Department for Business, Energy & Industrial Strategy

A REVIEW OF NOISE GUIDANCE FOR ONSHORE WIND TURBINES

Project Report

70081416-001-03-03
OCTOBER 2022

PUBLIC

Department for Business, Energy & Industrial Strategy

A REVIEW OF NOISE GUIDANCE FOR ONSHORE WIND TURBINES

Project Report

REVISION 03: PUBLIC

PROJECT NO. 70081416

OUR REF. NO. 70081416-001-03-03

DATE: OCTOBER 2022

WSP

Kings Orchard
1 Queen Street
Bristol
BS2 0HQ

WSP.com

QUALITY CONTROL

Issue/revision	First issue	Revision 1	Revision 2	Revision 3
Remarks	Issue 01 (Revision 0)	Revision 01 (Issue 02)	Revision 02 (Issue 03)	Revision 03 (Issue 04)
Date	04/04/2022	05/05/2022	27/06/2022	27/10/2022
Prepared by	Michael Lotinga	Michael Lotinga	Michael Lotinga	Michael Lotinga
Signature				Lotinga, Michael (Michael.Lotinga) I am the author of this document 2022.10.27 12:44:05 +01'00'
Checked by	Toby Lewis	Toby Lewis	Toby Lewis	Toby Lewis
Signature				Lewis, Toby (UKTWL001) Digitally signed by Lewis, Toby (UKTWL001) DN: cn=Lewis, Toby (UKTWL001), ou=Active, email=Toby.Lewis@wsp.com Reason: I have reviewed this document Date: 2022.10.27 13:18:41 +01'00'
Authorised by	Louise Beamish	Jim Powlson	Jim Powlson	Jim Powlson
Signature				Powlson, James (UKJGP003) Digitally signed by Powlson, James (UKJGP003) DN: cn=Powlson, James (UKJGP003), ou=Active, email=James.Powlson@wsp.com Reason: I am approving this document Date: 2022.10.28 11:34:46 +01'00'
Project number	70081416	70081416	70081416	70081416
Document number	70081416-001-03	70081416-001-03-01	70081416-001-03-02	70081416-001-03-03

External peer-review of sections 3, 6.1, 6.2 and 7 has also been completed by Bernard Berry (an independent specialist consultant, as commissioned by WSP).

LIMITATIONS TO THIS REPORT

This report has been produced by WSP UK Limited as commissioned by the Department for Business, Energy and Industrial Strategy. Any views expressed within it do not necessarily represent the views of the UK government or the governments of any of the devolved administrations.

This report has been prepared for the titled project or named part thereof, and should not be used in whole or part and relied upon for any other project without the written authorisation of WSP UK Limited. WSP UK Limited accepts no responsibility or liability for the consequences of this document if it is used for a purpose other than that for which it was commissioned. Persons wishing to use or rely upon this report for other purposes must seek written authority to do so from the owner of this report or WSP UK Limited and agree to indemnify WSP UK Limited for any and all loss or damage resulting therefrom. WSP UK Limited accepts no responsibility or liability for this document to any other party other than the person by whom it was commissioned.

The findings and opinions expressed are relevant to the dates of the reported study and should not be relied upon to represent the situation at later dates. Opinions included therein are based on information gathered during the study and from our experience. If additional information becomes available which may affect our comments, conclusions, or recommendations, WSP UK Limited reserves the right to review the information, reassess any new potential concerns and modify our opinions accordingly.

Limitations associated with the research methodology and evidence base should also be considered alongside the study findings. These are acknowledged and discussed in the report summaries, and in section 7.3.

ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance of Andrea Bauerdorff, Dick Bowdler, Professor Guillaume Dutilleux, Dr Kristy Hansen, Dr Anders Johansson, Dr Yasuaki Okada and Dr Fei Qu in responding to research queries.

We also acknowledge the contributions of the government steering group overseeing the project, and the valuable feedback received during the project delivery and the preparation of this report.

CONTENTS

APPENDICES

ABBREVIATIONS

%A	% annoyed
%HA	% highly annoyed
%VA	% very annoyed
AI	Artificial intelligence
AM	‘amplitude modulation’ or ‘amplitude-modulated’ (context-dependent)
ANC	Association of Noise Consultants

BEIS	Department for Business, Energy & Industrial Strategy
BSi	British Standards Institution
CFD	Computational fluid dynamics
CTL	Community Tolerance Level
DECC	Department of Energy & Climate Change
Defra	Department for Environment, Food & Rural Affairs
DLUHC	Department for Levelling Up, Housing and Communities
DNS	Developments of National Significance
DOI	Digital object identifier
EHO	Environmental Health Officer
EIA	Environmental Impact Assessment
ENGER	(WHO Regional Office for Europe, 2018) Environmental Noise Guidelines for the European Region
GCN	(WHO, 1999) Guidelines for Community Noise
GIS	Geographic Information System
GPG	Good Practice Guide
GRADE	Grading of Recommendations, Assessment, Development and Evaluations
HRQoL	Health-related quality of life
IGCB(N)	Interdepartmental Group on Costs and Benefits (Noise subject group)
IOA	Institute of Acoustics
IOA NWG (WTN) AMWG	Institute of Acoustics Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group
LPA	Local planning authority
MHCLG	Ministry of Housing, Communities & Local Government
NERC	Natural Environment Research Council
NHMRC	National Health and Medical Research Council
NPL	National Physical Laboratory
NPS	National Policy Statement
NPSE	Noise Policy Statement for England
NPSNI	Noise Policy Statement for Northern Ireland
NNGE	(WHO Regional Office for Europe, 2009) Night Noise Guidelines for Europe
NSIP	Nationally significant infrastructure project
PAN	Planning Advice Note
PPG	Planning Practice Guidance
PPS	Planning Policy Statement
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSG	Polysomnography
SCADA	Supervisory control and data acquisition
SGN	Supplementary Guidance Note
SNR	Signal-to-noise ratio
SPP	Scottish Planning Policy
SPPS	Strategic Planning Policy Statement
TAG	Transport Analysis Guidance
TAN	Technical Advice Note

TEDCAR-AM	Trailing edge directivity and convective amplification-related amplitude modulation
QoL	Quality of life
QSR	Quick scoping review
WFG Act	Well-being of Future Generations (Wales) Act 2015
WHO	World Health Organization

BRIEF NON-TECHNICAL SUMMARY

PUBLIC

BRIEF NON-TECHNICAL SUMMARY

ABSTRACT

This report documents a review of the current onshore commercial wind turbine noise assessment guidance applied in the UK.

The research has incorporated a scoping review of evidence, a stakeholder engagement exercise, and a limited sample of field measurements.

In view of the results of the research, this report concludes that the guidance would benefit from further review and updating of the aspects identified. This could be supported by currently available evidence, which is summarised in this report. However, the study has also highlighted gaps in the state of knowledge, which should be addressed by further research, to support any updates to the guidance.

The current UK wind turbine noise assessment guidance comprises a report known as ETSU-R-97, published by the Department of Trade and Industry in 1996[1], and a Good Practice Guide (GPG) on the application of ETSU-R-97, published by the Institute of Acoustics (IOA) in 2013[2] (with Supplementary Guidance Notes published by the IOA in 2014).

Since the ETSU-R-97 guidance was published, the context has changed:

- Onshore wind energy generation technology has evolved.
- There is increased understanding of the range of physical and operational factors that influence wind turbine sound.
- Further research has been undertaken to investigate the effects of wind turbine sound exposure on individuals and communities.
- A feature of wind turbine sound known as 'amplitude modulation' (AM[3]) has been reported as impacting people beyond the extent that was considered at the time of ETSU-R-97.
- New approaches to addressing the impacts of wind turbine noise, including AM, have been developed.
- The UK Government has introduced legislation mandating the target to reduce all greenhouse gas emissions to net zero by 2050 ('Net Zero'), the achievement of which will require increased deployment of onshore wind energy generation capacity[4].

The primary aim of the review was to make a recommendation on whether, in view of government policies on noise and Net Zero, and available evidence, the existing guidance requires updating, and, if so, which aspects need to be updated.

The project has comprised three workstreams:

---

[1] Working Group on Noise from Wind Turbines, 1996. *The assessment & rating of noise from wind farms: Final report*. ETSU-R-97. Department of Trade and Industry. [URL]

[2] IOA, 2013. *A good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise*. Institute of Acoustics. [URL]

[3] AM is a 'fluctuation' sound characteristic associated with the rotation of the turbine blades, by which the perceived volume (or level) of the sound periodically rises and falls.

[4] Achieving the Government's 2050 'Net Zero' target will require increases in renewable electricity generation, which entails an increase in deployment across a range of technologies, including onshore wind. The Government's 2020 Energy White Paper: *Powering our net zero future* stated that sustained growth in the capacity of onshore wind will be needed over the next decade, alongside solar and offshore wind generation capacity.

1. Evidence review of relevant research and guidance identified from a systematic search and screening process[5].
2. Stakeholder engagement with organisations including government bodies, local planning authorities, industry professional associations and civic groups – the aim of this workstream was to gather views on the current guidance, identify any areas of concern, and gather suggestions for addressing perceived issues[6].
3. Field measurements of wind turbine sound – the aim of this workstream was to obtain a snapshot of measurements at a sample of wind farm sites, and to quantify[7] and consider the AM characteristics in the sound measured within the context of the current guidance.

The evidence reviewed in this study, combined with the responses from the stakeholder engagement, indicates that the guidance would benefit from further review and updating of the aspects identified. Views from stakeholders on the extent of the updates required vary, with roughly half whose view is that the guidance requires some updating or amendment, and almost the same proportion whose view is that it requires substantial revision. Between these two viewpoints, there is consistency on the aspects of the guidance that the engagement respondents feel should be updated. These aspects are also consistent with the findings of the evidence review, which has identified a substantial body of evidence published since both ETSU-R-97 and the IOA GPG, that could inform an update of the areas in question. There are two primary aspects that this study has identified, which indicate the guidance requires updating:

- ETSU-R-97 noise limits:
  - The research indicates that the underlying basis for the ETSU-R-97 limits is outdated; there is now a volume of scientific evidence on the effects of exposure to wind turbine sound, which was unavailable at the time of ETSU-R-97, but could be used to support the development of an up-to-date framework of evidence-based effects thresholds.
  - The research also indicates that the common application of the ETSU-R-97 noise limits as a binary test of acceptability is considered to be potentially inconsistent with the wider policy frameworks in England and Northern Ireland (which require noise impacts to be addressed in a more nuanced way, with reference to expected effects and in view of guiding principles on sustainable development).
- The approach to controlling the impact of AM:
  - The research indicates that the current guidance does not fully address the potential impact of AM in wind turbine sound. The evidence identified in this study suggests that the assumptions about AM adopted in ETSU-R-97 do not adequately represent the nature of AM as experienced and measured. This study has identified evidence that could be used to develop a suitable control for AM, and stakeholder views indicate that official guidance on this issue would be welcomed.

[5] Collins, A.M., Coughlin, D., Miller, J., Kirk, S. 2015. *The production of Quick Scoping Reviews and Rapid Evidence Assessments: A how to guide*. Department for Environment, Food & Rural Affairs / Natural Environment Research Council. [URL]
[6] Government Communication Service, 2021. *Ensuring effective stakeholder engagement*. [URL]
[7] IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group, 2016. *Final report: A method for rating amplitude modulation in wind turbine noise*. [URL]

The review has also highlighted several other aspects of the current guidance that would benefit from further study and potential updating. A more detailed discussion of the conclusions and recommendations leading from this project is provided in sections 7.1 and 7.2.

The findings of this study should be considered within the context of its strengths and limitations:

- The design of the study has incorporated multiple workstreams, allowing a wide range of evidence to be considered. This approach has enabled a 'triangulation' approach to developing the study conclusions, which considers where the findings from each workstream are consistent with those of the other study components.
- The evidence review was based on a formal systematic approach, which ensures rigorous literature searching and screening procedures, reducing the risk of overlooking important information. However, in line with the project constraints, the methodology followed specifically precluded systematic evaluation of quality or risk of bias in the reviewed publications, which is a limitation of the approach. In the social field surveys that underpin many epidemiological community noise effect research studies, self-selection bias is a potential risk. However, the second stage of the review has been focussed on black literature, which should inherently provide a level of assurance on the quality of the study designs and publications, as these have already undergone an independent peer-review process. On the other hand, a focus on black literature can raise the risk of publication bias, however, this risk is reduced by the inclusion of grey literature in the first stage of the review.
- Epidemiological research into the effects of wind turbine noise is a relatively emergent field of study. This study has identified a lack of research undertaken in the UK, and there is uncertainty in the applicability to the UK of evidence available from studies undertaken overseas.
- Similarly, consideration of existing domestic and overseas guidance on managing wind turbine noise, must be informed by the awareness that any supporting scientific evidence could be relatively weak, and, in many cases, the foundation for published guidance may have been formed from professional judgements.
- As with any field of scientific research, the findings of studies vary and are not definitively consistent. This review has sought to highlight those aspects for which the evidence is relatively consistent, as well as acknowledging areas in which there remains scientific debate or uncertainty. Studies of human responses to wind turbine sound exposure typically observe considerable variation between individuals. There are multiple, complex elements that may contribute to this uncertainty, including varying study methods and controls, and it must be recognised that responses to sound or noise naturally vary widely, depending on a broad range of personal and contextual factors.
- The stakeholder engagement offered both online and offline response access options, and included follow-up communications encouraging stakeholders to respond – these measures would be expected to have contributed to increased response rates than may otherwise have been achieved.
- The response rate for local planning authorities (LPAs) to the stakeholder engagement was relatively low (at 10%), which may have reflected the time of year of the survey (coinciding with the summertime holiday period) and also the considerably larger overall number of LPAs invited to respond – many of the invited LPAs may have had relatively limited experience with onshore wind energy developments, with correspondingly lower motivation to respond.
- The lower LPA response rate may indicate a potential for bias in responses, for example, LPAs with negative experiences with onshore wind energy developments may have been more

motivated to respond than others. On the other hand, examination of recorded data for onshore wind energy installations indicates that the respondent LPAs for Scotland and Northern Ireland tended to represent those geographic areas with a greater density of wind turbine developments, indicating that it tended to be LPAs with the most experience of onshore wind developments that responded to the survey. This is less clear for respondent LPAs in England, within which onshore wind energy developments tend to be more sparsely distributed, and no LPAs in Wales responded to the survey invitation.

- There was relatively little engagement achieved with stakeholders representing Wales. In view of the growth in onshore wind generation capacity in Wales, the reasons for this are unclear.
- The project steering group suggested additional governmental and non-governmental stakeholders for inclusion in the stakeholder sample, which included one civic group. Other civic groups were not included, which may otherwise have presented a greater diversity of public experiences and attitudes towards wind energy.
- The stakeholder engagement survey questions asked respondents to identify the updates they considered to be required to the existing guidance. It did not explicitly ask respondents to identify aspects they felt were already effective, which instead was implicit in the responses when topics were not selected as requiring updating. It is acknowledged that the design of the questions may have encouraged respondents to focus more on negative aspects of the existing guidance than on positive aspects.
- The engagement interviews provided a constructive discussion environment that helped to clarify and expand the responses received from the interviewed stakeholders. However, the project constraints limited the numbers of stakeholders that could be interviewed in the stakeholder engagement.
- Project constraints limited the scope of the field measurements in duration and geographic extent. This means that the results, when considered in isolation, are not generalisable to other locations, types of wind turbine installation, or as a typical representation of the conditions at each measurement location. The approach taken does not provide a dataset that could be used to draw wider conclusions about prevalence of AM in general. Nonetheless, the data is informative when considered alongside the results of other longer-term measurement campaigns (identified in the literature evidence), with which some consistencies have been observed.

A more detailed discussion of the strengths and limitations of the study is provided in section 7.3.

EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

INTRODUCTION

The current approach applied in the UK to the assessment of commercial wind turbine noise, ETSU-R-97, was published by the Department of Trade and Industry in 1996[8]. Since the ETSU-R-97 guidance was published, the context has changed:

- Onshore wind energy generation technology has evolved, with larger, more efficient turbines, improved gearboxes, direct drive coupling and new blade designs.
- There is increased understanding of the conditions that influence wind turbine sound, including meteorological and atmospheric factors, as well as operational parameters.
- Further research has been undertaken to investigate the effects of wind turbine sound exposure on individuals and communities.
- Amplitude modulation (AM) of the aerodynamic sound from wind turbines[9] has been identified as a feature that may impact people beyond the extent that was considered at the time of ETSU-R-97.
- New approaches to addressing the impacts of wind turbine noise, including AM, have been developed.
- The UK Government has introduced legislation mandating the target to reduce all greenhouse gas emissions to net zero by 2050 ('Net Zero'), the achievement of which will require increased deployment of onshore wind energy generation capacity[10].

In 2013, the Institute of Acoustics (IOA) released a Good Practice Guide (GPG)[11] on the application of ETSU-R-97 (with Supplementary Guidance Notes published in 2014), which addressed many technical aspects that had been subject to scrutiny and debate, but did not cover:

- further guidance on assessing and controlling the impact of AM
- whether the limits for wind turbine noise defined in ETSU-R-97 remain consistent with government policies, and with available scientific evidence

This report documents a review of the current onshore commercial wind turbine noise assessment guidance applied in the UK. The primary aim of this review was to make a recommendation on whether, in view of government policies on noise and Net Zero, and available evidence, the existing guidance requires updating, and, if so, which aspects need to be updated.

