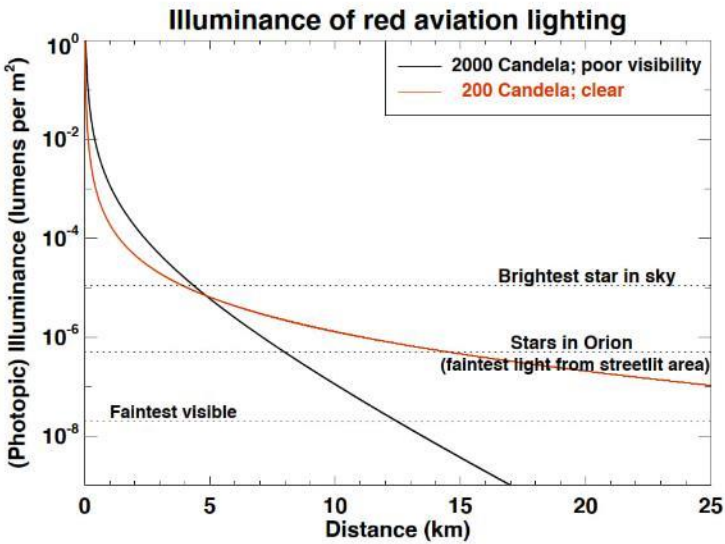


Figure 1: The illuminance of a single red light (633nm) as a function of distance, viewed horizontally at an altitude of 450m. The results are shown for a light with a luminous intensity of 200 candela for typical 'clear' atmospheric conditions. Also shown are the results for 2000 candela lights, at 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 x 10 ⁻⁶
Brightest star in the sky	13 x 10 ⁻⁶
Car brake lights at 10km distance	1 x 10 ⁻⁶
Typical bright stars (e.g. in Orion)	0.5 x 10 ⁻⁶
Faintest light visible from street-lit area	0.4 x 10 ⁻⁶
Visible limit for fully dark-adapted eyes	0.02 x 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.

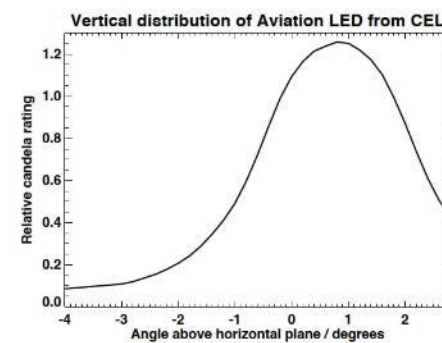


Figure 2: The attenuation of the illuminance of aviation lighting away from the horizontal plane. The figure shows technical data for an aviation LED from CEL, currently on the market. At an angle of 3 degrees below the horizontal plane, the brightness of the lights is suppressed by a factor of 10.

- 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 31 designated viewpoints, also taking into account the topology of the land between the turbine and the viewpoint. 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	5	1.88	8.6	0.09	4.4×10^{-6}	18.2×10^{-6}
2	6	1.22	10.5	0.09	10.8×10^{-6}	60.9×10^{-6}
3	1	1.46	12.4	0.09	7.5×10^{-6}	37.7×10^{-6}
4	14	4.29	4.3	0.09	0.75×10^{-6}	1.00×10^{-6}
5	7	11.15	2.0	0.20	0.19×10^{-6}	$<0.01 \times 10^{-6}$
6	14	18.32	1.1	0.45	0.12×10^{-6}	$<0.01 \times 10^{-6}$
7	14	31.53	0.5	0.83	0.04×10^{-6}	$<0.01 \times 10^{-6}$
8	21	2.33	6.8	0.09	2.8×10^{-6}	9.5×10^{-6}
9	5	23.01	-0.1	1.15	0.14×10^{-6}	$<0.01 \times 10^{-6}$
10	1	1.90	9.8	0.09	4.4×10^{-6}	17.8×10^{-6}
11	13	14.23	1.8	0.24	0.12×10^{-6}	$<0.01 \times 10^{-6}$
12	8	41.70	0.1	1.06	0.02×10^{-6}	$<0.01 \times 10^{-6}$
13	13	2.15	7.4	0.09	3.3×10^{-6}	12.1×10^{-6}
14	14	18.96	1.2	0.41	0.09×10^{-6}	$<0.01 \times 10^{-6}$
15	14	17.27	-0.9	0.52	0.15×10^{-6}	$<0.01 \times 10^{-6}$
16	14	7.12	3.2	0.10	0.29×10^{-6}	0.10×10^{-6}
17	21	2.89	7.7	0.09	1.8×10^{-6}	4.6×10^{-6}
18	5	33.20	-0.6	1.24	0.05×10^{-6}	$<0.01 \times 10^{-6}$
19	19	10.45	2.3	0.17	0.19×10^{-6}	0.01×10^{-6}
20	13	6.84	2.7	0.13	0.40×10^{-6}	0.16×10^{-6}
21	4	10.13	0.7	0.65	0.78×10^{-6}	0.07×10^{-6}
22	4	7.91	1.5	0.31	0.68×10^{-6}	0.16×10^{-6}
23	21	3.29	7.4	0.09	1.4×10^{-6}	2.9×10^{-6}
24	21	7.85	3.2	0.10	0.23×10^{-6}	0.06×10^{-6}
25	7	1.16	14.9	0.09	12.1×10^{-6}	70.0×10^{-6}
26	13	1.42	7.2	0.09	8.0×10^{-6}	40.9×10^{-6}
27	6	3.02	5.4	0.09	1.6×10^{-6}	3.9×10^{-6}
28	13	2.61	5.9	0.09	2.2×10^{-6}	6.5×10^{-6}
29	14	30.18	0.7	0.64	0.03×10^{-6}	$<0.01 \times 10^{-6}$
30	21	21.63	1.1	0.45	0.07×10^{-6}	$<0.01 \times 10^{-6}$
31	1	27.25	-0.3	1.20	0.09×10^{-6}	$<0.01 \times 10^{-6}$

Table 2: Calculated illuminances of the brightest turbine aviation light visible from the 31 viewpoints. 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).

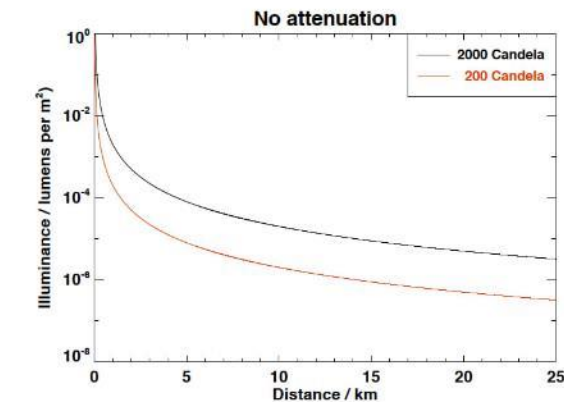


Figure A1: The illuminance of 2000 candela and 200 candela luminous intensity lights as a function of distance, in the absence of any atmospheric attenuation (i.e. considering geometric effects only).

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(λ) 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'(λ) 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.

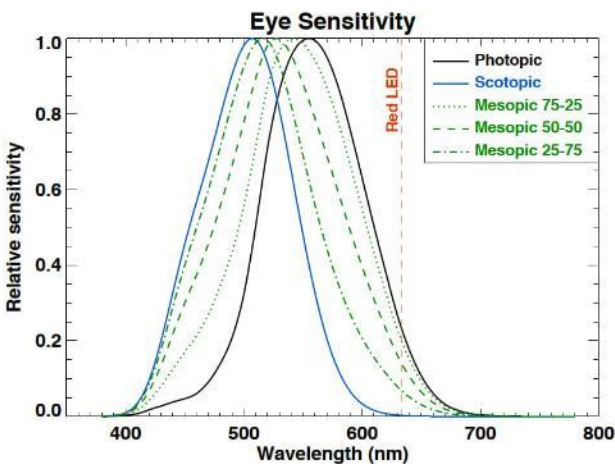


Figure B1: The relative sensitivity of the eye as a function of wavelength, in the photopic regime (black line; vision mediated by cones, at high light levels) and the scotopic regime (blue line; vision mediated by rods, at low light levels). The data are the accepted CIE 1978 and CIE 1951 standard values (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.