The BEIS research questions motivating the project included:

- *Do contemporary acoustic measurement methodologies challenge those that are used in ETSU-R-97?*

[8] Working Group on Noise from Wind Turbines, 1996. *The assessment & rating of noise from wind farms: Final report*. ETSU-R-97. Department of Trade and Industry. [URL]
[9] AM is a 'fluctuation' sound characteristic associated with the rotation of the turbine blades, by which the perceived volume (or level) of the sound periodically rises and falls.
[10] Achieving the Government's 2050 'Net Zero' target will require increases in renewable electricity generation, which entails an increase in deployment across a range of technologies, including onshore wind. The Government's 2020 Energy White Paper: *Powering our net zero future* stated that sustained growth in the capacity of onshore wind will be needed over the next decade, alongside solar and offshore wind generation capacity.
[11] IOA, 2013. *A good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise*. Institute of Acoustics. [URL]

- *Do modern onshore wind turbines (composite blades, gearless transmission) emit more, less, or different characteristics of noise that ETSU-R-97 guidance does not currently account for?*
- *Do any changes in the way more modern turbines are sited in newer wind farms result in more, less, or different cumulative noise levels, both within the wind farm and also where these newer wind farms are located in proximity to other wind farms?*
- *Do modern onshore wind turbines produce excessive AM, to what extent, and to what effect?*
- *Is there evidence of the need for a more comprehensive measurement campaign for AM from new turbine types?*
- *Does the extent of AM change as turbines get older or suffer more wear and tear?*
- *Do international comparisons suggest that ETSU-R-97 guidance, methodologies, and ratings are not up to date, or can be adapted?*
- *Taking the above into account, should BEIS consider refreshing ETSU-R-97 guidance and, if so, how?*

The project has sought information relevant to the research questions within three workstreams:

1. Evidence review
2. Stakeholder engagement
3. Field measurements

This report documents the project methodology, the findings drawn from each of the workstreams, and makes recommendations based on the evidence identified.

REPORT STRUCTURE

- Section 1 introduces the project, summarises its aims and scope, and outlines the policy context for each of the UK devolved administrations.
- Section 2 provides an overview of wind turbine acoustical information and concepts that are fundamental to understanding the technical content of this report. This report is a necessarily technical document and, while efforts have been made to avoid unnecessary jargon, technical terminology is used throughout. A glossary of technical terms is provided in Appendix A.
- Section 3 describes the methodology and results of the evidence review, including the evidence characteristics, and a synthesis of the relevant findings. This is supported by more detailed evidence review summaries for each reviewed publication, which are provided in Appendix B.
- Section 4 describes the methodology and results of the stakeholder engagement, including survey data analysis and information obtained from stakeholder interviews. This is supported by additional information and analysis provided in Appendix C.
- Section 5 describes the methodology and results of the field measurements and analysis.
- Section 6 contains a discussion of the various aspects covered during the study, which draws together the findings from each work stream to address the research questions.
- The conclusions and recommendations of the study are summarised in section 7.

METHODOLOGY OVERVIEW

EVIDENCE REVIEW

The evidence review methodology is based on the Defra/NERC guidance on developing a 'Quick Scoping Review' (QSR)[12]. Part of the QSR approach involves the production of a 'systematic map', comprising a database of publications identified during the evidence review.

Research questions

The evidence review has addressed the following primary and secondary research questions:

- **1** (primary): Does the evidence indicate that the ETSU-R-97 guidance, when considered alongside the government-endorsed IOA best practice application guidance, requires updating to be consistent with the aims and objectives of current government policy and regulatory frameworks, and if so which aspects of it should be revised?
- **2a** (secondary): What further evidence or information may need to be obtained to robustly support updates to the current guidance (if it does require updating)?
- **2b** (secondary): What evidence is there on the influence of turbine age and design on the sound emission characteristics?

Search strategy

Following pilot literature searches, the search strategy has taken a two-stage approach:

1. For stage 1, an initial search, screening and review has been aimed at identifying issues raised within the literature concerning the current guidance.
2. In stage 2, the search focussed on two aspects that were highlighted as the priority by the stage 1 review.

Search sources comprised literature databases, conference proceedings, official guidance documents and national or international standards.

In stage 1, the screening of the identified publications produced 46 publications for review.

The stage 1 review indicated that the two most prevalent areas of concern identified in the literature regarding the ETSU-R-97 approach are:

1. the formulation of the limiting values (especially the night-time minimum limit) in relation to considerations of the likely noise effects
2. the guidance on the presence, character and control of AM

Accordingly, these two themes were carried forwards to use in screening of the studies identified in the stage 2 search.

In stage 2, the screening of the identified publications produced 91 publications for review (of which 5 were also reviewed in stage 1). In total, 132 publications were reviewed over stages 1 and 2.

The relevant evidence in the reviewed publications has been extracted into a 'systematic map', which comprises a database of all the publications identified during the search. The systematic map can be used to support further evidence reviews on wind turbine sound and noise.

[12] Collins, A.M., Coughlin, D., Miller, J., Kirk, S. 2015. *The production of Quick Scoping Reviews and Rapid Evidence Assessments: A how to guide*. Department for Environment, Food & Rural Affairs / Natural Environment Research Council. [URL]

STAKEHOLDER ENGAGEMENT

The methodology for stakeholder engagement has been based on relevant Government Communication Service guidance[13].

The engagement comprised two parts:

1. Online / email survey questionnaire sent to all invited stakeholders

   The questionnaire had three main response sections:

   i. questions gathering views and opinions about the current guidance and the need for any updates
   ii. requests for information about wind turbine technology, wind farm design, and how these may influence sound or noise, including any changes occurring since ETSU-R-97 was published
   iii. requests for ancillary information, including:

      – suggestions for managing guidance development and ongoing maintenance
      – any relevant published evidence stakeholders had not identified elsewhere in their response

2. Telephone interviews with key stakeholders

   Key stakeholders agreed with the project steering group were also invited to engage in a telephone interview to discuss their responses further.

Identification of stakeholders was initially carried out by discussion with the project steering group. Local planning authority (LPA) stakeholders were identified from the *Renewable Energy Planning Database: quarterly extract* (March 2021, published 28 April 2021[14]) as any authority that had recorded an onshore wind energy planning application. During the initial contact phase, the environmental health and development planning departments of LPA stakeholders were specifically targeted with the aim of ensuring that the most appropriate council officers were made aware of the exercise. During the engagement, additional stakeholders were also identified and incorporated into the exercise.

In total, 231 stakeholder organisations were invited to participate, of which 204 were LPAs. Of the invited organisations that were not LPAs (ie, government bodies, industry professional associations and a civic group), 44% responded to the invitation, while 10% of invited LPAs responded. This resulted in 32 completed survey questionnaires and telephone interviews with 7 stakeholder organisations.

Responses to closed survey questions were analysed quantitatively. Responses to open questions were analysed using a thematic analysis approach[15], in which underlying themes apparent in each response were extracted and grouped. The grouping enabled a quantitative analysis of the qualitative data to identify and highlight the most common themes. The qualitative data were used to support and illustrate the themes identified.

[13] Government Communication Service, 2021. *Ensuring effective stakeholder engagement*. [URL]
[14] https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract#history
[15] Kiger, ME & Varpio, L, 2020. Thematic analysis of qualitative data: AMEE Guide No. 131. *Medical Teacher*, 42 (8), 846-854. [URL]

FIELD MEASUREMENTS

The objective of the field measurement exercise was to obtain a snapshot of measurements of wind turbine sound under conditions thought most likely to result in clearly detectable AM, at distances representative of receptor locations around a sample of wind farm sites.

The survey has been limited in terms of duration, geographic coverage and land variability, and the measurements cannot be considered to be generalisable. The approach taken simply provides a snapshot of AM at the sites during the surveys; it does not provide a dataset that could be used on its own to draw wider conclusions about prevalence of AM in general, or to provide definitive evidence on the association of AM with particular turbine designs or ages. These issues could only be robustly addressed with wider site sampling taken over a considerably longer period.

Measurements were made at seven sites during the night-time. Measurement positions at each site were selected according to public accessibility, as well as the wind directions during site visits, which were monitored with the intention of targeting downwind conditions.

The measurements were analysed to quantify AM using the Reference Method developed by the IOA[16]. Measurements were attended, and sound recordings were made and used to verify the AM detection.

STUDY FINDINGS

The findings of the study in response to the motivating research questions are summarised below.

DO CONTEMPORARY ACOUSTIC MEASUREMENT METHODOLOGIES CHALLENGE THOSE THAT ARE USED IN ETSU?

There are several relevant aspects of sound measurements that have advanced since ETSU-R-97 was devised:

- The research shows that several methods have been developed to detect and quantify the magnitude of AM in wind turbine sound. Of those reviewed in this study, the IOA Reference Method, which was developed following a technical review of existing approaches, is believed to offer the best balance between robustness and practicality for use in the field. It is also known that the method has been incorporated into the working draft of the forthcoming IEC 61400-11-2 standard[17], albeit with some amendments[18], and refinements of the method have also been proposed during research applications.
- Research has shown that, during periods of AM with large modulation depths, the assumptions made in ETSU-R-97 supporting the choice of sound level index used to define the noise limits may not hold (see section 6.2.1). The rationale outlined in ETSU-R-97 to justify the choice of index is based on practical difficulties of measuring wind turbine sound, and remains valid. Therefore, this study recommends that the sound level index used to define controlling values is changed to the energy time-averaged sound level L_{Aeq} (described in section 2.1.2), and a suitable proxy measurement index is investigated and confirmed from further study.

[16] IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group, 2016. *Final report: A method for rating amplitude modulation in wind turbine noise*. [URL]
[17] At the time of preparing this report, the IEC 61400-11-2 standard is at drafting stages, and the standards development procedures mean it is unlikely to be published sooner than late-2022 or early-2023 [URL]
[18] Broneske, S & Søndergaard, B, 2021. *Development of IEC/TS 61400-11-2: Measurement of wind turbine noise characteristics in receptor position*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe.

- It was noted during the stakeholder engagement that there are several standardised methodologies available for evaluating tonality characteristics in sound immissions, which indicates that a review of these methods in comparison with the ETSU-R-97 approach should be undertaken.
- Researchers in Italy have devised a method for determining compliance of wind turbine sound immission levels with controlling values in the presence of residual sound, without the need to impose shutdowns on operations[19,20]. This type of procedure could have benefits for reducing the costs of undertaking compliance tests, and could be considered in future guidance development.

DO MODERN ONSHORE WIND TURBINES (COMPOSITE BLADES, GEARLESS TRANSMISSION) EMIT MORE, LESS, OR DIFFERENT CHARACTERISTICS OF NOISE THAT ETSU-R-97 GUIDANCE DOES NOT CURRENTLY ACCOUNT FOR?

Information gained during the stakeholder engagement has provided insights concerning this question:

- It was suggested that developments in turbine operational systems have influenced the sound emission profile of modern turbines: variable speed, pitch regulated turbines 'cut-in' with a relatively low sound level, which rises rapidly with wind speed, and 'plateaus' at or around rated power for the turbine; by contrast, sound emissions from the older fixed or dual-speed, stall regulated turbines more common at the time of ETSU-R-97 tend to increase steadily with wind speed, and do not plateau at rated power, as blade stall (which increases sound emissions) is used to regulate the turbine lift force at high wind speeds, to prevent damage.
- Stakeholders noted the increasing size of onshore turbines compared with those that were common when ETSU-R-97 was published, which has several potential implications:
  - The greater height means that wind speeds at blade and hub heights are typically higher for a given ground level wind speed. This may lead to situations in which, compared with a smaller turbine, larger turbines are generating similar sound levels, but wind-induced residual sound levels at receptors may be lower (due to the reduced ground level wind speed corresponding with a given hub height wind speed), which could lead to increased relative noise impact.
  - The larger rotor sizes may have two implications for AM characteristics at receptors:
    - the variation in the wind speed profile across the rotor span could be greater, which may contribute to transient blade stall, which in turn is associated with AM at long ranges
    - 'partial refractive shading' of the rotor could be greater, which could also lead to increased AM at long range (this was not raised in the engagement, but is discussed in the evidence review section 3.5.1)
  - Larger turbines lead to reduced turbine density for the same power capacity, which means that total sound emission levels tend to be similar to smaller turbine installations.
  - Larger turbines also mean increased distances between turbines and receptors, which may result in a more low-frequency sound immission character at long ranges, due to atmospheric effects on sound propagation.

[19] Gallo, P, Fredianelli, L, Palazzuoli, D, Licitra, G & Fidecaro, F, 2015. A procedure for the assessment of wind turbine noise. *Applied Acoustics*, 114, 213-217. [URL]
[20] Fredianelli, L, Gallo, P, Licitra, G & Carpita, S, 2017. Analytical assessment of wind turbine noise impact at receiver by means of residual noise determination without the wind farm shutdown. *Noise Control Engineering Journal*, 65 (5), 417-433. [URL]

- It was also suggested (citing research evidence[21]) that larger turbines may emit lower frequency tones than smaller turbines, when tones are present in the sound
- Research evidence on the general low frequency character of sound emissions from larger, more powerful turbines is conflicting. A study undertaken for the Danish government produced differing interpretations of the measurement data by two of the project partners: one concluded[21] that increasing turbine size and power ratings was not associated with a systematic increase in the proportion of low frequency sound emissions; another analysed the same dataset and reached the opposite conclusion[22]. Further analysis was later undertaken on an expanded dataset, which again concluded that the notion that larger turbines emit a greater proportion of low frequency sound energy compared with smaller turbines is not supported by the available evidence[23,24].

- It was highlighted that developments in turbine design features also have potential implications:
  - Several options for noise mitigation measures are available as standard on many commercial turbines, which include reduced sound operating modes and blade attachments, such as serrations, stall strips and vortex generators.
  - It was suggested that tonality characteristics in the sound emissions from modern turbines have been effectively addressed by improved technology and attention from manufacturers. However, it was also noted that the design features or mitigation measures introduced to reduce the overall broadband sound emissions could potentially mean that tones could 're-emerge' within the expected sound immissions from wind turbines.

Commercial onshore wind turbines employing direct drive transmission apparently remain relatively unusual. Although direct drive technology has been increasingly used for offshore turbines, it has not received widespread adoption for onshore applications, and it remains unclear whether gear-based or direct drive technology will be more dominant in the future of onshore wind energy[25,26]. Inspection of the onshore product portfolios for major wind turbine manufacturers (General Electric, Nordex, Siemens Gamesa and Vestas) has shown that, at the time of preparing this report, none of the current onshore turbine models available from these manufacturers employ direct drive technology, although it is found in some discontinued onshore products (and is available in current offshore turbines). This suggests that, while there was some commercial interest in direct drive transmission for onshore turbines in the recent past, demand for the technology in onshore applications has waned, and it is unclear whether it will be revived. From an acoustics perspective, there may be a slight advantage to direct drive transmission, in avoiding gear meshing sound. However, directly driven generators still produce tonal sound and vibration[27], and since the dominant part of the sound emission from turbines is generated by aerodynamic mechanisms, any acoustical advantage offered by direct drive transmission may be inconsequential.

[21] Madsen, KD & Pedersen, TH, 2010. *EFP-06 project: Low frequency noise from large wind turbines*. Final report. AV 1272/10. Danish Energy Authority.
[22] Møller, H & Pedersen, CS, 2011. Low-frequency noise from large wind turbines. *Journal of the Acoustical Society of America*, 129 (6), 3727-3744. [URL]
[23] Søndergaard, B, 2014. *Noise and low frequency noise from wind turbines*. Inter-noise 2014, 16-19 November, Melbourne. I-INCE [URL]
[24] Søndergaard, B, 2015. Low frequency noise from wind turbines: do the Danish regulations have any impact? An analysis of noise measurements. *International Journal of Aeroacoustics*, 14 (5-6), 909-915. [URL]
[25] van de Kaa, G, van Ek, M, Kamp, LM & Rezaei, J, 2020. Wind turbine technology battles: Gearbox versus direct drive - opening up the black box of technology characteristics. *Technological Forecasting and Social Change*, 153, 119933. [URL]
[26] Osmanbasic, E, 2020. *The future of wind turbines: Comparing direct drive and gearbox*. [URL]
[27] Schneider, L & Hanus, K-H, 2017. *Origin, transfer and reduction of structure-borne noise in wind turbines*. Wind Turbine Noise 2017, 2-5 May, Rotterdam. INCE-Europe.

DO ANY CHANGES IN THE WAY MORE MODERN TURBINES ARE SITED IN NEWER WIND FARMS RESULT IN MORE, LESS OR DIFFERENT CUMULATIVE NOISE LEVELS, BOTH WITHIN THE WIND FARM AND ALSO WHERE THESE NEWER WIND FARMS ARE LOCATED IN PROXIMITY TO OTHER WIND FARMS?

Responses to the stakeholder engagement suggested that the increased density of wind energy developments may have resulted in some situations in which properties become 'encircled' by wind turbines. This has the potential consequence that wind turbine sound could be incident from several directions, meaning that periods of 'respite', during which residents may otherwise have expected lower levels of wind turbine sound, would potentially be diminished, resulting in more prolonged impact.

Evidence from research identified during this study has suggested that wind turbine wakes, especially in stable atmospheric conditions, can enhance wind turbine sound propagation and the potential for AM. This indicates that turbine layouts could have some influence on sound emissions and character that may not yet be fully understood.

DO MODERN ONSHORE WIND TURBINES PRODUCE EXCESSIVE AM, TO WHAT EXTENT, AND TO WHAT EFFECT?

The characteristic of wind turbine sound known as 'blade swish' is a form of AM, which is connected with the turbine blade trailing edge sound directivity and convective amplification associated with a moving sound source. This form of AM is referred to in this report as 'TEDCAR-AM' (trailing edge directivity and convective amplification-related AM). TEDCAR-AM is most prominent at close ranges to and crosswind of turbines; it is inherently less prominent upwind or downwind of a turbine, and at longer ranges. TEDCAR-AM is described in ETSU-R-97, which states that the noise limits derived include for any additional impact due to perception of 'blade swish'.