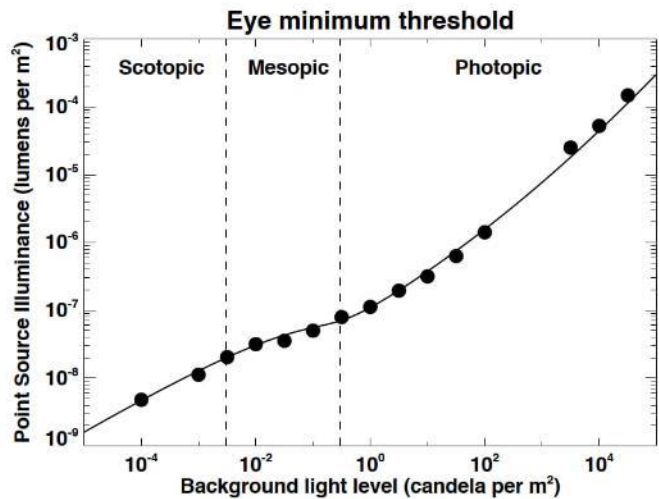


Figure B2: The minimum point source illuminance, which is detectable by the eye, as a function of the background ambient light level. Plotted data points are from Knoll et al. (1946), and the fitting function comes from Crumey (2014).

- 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):

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

where the numerical value corresponds to a wavelength λ of 500nm ($5 \times 10^{-7}\text{m}$) 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 $h_0 \approx 8\text{km}$.
- 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

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

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 ($\tau_{\text{ozone}} \approx 0.016$ 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,

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

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

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

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

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

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 $h_{\text{aerosol}} = 1.5\text{km}$ 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 $\alpha=0.3-0.7$, 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.

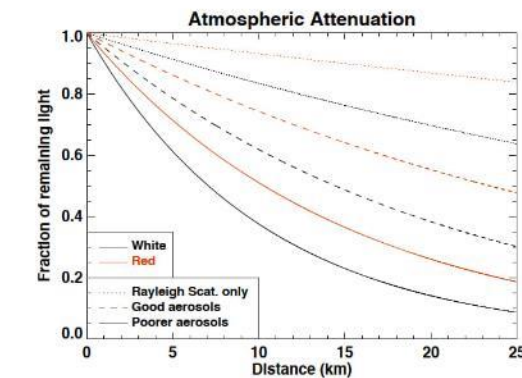


Figure C1: The attenuation of light as it passes horizontally through the atmosphere at an altitude of 450m. Results are shown for both white light (500nm) and red light (633nm). The dotted lines show the contribution from Rayleigh scattering by air molecules, in the absence of aerosols. The dashed and 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.

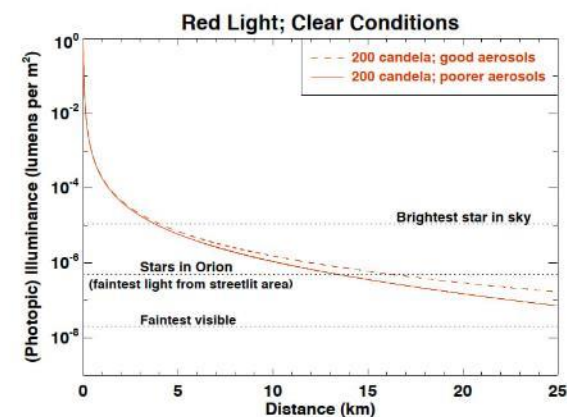


Figure C2: The illuminance of a single 200 candela red light (633nm) as a function of distance, viewed horizontally at an altitude of 450m. The results are shown considering the upper (solid line) and lower (dashed line) end of the realistic range of aerosol optical depth for typical clear conditions. 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 Civil Aviation Authority CAP764 guidance, 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 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 the atmospheric attenuation effects will be increased.

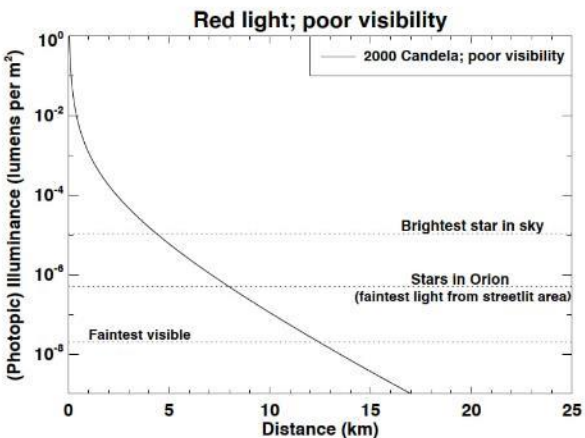


Figure C3: The illuminance of a 2000 candela light as a function of distance, as observed when the visibility conditions for the wind farm are at the threshold limit for requirement of such lights (visibility = 5%). This is compared against the illuminance provided by bright stars in the night sky.