Another form of AM is also associated with wind turbine sound, which is not caused by the effects of trailing edge directivity and convective amplification. This form of 'non-TEDCAR-AM' has a lower frequency sound character, and can be present at longer ranges and over different directions from turbines compared with 'blade swish'. Non-TEDCAR-AM has also been linked with reported noise disturbances, and is sometimes described as 'whoomphing'. Mechanisms and factors that may contribute to non-TEDCAR-AM are varying and complex, but the research indicates these include:

- transient blade stall, which is linked with the blade angle of attack, and may be affected by flow variation across the rotor span, which is linked with wind shear, wind veer, or 'low level jets' associated with atmospheric conditions, and with topography
- inflow turbulence variation
- complex turbine wake effects
- 'partial refractive shading' of the rotor, in which atmospheric effects cause 'shadow zones' and 'illuminated zones' with lower and higher sound levels respectively

The term 'excessive' is not a well-defined descriptive term to use for AM sound characteristics. The terms used in this study to describe the forms of AM discussed have the benefit of being related to an objective description of the generation mechanisms.

Research indicates that the occurrence of non-TEDCAR-AM (which, although apparently acknowledged in ETSU-R-97 in the form of 'blade thump' identified at one site, was not the focus of the guidance), is likely to be more prevalent at night-time than during the day, and potentially increases the noise annoyance impact of wind turbine sound, when it is present.

We undertook a limited field measurement exercise that showed detectable AM at distances and in wind directions that would not be considered as consistent with the more predictable TEDCAR-AM. This tentatively indicates that detectable non-TEDCAR-AM is probably not an unusual occurrence at the sites visited, although a larger dataset would be necessary to draw generalised conclusions about prevalence.

Evidence from the research identified during this study indicates that audible AM increases the distinctiveness of wind turbine sound and aggravates noise annoyance responses. The impact of AM is influenced by the modulation depth, as well as by its modulation frequency (see section 2.1.3 for information on these terms).

IS THERE EVIDENCE OF THE NEED FOR A MORE COMPREHENSIVE MEASUREMENT CAMPAIGN FOR AM FROM NEW TURBINE TYPES?

This study has not identified evidence to indicate that 'new turbine types' are associated with different AM characteristics. While some evidence suggests that larger turbines may be subject to increased risk of non-TEDCAR-AM occurrence, due to potential factors connected with turbine dimensions (including wind speed variation over the rotor span, partial refractive shading of the rotor disc, and wake effects), no studies have been identified that systematically investigated this possible connection, which therefore remains uncertain. On the other hand, the research indicates that modern turbines enable accurate control of blade pitch angle – this can be used to reduce the risk of blade stall occurrence, which is also associated with non-TEDCAR-AM.

This study has identified previous long-term campaigns comprising field measurements of AM in Australia (see section 3.5.1 and 6.3.2) and in Japan (section 6.3.2). Based on the findings from the evidence review and the stakeholder engagement, the potential value of such a campaign in the UK may lie more toward investigating wind turbine noise effects and responses to AM than in trying to establish whether particular turbine types, models or ages are more or less associated with AM occurrence or severity. This is because there are multiple complex factors that appear to influence AM generation, which could make it unlikely that any firm conclusions regarding the influence of specific turbine distinctions can be reached. It has also been highlighted in the stakeholder engagement that the challenges involved in attempting to obtain sufficiently robust data should not be underestimated (see section 4.2.4), and there could be no guarantee of achieving the objective.

DOES THE EXTENT OF AM CHANGE AS TURBINES GET OLDER OR SUFFER MORE WEAR AND TEAR?

The stakeholder engagement identified some evidence addressing this question: a member of an industry professional association shared their experience that delamination (roughening) of wind turbine blades over a period of 10 years led to increased AM identified at 2 sites. It was found that repairs were straightforward and resolved the issue.

The general consensus among stakeholders responding to the part of the engagement survey that addressed this question was that there is a commercial incentive for operators to maintain turbines, as degradation that adversely affects sound emissions also impacts on power generation. Routine maintenance and repairs can avoid or resolve such issues when they arise.

DO INTERNATIONAL COMPARISONS SUGGEST THAT ETSU-R-97 GUIDANCE, METHODOLOGIES AND RATINGS ARE NOT UP TO DATE, OR CAN BE ADAPTED?

The research suggests that the most apparent difference between ETSU-R-97 and overseas national or regional guidance and regulations is that the ETSU-R-97 night-time minimum noise limit is less stringent than the daytime. This study has found that this situation appears to be unique to the UK and Ireland (among the territories considered – see section 3.5.1). In 2019, the Government of Ireland published draft revised guidelines that indicated it is proposing to replace the existing noise limits with a regime that would effectively ensure that night-time limits are lower (more stringent) than the daytime[28]. However, at the time of preparing this report, the finalised guidance had not been published.

The research also suggests that the ETSU-R-97 daytime minimum noise limits appear to be similar to those imposed in overseas territories.

Comparison of relative 'margin above background sound level' limits indicates that the ETSU-R-97 approach is also taken in New Zealand, Ireland, and the Australian states of South Australia and Victoria, while Japan, and the states of New South Wales and Queensland impose a more stringent relative limit. This appears to be connected with the use of L_{Aeq} to characterise wind turbine sound immissions instead of L_{AF90}. France and Italy impose relative limits based on a different system known as 'sound emergence', which is not directly comparable with the 'margin above background sound level' approach. Research on the sound emergence approach indicates that it may not be a useful characterisation of relative impact[29]. However, there also appears to be very little (if any) scientific evidence supporting the margin above background approach taken in the other territories that apply relative impact controls (as discussed in section 6.2.1).

It is notable that the Japanese regulations were introduced following an extensive research programme involving observational epidemiological field studies and experimental studies of sound characteristics, including AM, tonality, and low frequency sound. The overall approach is very similar to ETSU-R-97, being based on a combined regime of absolute and relative limits. However, the controlling values tend to be slightly more stringent, and the sound level index used to control wind turbine sound is L_{Aeq} rather than L_{AF90} (although L_{AF90} is used as a proxy measurement index)[30].

A more detailed review of overseas national and regional guidelines on wind turbine sound and noise assessment could be valuable in providing further context for decisions on the policy balance between noise control and enabling renewable energy development (ie, contributing to achieving Net Zero). However, vigilance should be exercised in considering overseas guidance and regulations; the underlying scientific evidence and any professional judgements should be identified and considered, and if evidence or judgements are not clear, the information should be treated with caution.

---

[28] Government of Ireland, 2019. *Draft revised wind energy development guidelines.* [URL]

[29] Dutilleux, G, & Fosset, J, 2020. Comparing sound emergence and sound pressure level as predictors of short-term annoyance from wind turbine noise. *Acta Acustica*, 3 (4), 10. [URL]

[30] Shimada, A & Nameki, M, 2017. *Evaluation of wind turbine noise in Japan*. ICBEN 2017, 18-22 June, Zurich. International Commission on Biological Effects of Noise. [URL]

TAKING THE ABOVE INTO ACCOUNT, SHOULD BEIS CONSIDER REFRESHING ETSU-R-97 GUIDANCE AND, IF SO, HOW?

In view of the results of the evidence review, the stakeholder engagement and the field measurement exercise, this study concludes that the identified aspects of the current guidance should be reviewed and updated. To an extent, this could be supported by the currently available research evidence (some of which has been summarised in this report), alongside the relevant experience of stakeholders. However, this study has also highlighted gaps in the state of knowledge, which should be addressed by further research to support any updates to the guidance.

Our recommendations for aspects of the guidance that should be updated are summarised below.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The evidence reviewed in this study, combined with the responses from the stakeholder engagement, indicates that the guidance would benefit from further review and updating of the aspects identified. Views from stakeholders on the extent of the updates required vary, with roughly half whose view is that the guidance requires some updating or amendment, and almost the same proportion whose view is that it requires substantial revision. Between these two viewpoints, there is consistency on the aspects of the guidance that the engagement respondents feel should be updated. These aspects are also consistent with the findings of the evidence review, which has identified a substantial body of evidence published since both ETSU-R-97 and the IOA GPG that could inform updating of the areas in question. There are two primary aspects that this study has identified, which indicate the guidance requires updating:

- ETSU-R-97 noise limits:
  - The research indicates that the underlying basis for the ETSU-R-97 limiting values is outdated; there is now a volume of scientific evidence on the effects of exposure to wind turbine sound, which was unavailable at the time of ETSU-R-97, but could be used to support the development of an up-to-date framework of evidence-based effects thresholds.
  - The research also indicates that the common application of the ETSU-R-97 noise limits as a binary test of acceptability is considered to be potentially inconsistent with the wider policy frameworks in England and Northern Ireland (which require noise impacts to be addressed in a more nuanced way, with reference to expected effects and in view of guiding principles on sustainable development).
- The approach to controlling the impact of AM:
  - The research indicates that the current guidance does not fully address the potential impact of AM in wind turbine sound. The evidence identified in this study suggests that the assumptions about AM adopted in ETSU-R-97 do not adequately represent the nature of AM as experienced and measured. This study has identified evidence that could be used to develop a suitable control for AM, and stakeholder views indicate that official guidance on this issue would be welcomed.

The recommendations of this study are summarised in the table below, with the recommendations addressing the two main issues identified highlighted with light green shading.

In making these recommendations, we recognise that the delivery of further work is dependent upon a range of factors and constraints, and that the parties best placed to promote and progress the work may depend on its nature and scope, the availability of funding, and any wider potential benefits that might be associated with their involvement.

Recommendation	Rationale and justification	Supporting evidence and information
A review and update of the current guidance should be undertaken.	The review has identified that evidence on relevant aspects of wind turbine sound has expanded and improved in quality since the guidance was developed.	Sections 3.4, 3.5.1
	The engagement exercise confirmed that the majority (28 / 31) of respondent stakeholders agree that the current guidance requires updating, with a roughly even split between those who think some updating or amendment is required, and those whose view is that it requires substantial revision.	Section 4.2.3
	The evidence review and the stakeholder engagement were largely consistent in identifying the primary issues with the current guidance:	
	▪ The ETSU-R-97 noise limits are based on outdated or insubstantial evidence.	Sections 3.5.1, 4.2.3, 6.2, Appendix B sections 9.1.1, 9.2.1
	▪ The current guidance does not adequately address the adverse impact of amplitude modulation (AM), which increases noise annoyance, and is an expected characteristic of wind turbine sound immissions.	Sections 3.3.2, 3.5.1, 4.2.3, 6.3.2, Appendix B sections 9.1.2, 9.2.2
The review and updates should address the main areas identified as a priority, and should also consider the range of other issues and suggestions raised during this study, including:		

Recommendation	Rationale and justification	Supporting evidence and information
▪ A systematic review and meta-analysis of noise effects evidence on noise annoyance and sleep disturbance should be undertaken, with the aim of developing a robust framework of effects thresholds on which to base controls for wind turbine noise, which is consistent and compatible with wider national policy frameworks on noise. The review should include consideration of the potential influences of personal and contextual factors on subjective responses.	▪ Noise policy frameworks in England and Northern Ireland are based on 'observed effects levels' (effects thresholds).	Section 1.1.1
	▪ The quantity and quality of available evidence is now thought to be sufficient to obtain meaningful results from a meta-analysis of studies of wind turbine noise annoyance, and possibly also sleep disturbance.	Sections 3.5.1, 6.2.3, Appendix B section 9.2.1
	▪ Existing controlling values and guidelines for wind turbine sound levels are based on evidence and guidance that is outdated and may be unreliable.	Sections 6.2.1, 6.2.2, Appendix B section 9.2.1
	▪ The way in which ETSU-R-97 noise limits are applied in common practice is inconsistent with the wider framework of noise policies in England and Northern Ireland.	Sections 4.2.3, 4.3, 6.2.1
▪ Meta-analysis of exposure-response relationships for wind turbine sound should carefully consider the inter-study variation in methodologies for exposure and response estimations, and, where necessary, develop robust normalisation procedures to avoid combining or comparing data that use differing scales.	▪ The evidence review identified that varying exposure estimation and response modelling procedures are used in different studies.	Section 3.4
	▪ It has also been shown that these methodological differences have non-trivial implications for the exposure-response relationships developed.	Sections 3.4.2, 6.2.1
	▪ Some previous studies and guidance have combined or compared exposure-response relationships that are based on differing scales, which could be misleading.	Sections 3.5.1, 6.2.1, 6.2.2

Recommendation	Rationale and justification	Supporting evidence and information
▪ The existing WHO guidelines should not be used as a basis for developing a framework of effects thresholds for wind turbine sound.	▪ The evidence reviewed in WHO guidance up to and including 2009 did not include wind turbine sound, and it is widely recognised that different sound sources impart varying effects.	Section 6.2.2
	▪ The 2018 WHO ENGER made a 'conditional' strength recommendation on noise annoyance from wind turbine sound, which was based on a direct comparison of exposure-response functions from studies that employed differing methods, which consequently may be misleading.	Sections 3.5.1, 6.2.2, Appendix B section 9.2.1
	▪ The evidence reviews supporting the 2018 ENGER included studies up to 2014-15; the quantity and quality of studies have expanded since the reviews were completed.	Sections 3.5.1, 6.2.2, Appendix B section 9.2.1
▪ A study should be undertaken to (i) consider the relative impact control approach and whether this should remain a component of wind turbine noise assessment, and (ii), if it is to be retained, to identify effects thresholds, either in existing evidence, or otherwise gather new evidence (eg, via experimental testing) to support the approach.	▪ The ETSU-R-97 relative limit, and the relative impact assessment approach, appears to be historically based on consensus opinion, but has not been supported by scientific evidence.	Sections 3.5.1, 6.2.1, Appendix B section 9.2.1
	▪ Nonetheless, some emerging evidence on wind turbine sound masking does indicate that an influence of relative levels may be expected, although the potential magnitude of this effect has not been firmly established and may be smaller than previously assumed.	Sections 3.5.1, 6.2.1, Appendix B section 9.2.1
	▪ It is unclear whether a relative impact approach remains appropriate for the increasing size of turbines, which is connected with the background sound levels at which wind turbines are operational.	Sections 4.2.3, 4.4, 6.5.2

Recommendation	Rationale and justification	Supporting evidence and information
▪ A more detailed review of overseas national and regional wind turbine noise guidelines should be undertaken to provide context for decisions on the policy balance between noise control and enabling renewable energy development (to achieve Net Zero), which should also ensure that underlying scientific evidence and professional judgements are identified (and any guidelines for which evidence or judgements are unclear should be treated with caution).	▪ This study has provided an outline review of overseas national and regional guidelines, mainly extracted from secondary literature sources; a further review could confirm the details from the primary documents, and identify the underlying rationale, including scientific evidence and professional judgements. ▪ Some territories are in the process of developing new guidelines, which may provide helpful information for development of UK guidance.	Sections 3.5.1, Appendix B section 9.1.1 Section 3.5.1
▪ A UK-based observational study of effects of wind turbine sound exposure should be undertaken, including investigation of rural areas, the influence of prolongation and intermittency of exposure, and the impact of AM.	▪ There is very little UK-based evidence from observational studies of effects of wind turbine sound exposure. ▪ It is expected that subjective responses to wind turbine sound will be influenced by local circumstances and attitudes. ▪ There is very little evidence on the influence of prolongation and intermittency of exposure to wind turbine sound and effects. ▪ There is also very little evidence on AM impacts from observational studies (most of the evidence on responses to AM comes from experimental studies).	Sections 3.5.1, 3.5.2, 6.2.3, Appendix B section 9.2.1 Sections 3.5.1, 3.5.2, 4.3, 6.2.1 Sections 3.5.2, 4.4, 6.2.3, 6.4.7 Sections 3.5.1, 3.5.2, 6.3.2, Appendix B section 9.2.2

Recommendation	Rationale and justification	Supporting evidence and information
▪ Controlling values for noise during the night should not be higher (ie, less stringent) for night-time than during the day.	▪ This feature of the ETSU-R-97 noise limits appears to be unique to the UK and Ireland (which implements wind turbine noise guidance developed from ETSU-R-97).	Sections 3.5.1, 6.2.1, Appendix B section 9.1.1
	▪ AM prevalence is typically greater at night, which, combined with the higher minimum limit means overall night-time impacts could be increased compared with daytime.	Sections 3.5.1, 6.3.2, Appendix B section 9.2.2
▪ Consideration should be given to how to use noise controls to ensure that developments are prioritised according to renewable energy capacity value.	▪ The stakeholder engagement highlighted that the current guidance may result in larger, more valuable development proposals being made unviable due to the noise impact of smaller, less valuable, developments.	Sections 4.2.3, 4.4, 6.4.3
▪ Further clarification on the interpretation of 'financially involved' receptors for the application of noise controls, along with relevant examples, should be provided.	▪ The evidence review highlighted that some evidence supports the notion that financial involvement or direct economic benefits are associated with reduced annoyance.	Sections 3.5.1, 6.2.1, Appendix B section 9.2.1
	▪ The stakeholder engagement highlighted that some LPAs consider further guidance on the extent, nature and implications of financial involvement is required.	Sections 4.2.3, 4.4, 6.2.1