- 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.

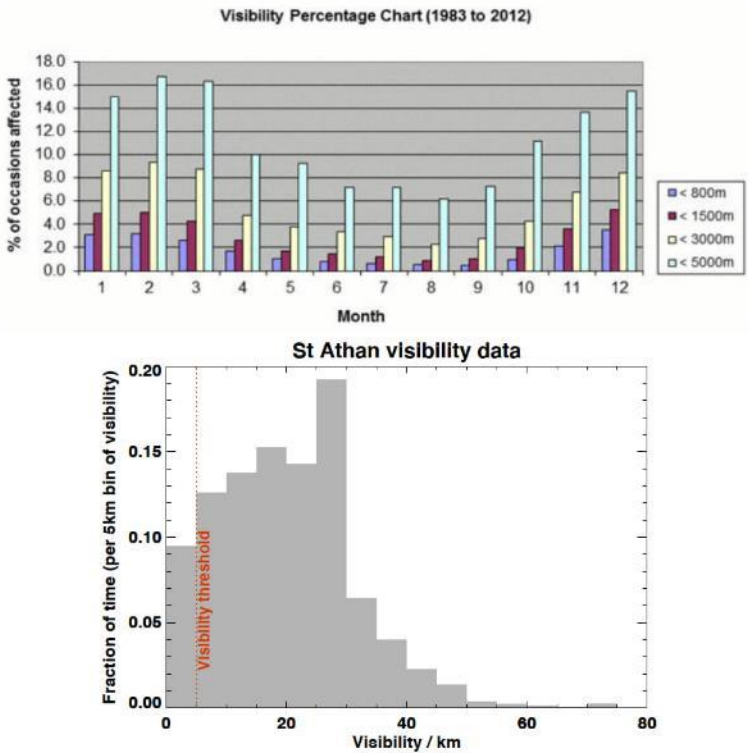


Figure C4: Top: the distribution of visibilities measured at the St Athan meteorological station over the past two decades (data from the MIDAS Open database). Bottom: the published visibility chart for Cardiff Airport (credit: Met Office).

- 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.

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A3.3.40 NRW RESPONSE TO NP EMAIL CONTAINING PROFESSOR BEST REPORT – APRIL 2022

Rafe Osborne

Subject: RE: Y Bryn Wind Farm - Aviation Lighting scheme, VPs and ZTVs NRW:01273097

From: SW Planning <>
Sent: 25 April 2022 10:51
To: Rafe Osborne <>
Subject: Y Bryn Wind Farm - Aviation Lighting scheme, VPs and ZTVs NRW:01273097

Dear Rafe,

My colleague Hannah Roberts who you have been dealing with regarding this case has left the Planning Team for a six month assignment to another job. I will be leading on this case in Hannah's absence.

Thank you for providing us with a copy of the Report on Light Propagation from the Aviation Warning Lights on the Y Bryn Wind Farm. I sent it to our Landscape Team for comments they have advised that the technical document would be assisted by illustrative examples of similar lighting effects from existing wind farms, if this were possible.

I hope this information is helpful.

Please don't hesitate to contact me if you have any further queries.

Kind regards,

Lisa

Lisa Jones
Ymgynghorydd Cynllunio Datblygu/ Development Planning Advisor
Cyfoeth Naturiol Cymru / Natural Resources Wales

In light of recent events, I am currently working from home and as such not contactable on the phone. If you need to get in touch, please email me and I will respond as quickly as possible.

Yn falch o arwain y ffordd at ddyfodol gwell i Gymru trwy reoli'r amgylchedd ac adnoddau naturiol yn gynaliadwy.
Proud to be leading the way to a better future for Wales by managing the environment and natural resources sustainably.
cyfoethnaturiol.cymru / naturalresources.wales
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Croesewir gohebiaeth yn Gymraeg a byddwn yn ymateb yn Gymraeg, heb i hynny arwain at oedi.
Correspondence in Welsh is welcomed, and we will respond in Welsh without it leading to a delay.