Recommendation	Rationale and justification	Supporting evidence and information
▪ A study should be undertaken to determine the most effective way to control the impact of AM, which should be based on the IOA Reference Method for measuring AM – the method itself should be reviewed in light of any refinements proposed (eg, by the IEC 61400-11-2 working group, or in relevant research).	▪ The evidence review and the field measurements indicate that AM is an expected characteristic in wind turbine sound immissions.	Sections 3.5.1, 5.5, 5.6, 6.3.2, Appendix B section 9.2.2
	▪ The evidence review indicates that AM increases adverse impact, that AM can be reliably and practically measured using the IOA metric, that a character penalty scheme is justified by the evidence, and that evidence-based schemes have been proposed.	Sections 3.5.1, 6.3.2, Appendix B section 9.2.2
	▪ The details of application of a suitable scheme in practice have also been considered, but need to be determined in relation to new guidance on the overall approach to assessing compliance with wind turbine noise controls.	Section 6.3.2
	▪ Some refinements to the IOA Reference Method have been proposed, for example it is known that the IEC 61400-11-2 working draft (which addresses measurements of wind turbine sound at receptor locations) currently includes the method, with some modifications.	Sections 3.5.1, 6.3.2, Appendix B section 9.2.2
▪ A review of methods for evaluating tonality characteristics in wind turbine sound should be undertaken, with the aim of establishing the most effective approach (this review should also consider the advice of the IEC 61400-11-2 working group).	▪ It was highlighted in the stakeholder engagement that methods for evaluating tonality have advanced since ETSU-R-97 and these should be reviewed.	Sections 4.2.3, 4.4, 6.4.6, 6.5.1
	▪ The IEC 61400-11-2 working draft (which addresses measurements of wind turbine sound at receptor locations) includes a method that is different to the ETSU-R-97 approach.	Sections 6.4.6, 6.5.1

Recommendation	Rationale and justification	Supporting evidence and information
▪ A review of the approach to compliance determination should be undertaken, to consider: (i) how these could be made less complex while also providing increased confidence in outcomes; (ii) the suitability of establishing a proxy measurement location approach, and (iii) how to address the challenges posed in cumulative situations.	▪ The evidence review and stakeholder engagement highlighted concerns about the difficulties of compliance determination process, which is considered to be complex, and costly, and in some cases the outcomes are not clear or not agreed by relevant parties. ▪ It was also noted in both the evidence review and the stakeholder engagement that cumulative situations increase the complexity of assessments and compliance determinations further, presenting particularly challenging issues. ▪ The potential benefits of using proxy measurement locations nearer to wind turbines were raised in the evidence review and the stakeholder engagement, and are known to be used in some overseas regulations.	Sections 3.3.3, 4.2.3, 4.4, 6.4.1, Appendix B section 9.1.3
▪ Further guidance on assessing and controlling cumulative impacts should be developed, incorporating existing evidence and best practice advice.	▪ It was highlighted in the stakeholder engagement and the evidence review that cumulative assessments and compliance determination are complex, and difficult, and further guidance would be valuable.	Sections 3.3.3, 4.2.3, 4.4, 6.4.2, Appendix B section 9.1.3
	▪ The stakeholder engagement suggested that the increase in wind energy development density may have led to more sustained noise impact for situations in which receptors have become ‘encircled’ by turbines.	Sections 4.2.4, 4.4, 6.4.2
	▪ It was also noted in the stakeholder engagement that further best practice advice has been proposed following the IOA GPG, and this could be incorporated into new guidance.	Sections 4.2.3, 4.2.4, 6.4.2

Recommendation	Rationale and justification	Supporting evidence and information
▪ A review of the approach to measurement data aggregation and analysis should be undertaken, to ensure the methods used are statistically robust, and adequately account for uncertainty.	▪ The evidence review highlighted concerns raised about the potential for the aggregation of measured sound levels to lead to underestimation of noise impact. ▪ It was also noted in the evidence review that the statistical methods recommended in the guidance may not be sufficiently rigorous, and differences of application may introduce uncertainty into assessments that is not considered.	Sections 3.3.3, 6.4.4, Appendix B section 9.1.3
	▪ Concerns were also raised in the stakeholder engagement that uncertainty may not be adequately addressed in the current guidance.	Sections 4.2.3, 6.4.4, Appendix C section 12.2.1
	▪ Some aspects of sound prediction uncertainty are considered in the guidance, but further consideration and guidance on uncertainty in other parts of the assessment may be needed.	Section 6.4.4
▪ Further guidance on sound and weather measurements should be developed, based on a review of research and available technology.	▪ The evidence review and stakeholder engagement highlighted that sound level meter microphone wind shield specifications, sound level meter self-noise, and weather instrumentation positioning are particular aspects that may require additional guidance.	Sections 3.3.3, 4.2.3, Appendix C, 12.2.1
	▪ The IOA GPG explicitly recognises that further research and guidance is needed on wind shielding devices used for measurements.	Section 6.4.5
	▪ Research has been undertaken examining the use of various microphone wind shielding devices for wind turbine sound measurements, which should be considered.	Section 6.4.5

Recommendation	Rationale and justification	Supporting evidence and information
▪ A review of evidence on wind turbine sound predictions should be undertaken, with the aim of (1) identifying the most effective methods for predicting sound propagation over (a) bodies of water and (b) concave terrain profiles, and (2) considering whether further evidence on directivity of turbine sound emissions in varying wind conditions indicates that updates may be required to the existing guidance.	▪ These propagation aspects of wind turbine sound predictions (topics 1a and 1b) were highlighted in the stakeholder engagement as requiring further attention. ▪ Research on these topics (1 and 2) has been published since the IOA GPG (which addressed these aspects).	Section 6.4.8, Appendix C section 12.2.1 Section 6.4.8
▪ Consideration should be given to including a clear position statement in guidance confirming the intended policy balance between protection from noise impact, and enabling of renewable energy development (to achieve Net Zero), linked with the wider policies that underpin the government approach to noise management. Such a statement should be supported by a 'what if' scenario study undertaken to consider the potential outcomes of selecting different approaches or controlling values for noise assessment.	▪ The value of a 'policy balance statement' was highlighted in the stakeholder engagement. The main benefit of such a statement would be management of expectations: it would be made clear that some adverse impact from wind turbine noise may be expected, and would not be prevented by the planning system, if the balance of impacts and renewable energy meets with the relevant policies. ▪ With suitable assumptions, effective collaboration, and sensitivity testing of an appropriate range of scenarios, a scenario study could provide a defensible basis for a policy balance statement, and for taking decisions on the various aspects of the assessment approach that require updating.	Sections 4.2.3, 4.2.5, 4.4, 6.1.1
▪ Consideration should be given to including a clear position statement on wind turbine infrasound in guidance (research in this area is known to be ongoing, and such a statement should be reviewed against further evidence when published).	▪ The evidence review indicates that infrasound from wind turbines at typical exposure levels has no direct adverse effects on health. ▪ Some stakeholders suggested that a position statement on infrasound would be helpful for assessors and decision takers to understand the appropriate scope of wind turbine noise assessments.	Section 3.5.1, Appendix B section 9.2.1 Section 4.4, Appendix C section 12.2.1

Recommendation	Rationale and justification	Supporting evidence and information
▪ Consideration should be given to whether specific guidance for smaller wind turbines should be developed.	▪ The stakeholder engagement highlighted that small and single turbine installations are a particular concern in Northern Ireland, and the current guidance does not cover small turbines.	Sections 4.2.3, 6.4.9
▪ Consideration should be given to the range of other suggestions made by stakeholders during the engagement exercise.	▪ A wide range of suggestions for updates were made in the engagement, some of which it has only been possible to briefly touch upon in this study.	Sections 4.2, 4.3, 4.4, Appendix C section 12.2
Development of new or updated guidance should consider the following suggestions to manage the updates and long-term maintenance:		
▪ the formation of a working group comprising representatives of a range of stakeholder organisations to lead the development of guidance	▪ It was highlighted in the stakeholder engagement that a collaborative approach to guidance development could help to speed up the process (an example given of a longer process thought to be associated with a less collaborative approach was the revision to the Ireland Wind Energy Development Guidelines, which it was noted has been ongoing since 2013).	Sections 4.2.5, 4.4
▪ the separation of the 'policy position' (addressing the balance between controlling noise impact and enabling renewable energy development), 'technical guidance' (application of the assessment approach), and 'technical justification' (the supporting evidence) into discrete, linked documents	▪ It was suggested in the stakeholder engagement that separation of these parts would help to ensure that updates can be made to technical guidance and supporting evidence more quickly without the need to address the policy balance. ▪ It was also suggested in the stakeholder engagement that the existing guidance is too discursive, and separating the supporting evidence would improve clarity and brevity, while retaining the justifications for the approach taken.	Sections 4.2.5, 4.4
▪ the introduction of a guidance review programme (suggestions for periodic reviews were in the range 2-5 years)	▪ It was suggested in the stakeholder engagement that this would help to keep technical guidance up to date with developments in the scientific evidence.	Sections 4.2.5, 4.4

STUDY STRENGTHS AND LIMITATIONS

The findings of this study should be considered within the context of its strengths and limitations, which are summarised below. A more detailed discussion of the strengths and limitations of the study is provided in section 7.3.

- Evidence review:
  - The design of the study has incorporated multiple workstreams, allowing a wide range of evidence to be considered. This approach has enabled a 'triangulation' approach to developing the study conclusions, which considers where the findings from each workstream are consistent with those of the other study components.
  - The evidence review was based on a formal systematic approach, which ensures rigorous literature searching and screening procedures, reducing the risk of overlooking important information. However, in line with the project constraints, the QSR methodology followed specifically precluded systematic evaluation of quality or risk of bias in the reviewed publications, which is a limitation of the approach.
  - In the social field surveys that underpin many epidemiological community noise effect research studies, self-selection bias is a potential risk. However, the second stage of the review has been focussed on black literature, which should inherently provide a level of assurance on the quality of the study designs and publications, as these have already undergone an independent peer-review process. On the other hand, it is also recognised that a focus on black literature can raise the risk of publication bias, however, this risk is reduced by the inclusion of grey literature in the first stage of the review. This approach to the evidence review is consistent with the project scope, aims and constraints.
  - Epidemiological research into the effects of wind turbine noise is a relatively emergent field of study. This study has identified a lack of research undertaken in the UK, and there is uncertainty in the applicability to the UK of evidence available from studies undertaken overseas.
  - Similarly, consideration of existing domestic and overseas guidance on managing wind turbine noise, must be informed by the awareness that any supporting scientific evidence could be relatively weak, and in many cases, the foundation for published guidance may have been formed from professional judgements.
  - As with any field of scientific research, the findings of studies vary and are not definitively consistent. This review has sought to highlight those aspects for which the evidence is relatively consistent, as well as acknowledging areas in which there remains considerable scientific debate or uncertainty. Studies of human responses to external stressors typically observe considerable variation between individuals, and this is found to be the case with the evidence concerning wind turbine sound exposure. There are multiple, complex elements that may contribute to this uncertainty, including varying study methods and controls, and it must be recognised that responses to sound or noise naturally vary widely, depending on a broad range of personal and contextual factors.
- Stakeholder engagement:
  - The stakeholder engagement offered both online and offline response access options, supported by follow-up communications encouraging stakeholders to respond – these

measures would be expected to have contributed to increased response rates than may otherwise have been achieved.

- The response rate for LPAs to the stakeholder engagement was relatively low, at 10%. Several factors may have contributed to a lower LPA response rate (which was 44% for non-LPA invitees), including:
  - the time of year of the survey, which partly coincided with the summertime holiday period
  - the considerably larger overall number of LPAs invited to respond, compared with other stakeholder types (204 LPAs comprised ~88% of the invitee sample), which was the result of inviting all UK LPAs that had recorded at least one onshore wind energy planning application – many of the invited LPAs may therefore have had relatively limited experience with onshore wind energy developments, with correspondingly lower motivation to respond
- The lower LPA response rate may indicate a potential for bias in responses, for example, LPAs with negative experiences with onshore wind energy developments may have been more motivated to respond than others. On the other hand, (as discussed in section 4.2.2) examination of recorded data for onshore wind energy installations indicates that the respondent LPAs for Scotland and Northern Ireland tended to represent those geographic areas with a greater density of wind turbine developments, indicating that it tended to be LPAs with the most experience of onshore wind developments that responded to the survey. This is less clear for respondent LPAs in England, within which onshore wind energy developments tend to be more sparsely distributed, and no LPAs in Wales responded to the survey invitation.
- There was relatively little engagement achieved with stakeholders representing Wales. In view of the growth in onshore wind generation capacity in Wales, the reasons for this are unclear.
- The project steering group suggested additional governmental and non-governmental stakeholders for inclusion in the stakeholder sample, which included one civic group. Other civic groups were not included, which may otherwise have presented a greater diversity of public experiences and attitudes towards wind energy.
- The stakeholder engagement survey questions asked respondents to identify the updates they considered to be required to the existing guidance. It did not explicitly ask respondents to identify aspects they felt were already effective, which instead was implicit in the responses when topics were not selected as requiring updating. It is acknowledged that the design of the questions may have encouraged respondents to focus more on negative aspects of the existing guidance than on positive aspects.
- The engagement interviews provided a constructive discussion environment that helped to clarify and expand the responses received from the interviewed stakeholders. However, the project constraints limited the numbers of stakeholders that could be interviewed in the stakeholder engagement.

- Field measurements:
  - Project constraints limited the scope of the field measurements in duration and geographic extent. This means that the results, when considered in isolation, are not generalisable to other locations, types of wind turbine installation, or as a typical representation of the conditions at each measurement location. The approach taken does not provide a dataset that could be used to draw wider conclusions about prevalence of AM in general. Nonetheless, the data is informative when considered alongside the results of other longer-term measurement

campaigns (identified in the literature evidence), with which some consistencies have been observed.

1

INTRODUCTION

1 INTRODUCTION

1.1 PROJECT BACKGROUND

The current approach applied in the UK to assessment of commercial wind turbine noise, ETSU-R-97[31], was published in 1996. This was developed by a Noise Working Group on the basis of the knowledge and turbine technology at the time, with the acknowledgement that "*as more experience and information become available and as circumstances develop it may become necessary to revise and improve the contents of this report*"[32].

In 2013, the Institute of Acoustics (IOA) released a Good Practice Guide (GPG)[33] on the application of ETSU-R-97, which addressed many technical aspects that had been subject to scrutiny and debate. As discussed below, the GPG has been endorsed as representing accepted best practice for wind turbine noise development planning and assessment by all UK devolved administrations. Two issues that the GPG did not cover in any detail are:

- further guidance on the wind turbine acoustic characteristic known as amplitude modulation (AM) of the aerodynamic sound
- whether the limits for wind turbine noise defined in ETSU-R-97 remain consistent with the wider Government policy framework, and with available scientific evidence

Since the ETSU-R-97 guidance was published, the context has changed:

- Onshore wind energy generation technology has evolved, with larger, more efficient turbines, improved gearboxes, direct drive coupling and new blade designs.
- There is increased understanding of the conditions that influence wind turbine sound, including meteorological and atmospheric factors, as well as operational parameters.
- Further research has been undertaken to investigate the effects of wind turbine sound exposure on individuals and communities.
- Amplitude modulation (AM) of the aerodynamic sound from wind turbines has been identified as a feature that may impact people beyond the extent that was considered at the time of ETSU-R-97.
- New approaches to addressing the impacts of wind turbine noise, including AM, have been developed.
- The UK Government has introduced legislation mandating the target to reduce all greenhouse gas emissions to net zero by 2050, the achievement of which will require increased deployment of onshore wind energy generation capacity[34].

Given these changes, it is important that local planning authorities, environmental protection departments, developers and operators have the most relevant and up-to-date guidance possible when planning and assessing noise from wind turbines.

[31] Working Group on Noise from Wind Turbines, 1996. *The assessment & rating of noise from wind farms: Final report*. ETSU-R-97. Department of Trade and Industry. [URL]
[32] ETSU-R-97, section 9, page 111
[33] IOA, 2013. *A good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise*. Institute of Acoustics. [URL]
[34] Achieving the Government's 2050 'Net Zero' target will require increases in renewable electricity generation, which entails an increase in deployment across a range of technologies, including onshore wind. The Government's 2020 Energy White Paper: *Powering our net zero future* stated that sustained growth in the capacity of onshore wind will be needed over the next decade, alongside solar and offshore wind generation capacity.

1.1.1 BEIS RESEARCH QUESTIONS

The research questions motivating the project include:

- *Do contemporary acoustic measurement methodologies challenge those that are used in ETSU-R-97?*
- *Do modern onshore wind turbines (composite blades, gearless transmission) emit more, less, or different characteristics of noise that ETSU-R-97 guidance does not currently account for?*
- *Do any changes in the way more modern turbines are sited in newer wind farms result in more, less or different cumulative noise levels, both within the wind farm and also where these newer wind farms are located in proximity to other wind farms?*
- *Do modern onshore wind turbines produce excessive AM, to what extent, and to what effect?*
- *Is there evidence of the need for a more comprehensive measurement campaign for AM from new turbine types?*
- *Does the extent of AM change as turbines get older or suffer more wear and tear?*
- *Do international comparisons suggest that ETSU-R-97 guidance, methodologies and ratings are not up to date, or can be adapted?*
- *Taking the above into account, should BEIS consider refreshing ETSU-R-97 guidance and, if so, how?*

The study findings in response to these questions are addressed in section 6.5.

1.1.2 PROJECT SCOPE AND AIMS

The project has sought information relevant to the research questions within three workstreams:

1. Evidence review (detailed in section 3)
2. Stakeholder engagement (detailed in section 4)
3. Field measurements (detailed in section 5)

The project addresses airborne sound from onshore commercial wind turbines. Domestic, small, micro and offshore turbines are not considered.

The primary aim of the project is to make a recommendation on whether, in view of government policies on noise and Net Zero, and available evidence, the existing guidance requires updating, and, if so, which aspects need to be updated. The actual work of developing new guidance is outside the scope of the project.

In addressing the primary aim, project objectives comprise:

- providing a robust evidence-based platform from which to make a decision on the necessity of any future guidance development
- informing the directions that any such guidance development might need to take
- identifying knowledge gaps that may require further investigation or research

1.2 DOCUMENT PURPOSE AND SCOPE

This report documents the project methodology, the findings drawn from each of the workstreams, and makes recommendations on the basis of the evidence identified.

Key technical concepts that are referred to throughout the report are outlined in section 2, alongside a summary outline of the assessment approach defined in the guidance under review, ie, ETSU-R-97 and the IOA GPG.

This report is a necessarily technical document and, while efforts have been made to avoid unnecessary jargon, technical terminology is used throughout. A glossary can be found in Appendix A, and a list of Abbreviations is included in the report front matter.

1.3 POLICY CONTEXT

Policies on noise, energy, planning and the environment are devolved responsibilities in the UK, with each administration maintaining policy and guidance frameworks within which national and local plans and planning decisions are made.

1.3.1 ENGLAND

Figure 1-1 illustrates the relevant policy context for England.

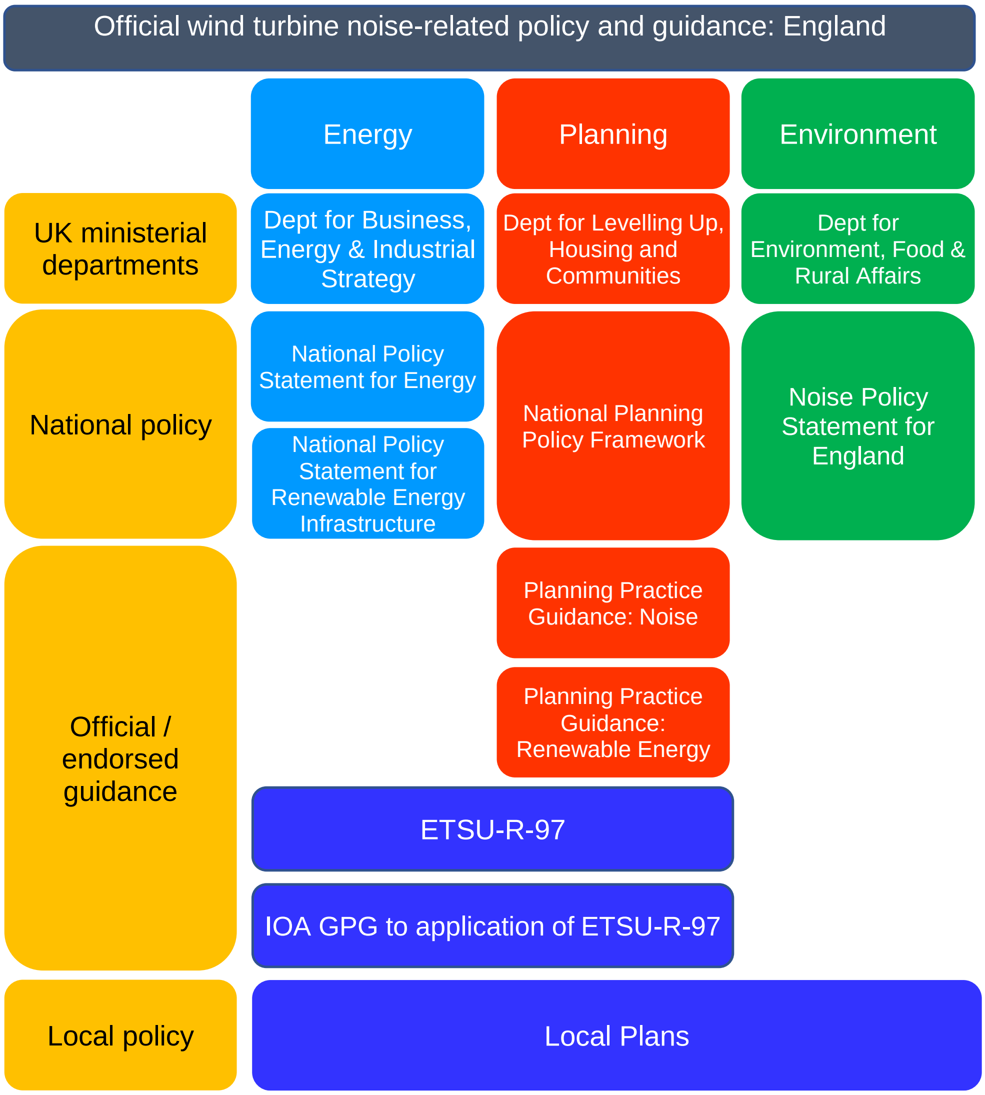


Figure 1-1: Policy map for England

The 2011 *Overarching National Policy Statement* (NPS) *for Energy* (EN-1)[35] recognises that noise can impact on quality of life, health and amenity, and highlights that Government policy on noise is

[35] DECC, 2011. *Overarching national policy statement for energy (EN-1)*. Department of Energy and Climate Change. [URL]

set out in the 2010 *Noise Policy Statement for England* (NPSE)[36]. The NPSE is a Defra policy statement that sets out the overall vision and aims of government policy on noise management, and is applicable across a wide range of sources, encompassing transport, industry, commerce, construction and domestic noise, as discussed further below.

NPS EN-1 also notes that applicants should seek guidance on assessment in the relevant technology-specific NPSs. NPS EN-3: *Renewable Energy Infrastructure*[37] advised that, for wind turbine projects in England with a generation capacity >50 MW, ETSU-R-97 should be applied in noise assessments, while taking account of current industry good practice. The 50 MW criterion was connected with a legislative distinction made between projects with generating capacity ≤50 MW that were considered by local planning authorities under the *Town and Country Planning Act 1990*[38], and those >50 MW, considered by the Secretary of State as nationally significant infrastructure projects (NSIPs) under the enacted version of the *Planning Act 2008*[39]. This distinction has now been removed in a revision to the *Planning Act 2008*[40], with the effect that all wind energy projects are considered by local planning authorities under the *Town and Country Planning Act 1990*.

In addition to highlighting ETSU-R-97, NPS EN-3 confirms that any successor guidance or supplementary advice endorsed by the Government should be applied.

The *National Planning Policy Framework* (NPPF, updated in 2021[41]), which is a DLUHC[42] policy document, echoes the NPSE noise management principles as applied to development planning.

The NPSE principles are also supported by further practice guidance in the online *Planning Practice Guidance* (PPG): *Noise* (last updated 2019[43]).

The online PPG: *Renewables and low carbon energy* (last updated June 2015[44]) confirms that ETSU-R-97 should continue to be used by planning authorities for assessing noise from wind energy developments, and endorses the IOA GPG as supplementary best practice.

Key concepts set out in these policies and supporting guidance are discussed further below.

Observed effects levels

The NPSE introduced the application of an existing concept (borrowed from toxicology) of 'observed effects levels' to the potential adverse effects associated with non-occupational sound exposure. Observed effects levels represent the sound exposure threshold values above which specific health outcomes or behavioural responses to noise are expected to occur.

There are two thresholds that are considered key to the aims of the NPSE, which are:

- the lowest observed adverse effects level (LOAEL):
  - This is the threshold above which adverse effects on health and quality of life can be detected.

[36] Defra, 2010. *Noise policy statement for England*. Department for the Environment, Food & Rural Affairs. [URL]
[37] DECC, 2011. *National policy statement for renewable energy infrastructure (EN-3)*. Department of Energy and Climate Change [URL]
[38] *Town and Country Planning Act 1990*. [URL]
[39] *Planning Act 2008*. (As enacted). [URL]
[40] *Planning Act 2008*. [URL]
[41] MHCLG, 2021. *National planning policy framework*. Ministry of Housing, Communities & Local Government. [URL]
[42] Department for Levelling Up, Housing and Communities – previously the MHCLG (see Abbreviations), renamed in 2021
[43] MHCLG, 2019. *Planning practice guidance: Noise*. Ministry of Housing, Communities & Local Government. [URL]
[44] DCLG, 2015. *Planning practice guidance: Renewable and low carbon energy*. Department for Communities and Local Government. [URL]

- One aim of the NPSE is to 'mitigate and minimise' adverse effects on health and quality of life (which means noise impacts exceeding the LOAEL), within the context of policy on sustainable development.

- the significant observed adverse effects level (SOAEL):
  - This is the threshold above which significant adverse effects on health and quality of life occur.
  - Another aim of the NPSE is to 'avoid' significant adverse effects (which means noise impacts above the SOAEL), within the context of policy on sustainable development.

Observed effects levels offer a framework on which risk-based assessments of noise impacts can be made. The meaning of 'adverse effects' and 'significant adverse effects' is illustrated using examples of potential health outcomes and behavioural responses in the PPG: *Noise* guidance[43], which includes an 'exposure hierarchy' based on the expected 'average response of those affected', as shown in Table 1-1.

Table 1-1: Observed effects levels examples – PPG: *Noise* (2019[43]), exposure hierarchy

Response	Examples of outcomes	Increasing effect level	Action
No observed effect level			
Present and not intrusive	No effect	No observed effect	No specific measures required
No observed adverse effect level			
Present and not intrusive	Noise can be heard, but does not cause any change in behaviour, attitude or other physiological response. Can slightly affect the acoustic character of the area but not such that there is a change in the quality of life.	No observed adverse effect	No specific measures required
Lowest observed adverse effect level			
Present and intrusive	Noise can be heard and causes small changes in behaviour, attitude or other physiological response, eg turning up volume of television; speaking more loudly; where there is no alternative ventilation, having to close windows for some of the time because of the noise. Potential for some reported sleep disturbance. Affects the acoustic character of the area such that there is a small actual or perceived change in the quality of life.	Observed adverse effect	Mitigate and reduce to a minimum (within the context of policy on sustainable development)

wsp

Response	Examples of outcomes	Increasing effect level	Action
Significant observed adverse effect level			
Present and disruptive	The noise causes a material change in behaviour, attitude or other physiological response, eg avoiding certain activities during periods of intrusion; where there is no alternative ventilation, having to keep windows closed most of the time because of the noise. Potential for sleep disturbance resulting in difficulty in getting to sleep, premature awakening and difficulty in getting back to sleep. Quality of life diminished due to change in acoustic character of the area.	Significant observed adverse effect	Avoid (within the context of policy on sustainable development)
Present and very disruptive	Extensive and regular changes in behaviour, attitude or other physiological response and/or an inability to mitigate effect of noise leading to psychological stress, eg regular sleep deprivation/awakening; loss of appetite, significant, medically definable harm, eg auditory and non-auditory.	Unacceptable adverse effect	Prevent

In practice, the concept, interpretation, and application of observed effects levels to noise can be complicated. Complicating factors include consideration of the required representation within the population for an effect to be considered 'observed'. For example, the WHO confirmed in 2018[45] that the 2009 WHO *Night Noise Guidelines for Europe*[46] were intended to represent LOAELs that protected the whole population, including ("*to an extent*") especially vulnerable groups, and some of these values have subsequently been adopted as LOAELs in UK infrastructure technical guidance (eg, National Highways LA111 *Noise and Vibration*[47]). By contrast, in 2017, the Department for Transport consulted on proposals to update UK airspace policies, which proposed higher LOAEL threshold values, and took the stated position that LOAELs can be regarded as the onset of adverse effects on a community basis, suggesting a broader application of the concept to the population[48]. The hierarchy in Table 1-1 does not indicate what proportion of people would be expected to exhibit each outcome for the designated response to be deemed to apply – as discussed in sections 3 and 6, there is a wide range of sensitivity in human responses to sound exposure, which complicates setting a criterion for acceptability.

Complicating factors also include the acoustical, personal and contextual influences on the observed response, which are not necessarily reflected by a single 'level' value. Some examples of these factors are explicitly recognised in the PPG: *Noise*, such as sound character, patterns of occurrence, added noise impacts from other sources in the area, and the general residual sound environment (see Appendix A). These factors mean that identifying a single threshold value for a particular type of sound source that reliably maps to the descriptions of behavioural responses and health

[45] World Health Organization Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region.* [URL]
[46] WHO Regional Office for Europe, 2009. *Night noise guidelines for Europe*. World Health Organization. [URL]
[47] *Design Manual for Roads and Bridges LA111: Noise and vibration*. National Highways. [URL]
[48] Department for Transport, 2017. *UK airspace policy: A framework for balanced decisions on the design and use of airspace*. [URL]

outcomes that underpin the framework across different contexts and communities may be unrealistic.

These issues could be addressed from the perspective of technical guidance by deciding what representation is appropriate within the context of the policies being supported, which is discussed further in section 6.

Observed effect levels also form part of the *Noise Policy Statement for Northern Ireland* (NPSNI)[49], as outlined in section 1.3.3.

Sustainable Development

The NPSE sets out a vision and a set of aims for noise policy in England, clarified with the underpinning caveat that these all have regard to and context within the UK principles of 'sustainable development'. These principles are defined in the NPSE as:

- **Ensuring a Strong Healthy and Just Society**: Meeting the diverse needs of all people in existing and future communities, promoting personal wellbeing, social cohesion and inclusion, and creating equal opportunity for all.
- **Using Sound Science Responsibly**: Ensuring policy is developed and implemented on the basis of strong scientific evidence, while taking into account scientific uncertainty (through the precautionary principle) as well as public attitudes and values.
- **Living Within Environmental Limits**: Respecting the limits of the planet's environment, resources and biodiversity – to improve our environment and ensure that the natural resources needed for life are unimpaired and remain so for future generations.
- **Achieving a Sustainable Economy**: Building a strong, stable and sustainable economy which provides prosperity and opportunities for all, and in which environmental and social costs fall on those who impose them (polluter pays), and efficient resource use is incentivised.
- **Promoting Good Governance**: Actively promoting effective, participative systems of governance in all levels of society – engaging people's creativity, energy and diversity.

The NPSE and the PPG: *Noise* confirm that policy on noise in England does not direct that adverse effects are to be prevented at all costs; it is made clear that some adverse effects may be acceptable, provided that reasonable steps have been taken to reduce the effects, and that such mitigating measures are reasonable and sustainable.

1.3.2 WALES

Figure 1-2 illustrates the relevant policy context for Wales.

In Wales, the national high-level plans and policies are detailed in Edition 11 of *Planning Policy Wales* (PPW, 2021)[50] and the *Future Wales 2040 National Plan* (2021)[51].

PPW advises that guidance on wind turbine noise assessment is found in ETSU-R-97 and the IOA GPG. The PPW framework addresses renewable energy development planning with a presumption in favour of wind energy 'Developments of National Significance' (DNSs, defined as an installed generation capacity of ≥10 MW) within the 'Pre-Assessed Areas for Wind Energy' defined in the *Future Wales 2040 National Plan*. The PPW publication coincided with the withdrawal of the

[49] DAERA, 2014. *Noise Policy Statement for Northern Ireland*. Department of Agriculture, Environment and Rural Affairs. [URL]
[50] Welsh Government, 2021. *Planning Policy Wales*. Edition 11. [URL]
[51] Welsh Government, 2021. *Future Wales 2040: The National Plan*. [URL]

previous 2005 *Technical Advice Note* (TAN) *8: Planning for Renewable Energy*[52] document (which also referred to ESTU-R-97, but preceded the IOA GPG).

The *Future Wales 2040 National Plan* sets out the strategic spatial policies, including defining the Pre-Assessed Areas for Wind Energy, within which the presumption in favour of wind energy DNSs is subject to demonstration that (among other things) developments will not have 'unacceptable adverse impacts' due to noise.

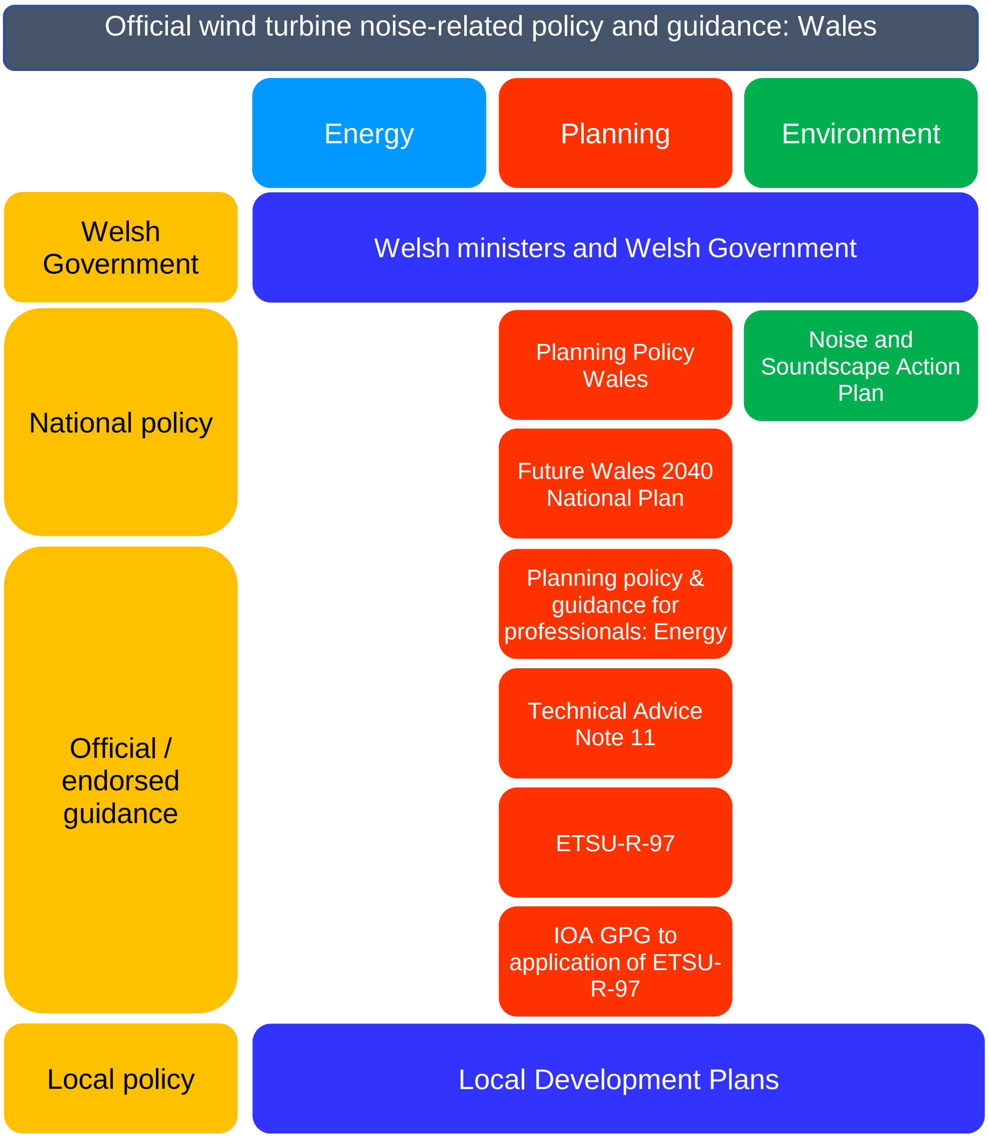


Figure 1-2: Policy map for Wales

The Welsh Government *Noise and Soundscape Action Plan 2018-2023* (2018)[53] is in part intended to discharge legislative obligations to make action plans for reducing transportation noise, but the TAN 11 (discussed below) review consultation document also confirms that the Plan is "*the central noise policy document in Wales*"[54]. As well as transportation, it does cover industrial sound

[52] Welsh Assembly Government, 2005. *Planning Policy Wales Technical Advice Note 8: Planning for renewable energy*. [URL]
[53] Welsh Government, 2018. *Noise and Soundscape Action Plan 2018-2023*. [URL]
[54] Welsh Government, 2020. *Consultation document: Call for evidence: Review of Technical Advice Note 11 Noise, to incorporate air quality and soundscape*. WG 40017. [URL]

emissions and noise impacts, noting that BS 4142[55] is commonly applied in assessing adverse impacts of industrial noise – at present however, the Plan does not specifically address wind energy developments. The Plan refers to the application of concepts defined in the *Well-being of Future Generations (Wales) Act 2015*[56] (WFG Act) to noise and soundscape. In particular, the principle of sustainable development, which is defined as acting "*in a manner which seeks to ensure that the needs of the present are met without compromising the ability of future generations to meet their own needs*". The Plan also outlines the manner in which noise and soundscape management should be carried out, in the context of the WFG Act legislation:

- *pursuing long-term, enduring solutions to any existing instances of noise nuisance*
- *seeking to manage noise and soundscapes at the same time as achieving other, related outcomes*
- *taking opportunities to talk to the public about the challenges associated with exposure to noise and unhealthy soundscapes, listen to their concerns and seek their views on potential solutions and their involvement in delivering them*
- *working actively with internal and external partners to mutual benefit in the delivery of desired outcomes*
- *keeping exposure to noise (that is, unwanted or harmful sound) as low as reasonably practicable across the whole of the population, looking out in particular for areas where noise levels might qualify as a statutory nuisance or noise action planning priority area, or where public amenity might be adversely affected by noise at some point in the future, and acting pre-emptively to prevent those things from happening*

The 1997 TAN 11: *Noise*[57] provides general technical guidance on noise assessment that is largely based on the withdrawn *Planning Policy Guidance 24*[58], and refers to (the withdrawn) TAN 8[52] for guidance on wind turbine noise. TAN 11 is currently under review, with the stated commitment to replace it with a new TAN addressing air quality and soundscape alongside noise[59,60]. In 2015, Welsh Government issued a letter to local planning authorities advising that the TAN 11 guidance be amended to reference later versions of standards and guidance documents[61]. This letter included a reiteration of the Welsh Government endorsement of the IOA GPG, and also highlighted the subsequent publication of the SGNs.

The online *Planning policy and guidance for professionals: Energy*[62] advises that the use of the IOA GPG for assessing wind turbine noise is encouraged.

High-level guidance for local authorities is also found in the PG(W)(17) *Local Air Quality Management in Wales Policy Guidance* (2017)[63], which does not specifically address noise from wind energy development.

[55] BSi, 2019. *BS 4142:2014+A1:2019 Methods for rating and assessing industrial and commercial sound*. British Standards Institution. [URL]
[56] *Well-being of Future Generations (Wales) Act 2015*. [URL]
[57] Welsh Assembly Government, 1997. *Planning guidance (Wales), Technical Advice Note 11, Noise*. [URL]
[58] ODPM, 1994. *Planning Policy Guidance 24: Planning and noise*. Office of the Deputy Prime Minister. [URL]
[59] Welsh Government, 2020. *Consultation document*: *Call for evidence: Review of Technical Advice Note 11 Noise, to incorporate air quality and soundscape*. WG 40017. [URL]
[60] During the preparation of this report, the Welsh Government opened a consultation on a draft version of the revised TAN 11, the proposed content of which has not been considered within the scope of the present study. [URL]
[61] Welsh Government, 2015. *Updates to technical advice note (TAN) 11 on noise (CL-01-15)*. [URL]
[62] Welsh Government, (no date). *Planning policy and guidance for professionals: Energy*. [URL]
[63] Welsh Government, 2017. *Local air quality management in Wales: Policy guidance*. PG(W)(17). [URL]

The Welsh Government policy context is complicated by the fact that it currently has in place a technical noise guidance document (TAN 11) that is relatively old (compared with the equivalent guidance documents for the other devolved administrations) and has been identified for replacement in the near future[64]. The emphasis on 'soundscape' in the wider Welsh Government policy framework indicates the updated TAN 11 will include guidance addressing this aspect, and it is not yet clear what implications this approach may have for future assessment and management of wind turbine noise impact in Wales[60].

1.3.3 NORTHERN IRELAND

Figure 1-3 illustrates the relevant policy context for Northern Ireland.

Figure 1-3: Policy map for Northern Ireland

In Northern Ireland, the *Strategic Planning Policy Statement* (SPPS) published in 2015[65,66] provides strategic planning policy for a range of subject matters, including renewable energy. The SPPS

[64] The initial consultation calling for evidence to support the review of TAN 11 ended in 2020. https://gov.wales/air-quality-and-soundscape-review-tan-11
[65] DfI, 2015. *Strategic Planning Policy Statement for Northern Ireland (SPPS): Planning for sustainable development*. Department for Infrastructure. [URL]
[66] In 2021 a review of the 2015 Strategic Planning Policy Statement aspects concerning renewable energy was announced: https://www.infrastructure-ni.gov.uk/news/mallon-gives-green-light-renewable-energy-planning-review

confirms that the policies of the *Planning Policy Statement* (PPS) *18: Renewable Energy* (2009)[67] remain in place (until such times as a Plan Strategy for the whole of the council area has been adopted). The accompanying *Best Practice Guidance to PPS 18* (2009)[68] advises the use of ETSU-R-97 in assessing noise from wind energy developments (having preceded the IOA GPG, which was endorsed by the Northern Ireland Department of the Environment in 2013[69]). These documents also highlight the policy of applying minimum separation distances between turbines and occupied premises to control noise, which contrasts with the less prescribed approach taken in EN-3.

In 2014, Northern Ireland introduced the NPSNI[70], which echoes the NPSE and establishes the same system of effects thresholds, although planning guidance in Northern Ireland does not currently provide the exposure hierarchy examples set out in the England PPG: *Noise*.

1.3.4 SCOTLAND

Figure 1-4 illustrates the relevant policy context for Scotland.

Similarly to the NSIP distinction previously made for onshore wind projects in England, and the current DNS distinction made in Wales, a legislative distinction also remains in place in Scotland under the provisions of the Electricity Act 1989[71]. This directs onshore wind energy developments >50 MW capacity to be considered by Scottish Ministers, a process that is administered by the Scottish Government's Energy Consents Unit.

In Scotland, *Scottish Planning Policy*[72] (published in 2014[73]), and the 2014 *Third National Planning Framework* (NPF3)[74], describe overarching high-level policies that include commentary on noise management[75].

The 2017 *Onshore Wind Policy Statement*[76] mentions the need to avoid significant adverse impact, but noise is not specifically addressed[77].

Noise matters in Scottish development planning are managed on a technical level by way of *Planning Advice Note* (PAN) *1/2011*[78], which is a material consideration in planning decisions. PAN1/2011 provides general advice on the mitigation and avoidance of significant adverse noise impacts during planning. PAN1/2011 also refers to the online guidance *Onshore wind turbines: planning advice* (published in 2014)[79], which advises that ETSU-R-97 and the IOA GPG should be applied to planning-stage assessments, and to the Defra NANR 277 report[80] for assistance in

---

67 Department of the Environment Planning and Environmental Policy Group, 2009. *Planning Policy Statement 18: Renewable energy*. [URL]
68 Department of the Environment Planning and Environmental Policy Group, 2009. *Best practice guidance to Planning Policy Statement 18: Renewable energy*. [URL]
69 IOA, 2014. *Northern Ireland approval for wind turbine guide*. Institute of Acoustics. [URL]
70 DAERA, 2014. *Noise Policy Statement for Northern Ireland*. Department of Agriculture, Environment and Rural Affairs. [URL]
71 *Electricity Act 1989*. [URL]
72 Scottish Government, 2014. *Scottish Planning Policy*. [URL]
73 At the time of preparing this report, the 2020 update to the SPP had been withdrawn for legal reasons, returning the SPP to its 2014 version.
74 Scottish Government, 2014. *Scotland's Third National Planning Framework*. [URL]
75 At the time of preparing this report, the Scottish Government is in the process of developing a new National Planning Framework 4 (NPF4), which is intended to replace both the NPF3 and the SPP in 2022, and will form part of the statutory development plan. transformingplanning.scot/national-planning-framework
76 Scottish Government, 2017. *Onshore wind policy statement*. [URL]
77 In 2021, the Scottish Government published a consultative draft seeking views on refreshing the Onshore Wind Policy Statement: https://www.gov.scot/publications/onshore-wind-policy-statement-refresh-2021-consultative-draft/
78 Scottish Government, 2011. *Planning Advice Note PAN1/2011: Planning and noise*. [URL]
79 Scottish Government, 2014. *Onshore wind turbines: planning advice*. [URL]
80 AECOM, 2011. *Wind farm noise statutory nuisance complaint methodology*. Contract no. NANR 277. Department for Environment, Food & Rural Affairs. [URL]

statutory nuisance cases. A further reference is made to the guidance in the 2011 TAN: *Assessment of noise* (owned by the Environment and Forestry Directorate)[81], which provides general advice on noise assessments, not specific to wind energy development.

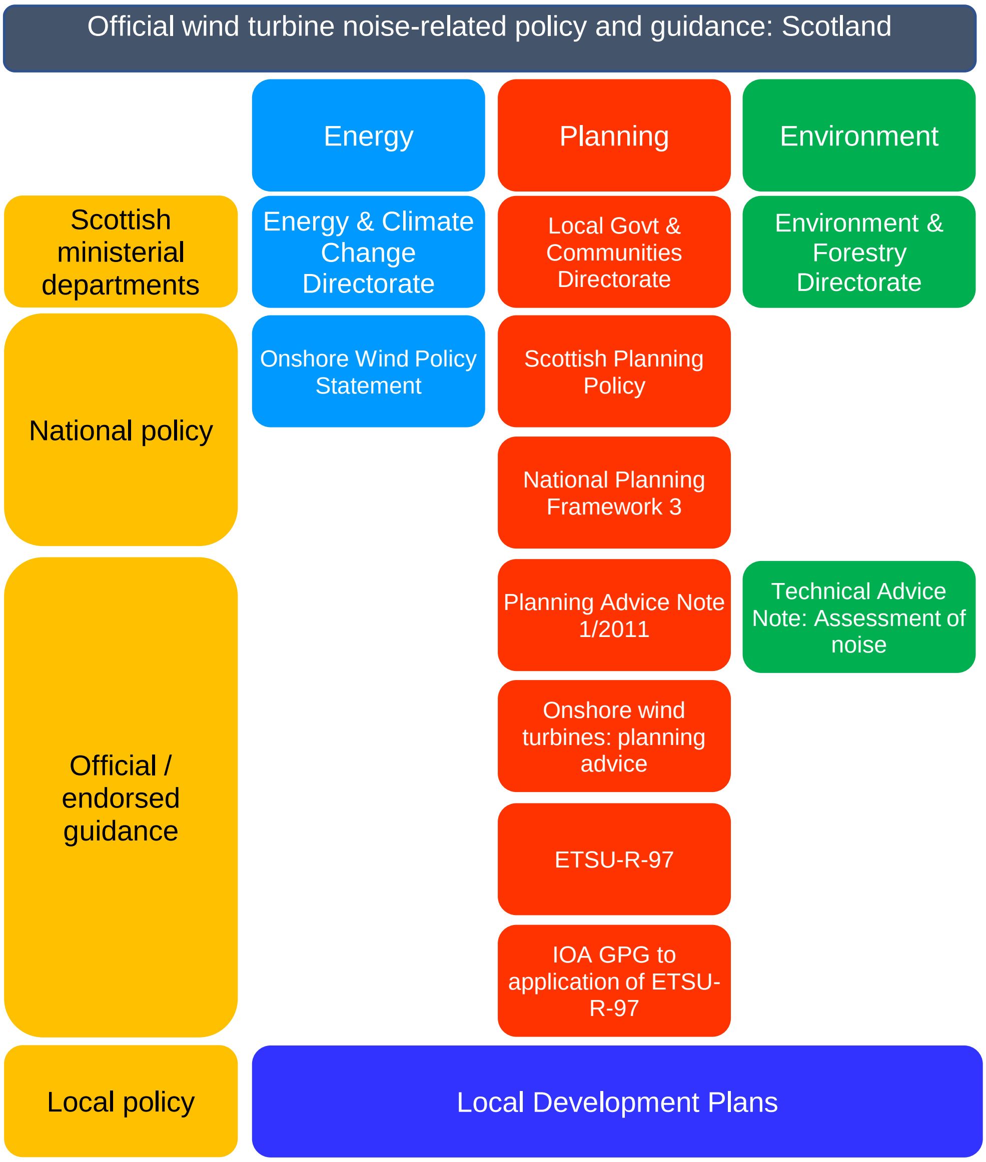


Figure 1-4: Policy map for Scotland

The TAN guidance sets out a framework for assessing noise impacts, which indicates that assessments should comprise quantitative and qualitative stages to determine the overall significance of any effects. The quantitative assessment guidance follows an approach based on identifying effects significance, which would differ from the pass/fail approach of ETSU-R-97. However, since the directive under the *Onshore wind turbines: planning advice* is towards ETSU-R-97, the TAN approach is not generally applied in practice to wind energy developments.

Under the TAN qualitative assessment guidance, an example table of descriptors for residential impact is provided that is very similar to the observed effects classifications provided in the later

[81] Scottish Government, 2011. *Assessment of noise: technical advice note*. [URL]

PPG: *Noise* for England (see Table 1-1). In a set of examples provided in the section entitled "*Appropriate noise impact assessment methodology*", the TAN guidance clarifies that the qualitative assessment is only necessary if it is thought that the quantitative assessment does not adequately address the noise impacts. In practice, it is unusual (in our experience, and according to a research study of wind turbine noise assessments in Scotland[82]) for assessments of wind energy developments to include qualitative assessments in addition to the ETSU-R-97 and IOA GPG quantitative assessment. This suggests that assessors typically consider the quantitative assessment to adequately address noise impacts from wind energy developments.

1.3.5 NET ZERO

In 2019, the UK government amended the *Climate Change Act 2008*[83] to include a target for UK greenhouse gas emissions to be reduced 100% by 2050. This commitment is described in this report as 'Net Zero'.

The *Climate Change (Emissions Reduction Targets) (Scotland) Act 2019*[84] commits Scotland to achieving net zero greenhouse gas emissions by 2045, with two interim targets to reduce emissions by 75% by 2030 and 90% by 2040.

1.3.6 POLICY OBJECTIVE

The policy objective underpinning this research is to ensure that wind turbine planning guidance supports decision-making that is consistent with the policy framework for noise and Net Zero.

[82] SLR & Hoare Lea, 2015. *Wind Farm Impacts Study: Review of the visual, shadow flicker and noise impacts of onshore wind farms.* Final report: 405.04528.00001. ClimateXChange. [URL]
[83] *Climate Change Act 2008*. [URL]
[84] *Climate Change (Emissions Reduction Targets) (Scotland) Act 2019*. [URL]

2

WIND TURBINE ACOUSTICS OVERVIEW

2 WIND TURBINE ACOUSTICS OVERVIEW

This section provides a brief outline of key technical concepts that are addressed throughout this report. A glossary of technical terms is also included in Appendix A, and a list of Abbreviations can be found in the report front matter.

2.1 GENERAL TECHNICAL CONCEPTS

2.1.1 SOUND, NOISE AND SOUNDSCAPE

Sound is mechanical vibrations in the air transmitted as waves of sound energy. An acoustic environment is made up of the sounds from all sources that contribute to the total sound at a given location. Sound pressure is measured as Pascals (force per area), but usually expressed in decibels, which is a ratio of sound energy against a magnitude that is only just above the normal threshold of human hearing.

'Noise' is used to describe a sound that is considered undesirable in the acoustic environment, which requires a subjective judgement. Some people consider wind turbine sound to be noise, especially in and around domestic environments. This report typically uses the word noise only where it is clear that a judgement about the sound being unwanted is made, or that the sound is likely to be judged negatively, eg: noise annoyance, noise mitigation, noise control, noise limit etc. It does not apply the word noise when describing objective aspects of sound, such as sound source, sound level, sound measurements, sound propagation etc.

Soundscape is a sub-discipline within acoustics as well as a technical concept: ISO 12913-1[85] defines the concept as the "*acoustic environment as perceived or experienced and/or understood by a person or people, in context*". Soundscape is not directly addressed in ETSU-R-97, but has emerged in recent Welsh Government planning policies (see section 1.3.2). It is only briefly touched upon in this report, which focusses on the noise control approach that is defined in ETSU-R-97 and addressed in the policies of the other devolved administrations.

2.1.2 SOUND EXPOSURE INDICES

Energy time-average sound level and percentile sound levels

There are numerous sound level exposure indices used for a variety of different purposes. The ones most relevant to this report are outlined below:

- The energy time-averaged sound level $L_{eq,T}$ – this index sums all the sound energy in a given time period T, and averages it over the length of the period. It is commonplace to omit the 'T' if the duration is irrelevant to the value denoted – this is the case when a source is assumed to have a sound power that is effectively invariant over time, as is often the case with wind turbine sound level predictions, for example.
- The Nth percentile sound levels $L_{(100\text{-}N)}$ – this family of indices is based on statistical analysis of the cumulative distribution function of the measured sound pressure levels. The most important index within this family for this study is the L_{90}, which is the 10th percentile of the cumulative distribution function of the measured sound levels (90% of the measured levels exceed the 10th

[85] ISO, 2014. *ISO 12913-1:2014 Acoustics – Soundscape – Part 1: Definition and conceptual framework*. International Organization for Standardization. [URL]

percentile, which is why the '90' is used in the level descriptor subscript). This index is a low-weighted estimate of the level of sound present in a period, and is defined in BS 4142[86] as an indicator for the 'background sound level', as it represents an estimate of the level of steadier sounds that underly other, higher level, fluctuating sounds during a measurement. The L_{90} is used in ETSU-R-97 to represent both background sound and wind turbine sound, due to the difficulties in measuring wind turbine sound that is low in level and close to the level of residual sounds[87] (this is discussed in section 6.2.1).

'A-weighting' of frequency spectra

The 'A weighting' function is commonly applied to the measurements made of environmental sounds affecting humans, which is designed to represent the non-linearity of the frequency response of the hearing system (ie, the ear sensitivity to sounds of different pitch). The main benefit of this weighting is that it enables a single number to approximately represent the perceived loudness of a wide range of sounds. Levels that have A-weighting applied include the descriptor, eg L_{Aeq}, L_{A90} etc.

A common misapprehension is that A-weighting only corresponds with the frequency response of the hearing system for relatively quiet sounds. This is for historical reasons concerning the original development of A-weighting from early 'equal loudness contours', but contemporary measurements of equal loudness demonstrate this notion is inaccurate[88,89].

At frequencies below 20 Hz (often referred to as the 'infrasonic' frequency range), A-weighting does not closely follow the shape of equal loudness curves[90], but (as discussed in section 3.5.1) this range is generally not of great importance for the perception of wind turbine sound.

Fast time weighting

A further weighting commonly applied to measured sound pressure levels is 'time weighting'. When sound pressure levels are sampled at short intervals (eg, <1s), it is common practice to apply a time weighting in the averaging process, which effectively applies a 'smoothing' function to measured levels. The most relevant time weighting for wind turbine sound measurements is known as 'Fast' time weighting, which is again indicated in the level descriptor by 'F', eg L_{AF90}, L_{AFmax} etc. The Fast time weighting has a value of 125 ms, which is intended to approximate the response time of the human ear to the full sensation of loudness (typically in the range of around 100-150 ms, eg[91]).

The effect of the time weighting is illustrated in Figure 2-1, which shows sound level time series over a short period quantified using time-averaged and time-weighted indices, and also includes the 'Slow'-weighted signal (denoted 'S', with a weighting value of 1 second) for comparison; the longer the time-weighting constant, the more the signal is 'smoothed'.

The effect of time weighting has an important implication for measurements of amplitude modulation in wind turbine sound: since time weighting smooths out peaks and troughs in the sound level time series, the modulation depth (ie, the range between 'peaks' and 'troughs' in the sound level, described further below) derived from time-weighted sound level time series is generally smaller

[86] BSi, 2019. *BS 4142:2014+A1:2019 Methods for rating and assessing industrial and commercial sound*. British Standards Institution. [URL]
[87] See glossary in Appendix A
[88] ISO, 2003. *ISO 226: 2003 Acoustics – Normal equal-loudness-level contours.* International Organization for Standardization. [URL]
[89] Yokoyama, S, Sakamoto, S, Tsujimura, S, Kobayashi, T & Tachibana, H, 2015. Loudness experiment on general environmental noises considering low-frequency components down to infrasound. *Acoustical Science and Technology*, 36 (1), 24-30. [URL]
[90] Alamir, MA, Hansen, KL & Catcheside, P, 2021. Penalties applied to wind farm noise: Current allowable limits, influencing factors, and their development. *Journal of Cleaner Production*, 295 (2021). [URL]
[91] Fastl, H & Zwicker, E, 2007. *Psychoacoustics: Facts and models*. Springer-Verlag.

than that derived from the energy time-averaged sound level time series. Methods for measuring AM in wind turbine sound are reviewed in section 3.5.1.

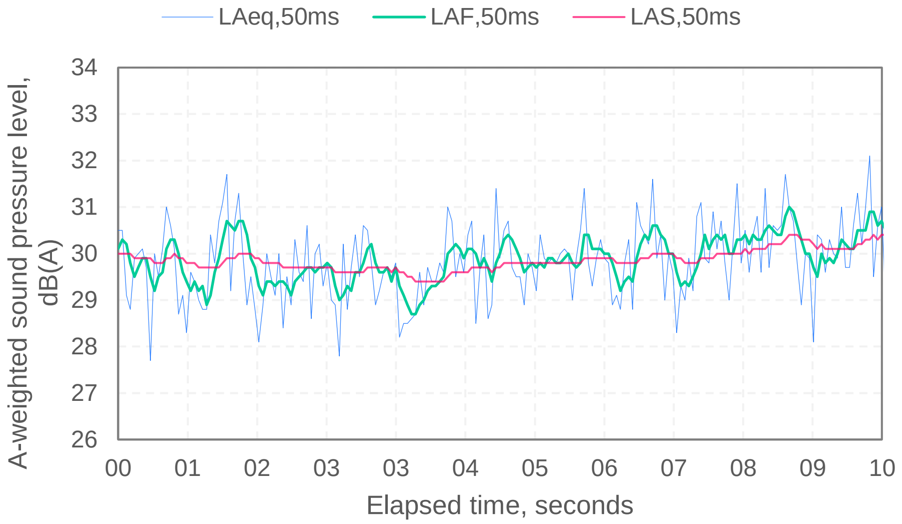


Figure 2-1: Example of time weighting in sound level time series (L_{AF}: Fast weighted with 125 ms weighting; L_{AS}: Slow weighted with 1 s weighting); NB: each time series is evaluated at 50 ms intervals

Loudness

Loudness is the perception of 'subjective intensity' of sound. Loudness is influenced by the total sound energy, but also by the frequency content and the structure of the sound over time.

It is commonly stated that a change in sound level of 10 dB is approximately equivalent to a doubling or halving of (subjective) loudness. This is based on the application of 'Stevens' power law', which describes the change in subjective loudness as proportional to exponential sound intensity. However, this convenient relationship only applies to sounds with sufficient energy; low intensity sounds do not follow the '10 dB: 2×loudness' relationship, and perceived loudness changes at a greater rate for quieter sounds[92]; in other words, a 10 dB change in quieter sounds may correspond with a greater than doubling or halving in subjective loudness.

Models for the loudness sensation have been proposed, which have enabled loudness measurement indices to be developed. However, these are not necessarily more effective in describing loudness than conventional sound level indices. For example, in the case of wind turbine sound, it has been shown that the A-weighted sound level is a more reliable indicator of subjective loudness than standardised 'loudness level' indices[89].

Sound level distribution and index hierarchy

A range of sound level indices calculated for a short sound level measurement is shown in Figure 2-2, which illustrates the hierarchy for the statistical percentile levels.

[92] Gelfand, SA, 2010. Hearing: *An introduction to psychological and physiological acoustics*. 5th edition. Informa Healthcare.

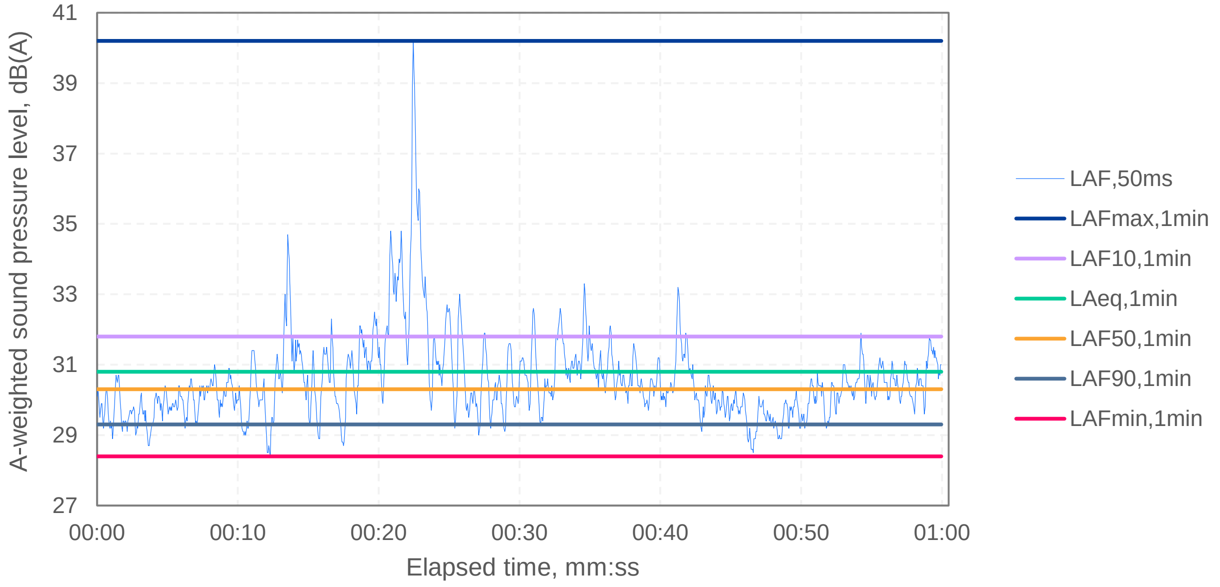


Figure 2-2: Illustrative example of sound level measurement indices

The distribution of the measured sound levels shown in Figure 2-2 is shown in Figure 2-3, which further illustrates the hierarchy of the statistical percentile levels and the manner in which these are determined from the cumulative distribution.

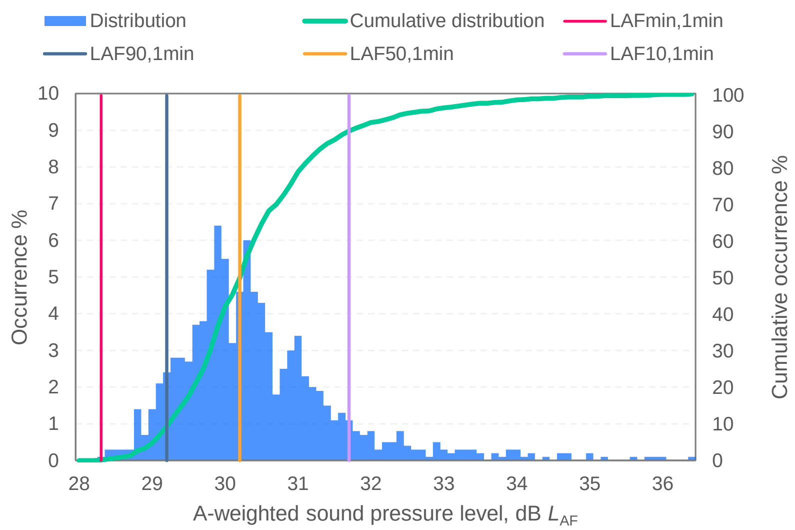


Figure 2-3: Illustrative example of sound level measurement indices: calculation of statistical percentile levels from measurement distribution (L_{AFmax} not shown)

Long-term average period-weighted sound levels

A further class of index relevant to this study is represented by the long-term average period-weighted 'day-evening-night' sound level L_{den} and 'day-night' sound level L_{dn}. These are important because they are used in some of the recent epidemiological studies of wind turbine noise effects, and because L_{den} has been employed by the WHO[93] and by Defra[94] to evaluate monetised health outcomes of sound exposure. They are both based on period-weighted energy time-averaged levels, which are also averaged over a year. The period weightings are intended to represent the sensitivity to noise impact at different times of day, and are expressed as a 'penalty' value added to the corresponding exposure level.

The day-evening-night sound level L_{den} is used more widely in the EU due to its adoption in the 'Environmental Noise Directive'[95], and is defined as the logarithmic average of the L_{day}, the $L_{evening}$ + 5 dB, and the L_{night} + 10 dB. The L_{day}, $L_{evening}$ and L_{night} are the $L_{Aeq,T}$ values for each respective period, averaged over one year, and the periods themselves are allowed to vary slightly depending on national particularities, based on default selections of 0700-1900 hrs, 1900-2300 hrs and 2300-0700 hrs respectively.

The day-night sound level L_{dn} is used more widely in North America, and is similarly defined[96] as the logarithmic average of the L_d, and the L_n + 10 dB, where L_d is the annual average of the daytime $L_{Aeq,0700-2200}$ and L_n is the annual average of the night-time $L_{Aeq,2200-0700}$.

The main advantage of these long-term average period-weighted indices is that they offer a single-figure value representing the overall exposure to a sound source over a relatively long time, weighted by expected sensitivities in different periods – ie, they compress a lot of information into a minimal expression. The disadvantages include (i) that the 'data compression' hides nuance within the index, (ii) the difficulty in predicting and evaluating compliance with long-term averaged levels (which strictly-speaking requires detailed understanding of annual propagation conditions, as affected by complex factors including weather and other variables), and (iii) that the scientific basis for the exposure period weightings is questionable, and can be interpreted as mixing up the objective exposure estimator (the sound level) with subjective response indicators (an expected greater adverse response at certain times of day). On the other hand, in relation to point (iii), it is not uncommon for factors expected to affect subjective responses to sound to be expressed as a numerical 'penalty' – in particular, for sound characteristics, which are discussed in section 2.1.3.

2.1.3 SOUND CHARACTERISTICS

Sound level describes the amount of energy in a sound, but doesn't directly provide any other information about its qualities. Characteristics of sound can have a considerable influence on the way in which people perceive and react to it. The sound characteristics most relevant to this study are referred to as 'amplitude modulation', 'tonality' and 'impulsivity'.

Amplitude modulation

In the context of wind turbine sound, amplitude modulation usually refers to the periodic fluctuation of the broadband aerodynamic sound emitted from the interaction of the rotating blades with the surrounding air. This characteristic of wind turbine sound may be described as 'swishing', 'whoomphing', 'lashing' etc, depending on the sound frequencies that exhibit the largest fluctuations.

---

[93] WHO Regional Office for Europe, 2011. *Burden of disease from environmental noise: Quantification of healthy life years lost in Europe*. World Health Organization. [URL]
[94] Defra, 2014. *Environmental noise: Valuing impacts on: Sleep disturbance, annoyance, hypertension, productivity and quiet*. Department for the Environment, Food & Rural Affairs. [URL]
[95] *Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise - Declaration by the Commission in the Conciliation Committee on the Directive relating to the assessment and management of environmental noise* [URL]
[96] US Environmental Protection Agency Office of Noise Abatement and Control, 1974. *Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety*. 550/9-74-004. [URL]

Amplitude modulation (AM) in wind turbine sound is characterised by the 'modulation depth', and the 'modulation frequency' (f_{AM}), as illustrated in Figure 2-4. The modulation depth is the range between the 'peak' and 'trough' points in the fluctuating sound level, while the modulation frequency represents the number of peaks or troughs within 1 second (and is the reciprocal of the AM period, as indicated in Figure 2-4).

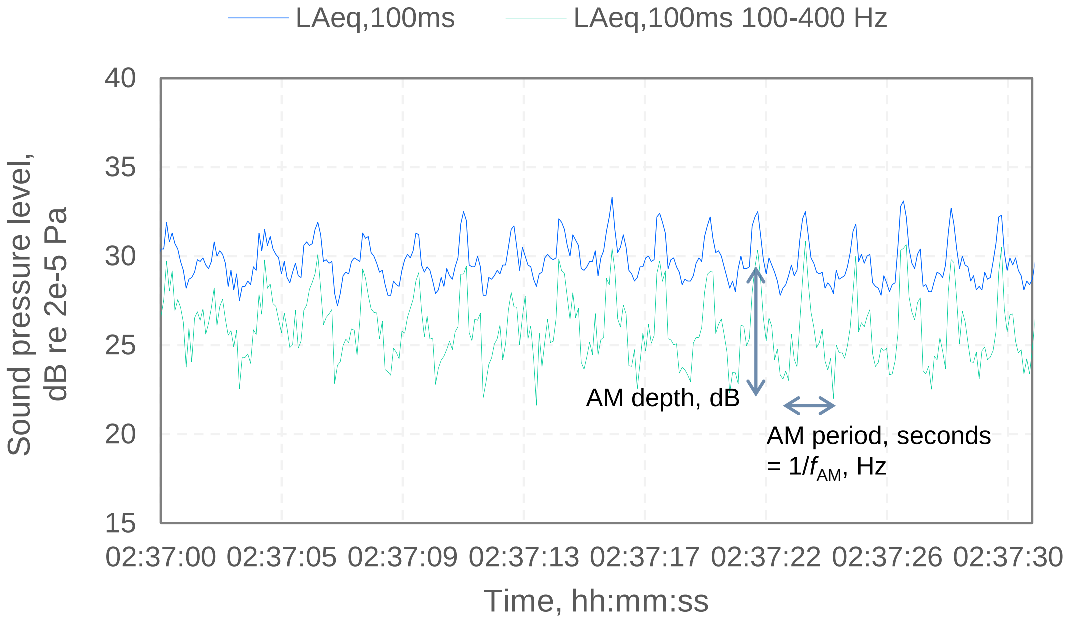


Figure 2-4: Example of wind turbine sound amplitude modulation

Figure 2-4 also illustrates that AM can be lesser or greater in different parts of the frequency spectrum – in this example, the total broadband $L_{Aeq,100ms}$ exhibits smaller modulation depths than the same A-weighted signal, bandpass filtered for the third-octave bands between 100 and 400 Hz. In this case, this is an indication that the modulation would probably not be perceived as a 'swishing' sound, as 'swish' is usually associated with modulation in higher frequency bands, eg 500-1500 Hz.

Tonality

Tonality is a characteristic that is applicable to a wide range of sound descriptions, such as 'humming', 'droning', 'whining', 'whistling', 'buzzing' etc, depending on the frequencies in the sound and its harmonic structure. These sounds are associated with concentrations of energy into very narrow parts of the frequency spectrum, which may include a single tone or multiple tones – tones that are related by integer multiples are harmonics.

An example of audible tones present in wind turbine sound is shown in Figure 2-5, which shows clear tones present at ~390 Hz and ~500 Hz.

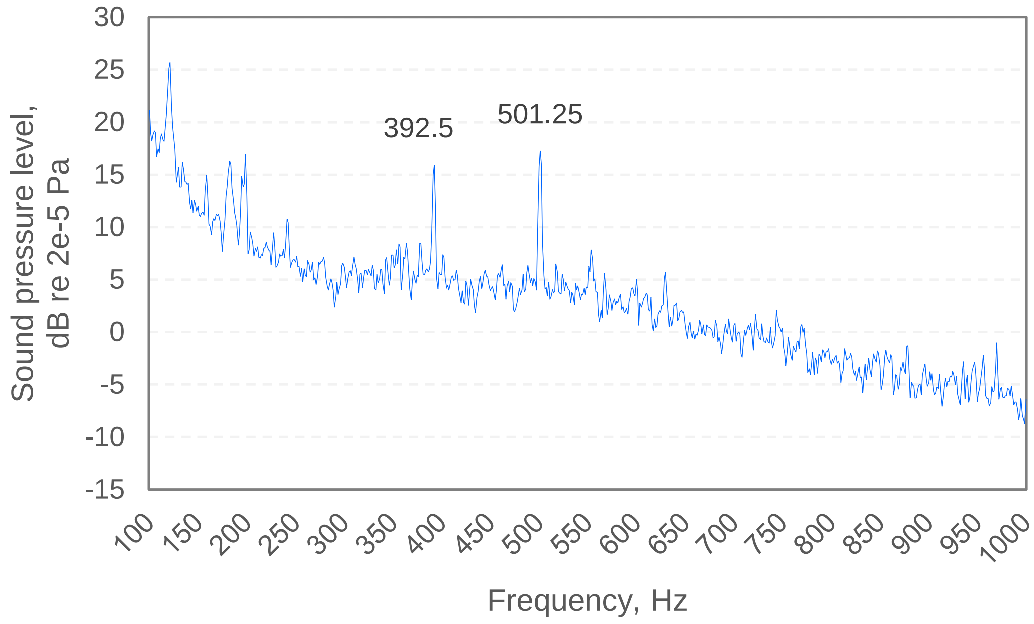


Figure 2-5: Example of wind turbine sound tonality

2.1.4 NOISE LIMITS AND EFFECTS THRESHOLDS

Noise limits usually comprise a numerical value that represents the maximum sound level allowed. There are generally two basic forms of limit: absolute or relative. An **absolute limit** takes a fixed numerical value that is independent of any other factor. A **relative limit** takes a value that depends on the sound level existing in the absence of the source being controlled by the limits.

As detailed further in section 2.3, the ETSU-R-97 approach combines absolute and relative limits into a hybrid regime that imposes a limit dependent on the background sound level in the absence of wind turbine sound. Hybrid noise limit regimes such as used in ETSU-R-97 lead to two further subdivisions of absolute noise limits: minimum ('floor') limits, and maximum ('ceiling') limits. A **minimum limit** is an absolute limit that applies only when the relative limit would otherwise go below a defined value. Conversely, a **maximum limit** is an absolute limit that applies when the relative limit would otherwise exceed a defined value – this is a value that the sound level must not exceed under any circumstances in order to comply with the limiting regime. These definitions are illustrated for a generic context (ie, unrelated to any specific methodology or guidance) in Figure 2-6.

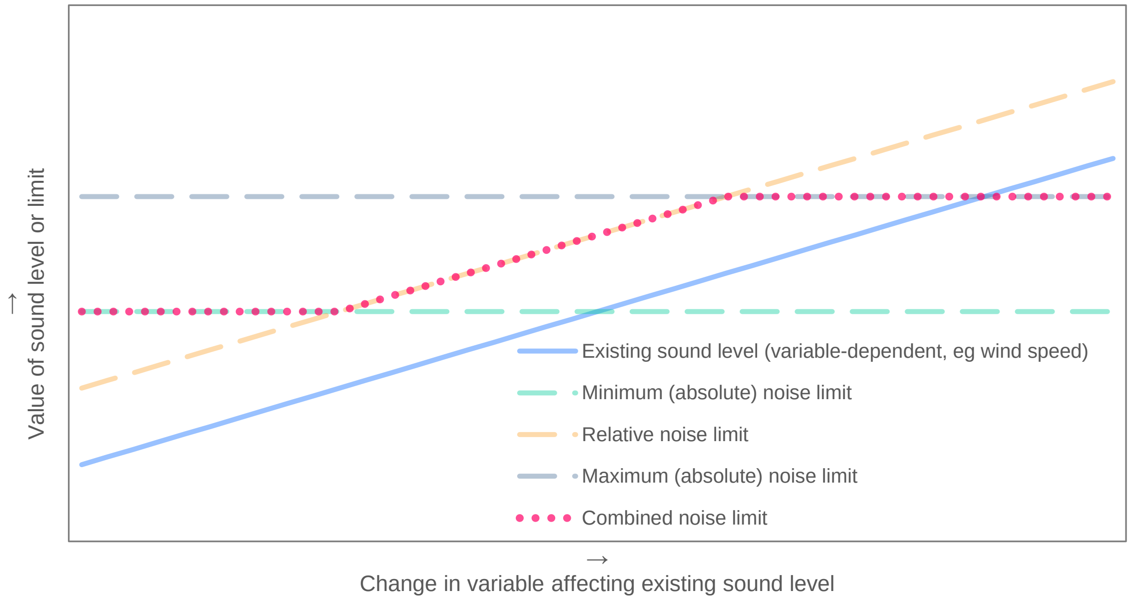


Figure 2-6: Generic example of absolute, relative and combined noise limit regimes

As discussed in section 1.3, some UK policies apply the concept of effects thresholds, which are not necessarily limits, but values above which specified effects are expected to occur or increase in consequence. The magnitude of sound (the sound level or an indicator of its characteristics) with the potential to give rise to an effect can be described as its 'impact'. When impact is considered in relation to the sound levels in the absence of the source under consideration, this can be considered as a 'relative impact'. An example of a methodology that employs relative impact assessment is defined in BS 4142[97] (as discussed further in 6.2.1).

The application of relative impacts in BS 4142 is qualified as potentially becoming less important than consideration of absolute sound levels in situations where residual sound levels are low (this is comparable with the concept of combined minimum and relative noise limits as outlined above. However, BS 4142 is not a 'limit-based' assessment method, but instead is 'impact-based').

2.2 DEVELOPMENTS IN UK WIND TURBINE NOISE ASSESSMENT

The current assessment framework applied in the UK for controlling wind farm noise, ETSU-R-97, was published in 1996. This was developed by a Noise Working Group on the basis of the knowledge and turbine technology at the time.

ETSU-R-97 is a detailed document that investigated and discussed the wind turbine acoustics information then available. It was recognised that some aspects were limited by the state of the knowledge and experience with commercial wind farms at that time. The wind farms described in ETSU-R-97 had turbine rated powers in the range 225-450 kW, with hub heights in the approximate range of ~30-40 m and tip heights ~60-70 m.

After policy adoption of the use of ETSU-R-97, concerns were raised about aspects of turbine noise that had not been well understood at the time of the development of the guidance. Anecdotal experiences of disturbing sound characteristics from wind farms led to formal research. This

[97] BSi, 2019. *BS 4142:2014+A1:2019 Methods for rating and assessing industrial and commercial sound*. British Standards Institution. [URL]

identified the occurrence of amplitude modulation of the aerodynamic sound, especially during the night-time. This phenomenon was attributed mainly to atmospheric effects; primarily the wind shear profile (the variation in wind speed with height above ground), which can be exaggerated by the stable atmospheric conditions more prevalent at night[98]. The wind shear effect is also coupled with well-known propagation effects during temperature inversions, which also leads to downward-refracting sound emissions (sound bending downwards from the turbine towards the ground during propagation through the air). These aspects, combined with the greater atmospheric absorption of higher frequency energy, can exaggerate the perception of AM with emphasised lower-frequency character for neighbouring residents.

While the presence of a form of AM in the sound from wind turbines was highlighted by the ETSU-R-97 authors, it was the blade 'swish' mechanism caused by the directivity of the rotating trailing edge sound and convective amplification (discussed in section 2.4.3) that was focussed on. This kind of AM, with a higher-frequency character, tends to occur at relatively short distances from turbines, and was not expected by the ETSU-R-97 Working Group to be a concern for most wind farm neighbours. A type of lower frequency 'thumping' sound had been known from wind turbine research programmes in the US during the 1980s, but this was believed to be due mainly to the turbulent interaction of the blade and tower wake inherent in downwind-rotor turbine designs, which had been precluded from commercial use in favour of upwind-rotor designs[99]. It is noted, however, in ETSU-R-97 that 'thump' had been reported in connection with a complaint at one site in the UK, but no further consideration of this was detailed in the guidance.

Concerns about 'low frequency noise' from wind turbines in the UK led to the commissioning of a government-funded study published in 2006, which examined sound measurements from three sites[100]. The study concluded that the noise complaints were more likely to be associated with AM that was found to be audible during the night.

A further government-funded study was published in 2007, which examined the prevalence of AM-related complaints from wind farms, based on a questionnaire survey of local authorities[101]. The study concluded that the number of people affected, in comparison with other sources of environmental sound, was probably too small to justify further publicly funded research. The conclusions concerning the actual number of AM-related complaints reported by the survey respondents was later challenged in a reanalysis of the survey data, which argued that the proportion of respondents identifying likely AM as a factor in complaints was greater than highlighted in the study[102,103].

Reports and evidence of wind turbine AM impacts continued to be researched in the UK[104], with resident concerns about potential noise effects at proposed developments informed by newspaper

[98] van den Berg, G P, 2004. *Effects of the wind profile at night on wind turbine sound*. [URL]
[99] Lotinga, MJB, Perkins, RA, Berry, B, Grimwood, CJ & Stansfeld, SA, 2017. *A review of the human exposure-response to amplitude-modulated wind turbine noise: health effects, influences on community annoyance, methods of control and mitigation*. ICBEN 2017, 18-22 June, Zurich. International Commission on Biological Effects of Noise. [URL]
[100] Hayes McKenzie Partnership, 2006. *The measurement of low frequency noise at three UK wind farms*. Contract: W/45/00656/00/00 URN: 06/1412
[101] Moorhouse, A, Hayes, M, von Hünerbein, S, Piper, B & Adams, M, 2007. *Research into aerodynamic modulation of wind turbine noise: final report*. [URL]
[102] van den Berg, F, 2009. *Why is wind turbine noise noisier than other noise?* Euronoise 2009, 26-28 October, Edinburgh. Institute of Acoustics.
[103] van den Berg, F, 2011. In: Effects of sound on people. Bowdler, D & Leventhall, G (eds), *Wind turbine noise* (chapter 6). Multi-Science Publishing.
[104] Bowdler, D, 2008. *Amplitude modulation of wind turbine noise.* [URL]

reports, civic groups, and the publication of a controversial 'popular science' book[105] claiming to demonstrate the emergence of a new medical condition coined 'wind turbine syndrome' (these claims were largely unsupported in the scientific literature[106] at the time, and remain largely unsupported by later research, as discussed in section 3.5.1).

In 2011, a government-funded study was undertaken to investigate the way in which ETSU-R-97 assessments were being carried out in practice, which recommended best practice guidance to be developed to clarify the procedures[107].

In 2013, the IOA published its GPG on the application of ETSU-R-97, which addressed many of the identified best practice clarifications. Its scope specifically excluded considering noise limits, which were acknowledged as a matter for Government. It also omitted AM guidance, on the basis that further research was expected to be published in the near future. A wide-ranging study into AM was then published later in 2013 by RenewableUK, which included investigations into possible causes for AM, methods of quantifying AM, turbine operational influences on AM, and subjective responses to AM exposure[108]. Among other things, the study proposed a 'penalty scheme' for AM, to be considered for inclusion in planning conditions, which echoed existing schemes in place to control other sound characteristics, such as tonality. The research also found theoretical evidence for a likely main cause for AM associated with mechanisms other than trailing edge directivity and convective amplification, in the form of the pressure differentials generated by the transient separation of the boundary layer from the blade that occurs during blade stall. Field measurements were also reported that supported the theoretical conclusions.

In 2014, the IOA published six Supplementary Guidance Notes (SGNs) to the GPG, which provided further information on specific aspects of the assessment procedures.

In 2016, the findings of two parallel AM studies were published: the IOA-led investigation of a method for detecting and evaluating AM in wind turbine sound[109], and the BEIS-published review of research into human response to AM[110], completed by WSP | Parsons Brinckerhoff. The IOA work resulted in the development of an AM measurement method, which has subsequently been adopted in research and field applications, and was incorporated into the WSP | Parsons Brinckerhoff study of AM effects on people. The WSP | Parsons Brinckerhoff report concluded that AM controls were needed at development planning stages, which should include a suitable penalty scheme. These conclusions subsequently led to the publication of a proposed example planning condition for AM control, developed in collaboration with other practitioners, which included some members of the ETSU-R-97 Noise Working Group[111].

Epidemiological research into the effects of wind turbine sound exposure has continued and advanced. In 2018, the WHO published its *Environmental Noise Guidelines for the European Region* (ENGER)[112], which included some specific, but tentative, recommendations on levels of wind turbine

[105] Pierpont, N, 2009. *Wind turbine syndrome: a report on a natural experiment.* [URL]
[106] Knopper, LD & Ollson, CA, 2011. Health effects and wind turbines: A review of the literature. *Environmental Health*, 10 (1), 78. [URL]
[107] Hayes McKenzie Partnership, 2011. *Analysis of how noise impacts are considered in the determination of wind farm planning applications*. Research Contract 01.08.09.01/492A. HM: 2293/R1. Department of Energy and Climate Change. [URL]
[108] RenewableUK, 2013. *Wind turbine amplitude modulation: research to improve understanding as to its cause and effect*. [URL]
[109] IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group, 2016. *Final report: A method for rating amplitude modulation in wind turbine noise*. [URL]
[110] WSP | Parsons Brinckerhoff, 2016. *Wind turbine AM review: Phase 2 report.* 3514482A Issue 3. Department for Business, Energy & Industrial Strategy. [URL]
[111] McKenzie, A, Cand, M, Bowdler, D, Jiggins, M, Irvine, G, Reid, M, Perkins, R, Lotinga, M, Hayes, M & Bullmore, A, 2017. A planning condition for wind turbines. *Acoustics Bulletin*, 42 (6), 56-60. [URL]
[112] World Health Organization Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region.* [URL]

sound exposure associated with adverse effects[113]. In 2021, the first peer-reviewed observational study of subjective responses to sound exposure from large-scale commercial wind turbines in the UK was published[114].

Onshore wind turbines have steadily increased in size to maximise generation efficiency: the UK renewable energy planning database[115] indicates that current operational commercial UK wind farms have turbines with rated powers up to ~3.5 MW, hub heights up to ~90 m and tip heights up to ~150 m. Onshore wind farms currently listed as 'under construction' will have turbines with rated powers up to 5 MW and tip heights up to 200 m. The increasing scale of turbines has inherent implications for the sound emissions and assessment of noise impact, as discussed further in sections 4 and 6.

[113] WHO Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region*. World Health Organization. [URL]
[114] Qu, F, & Tsuchiya, A, 2021. Perceptions of wind turbine noise and self-reported health in suburban residential areas. *Frontiers in Psychology, 12*, 3357. [URL]
[115] https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract#history

2.3 SUMMARY OUTLINE OF ASSESSMENT METHOD

This section summarises the elements of the ETSU-R-97 and IOA GPG assessment method that are most important in relation to considering the findings and discussions detailed in this report.

2.3.1 OVERVIEW

The development planning-stage assessment method is summarised in the flow chart in Figure 2-7, which is from the IOA GPG.

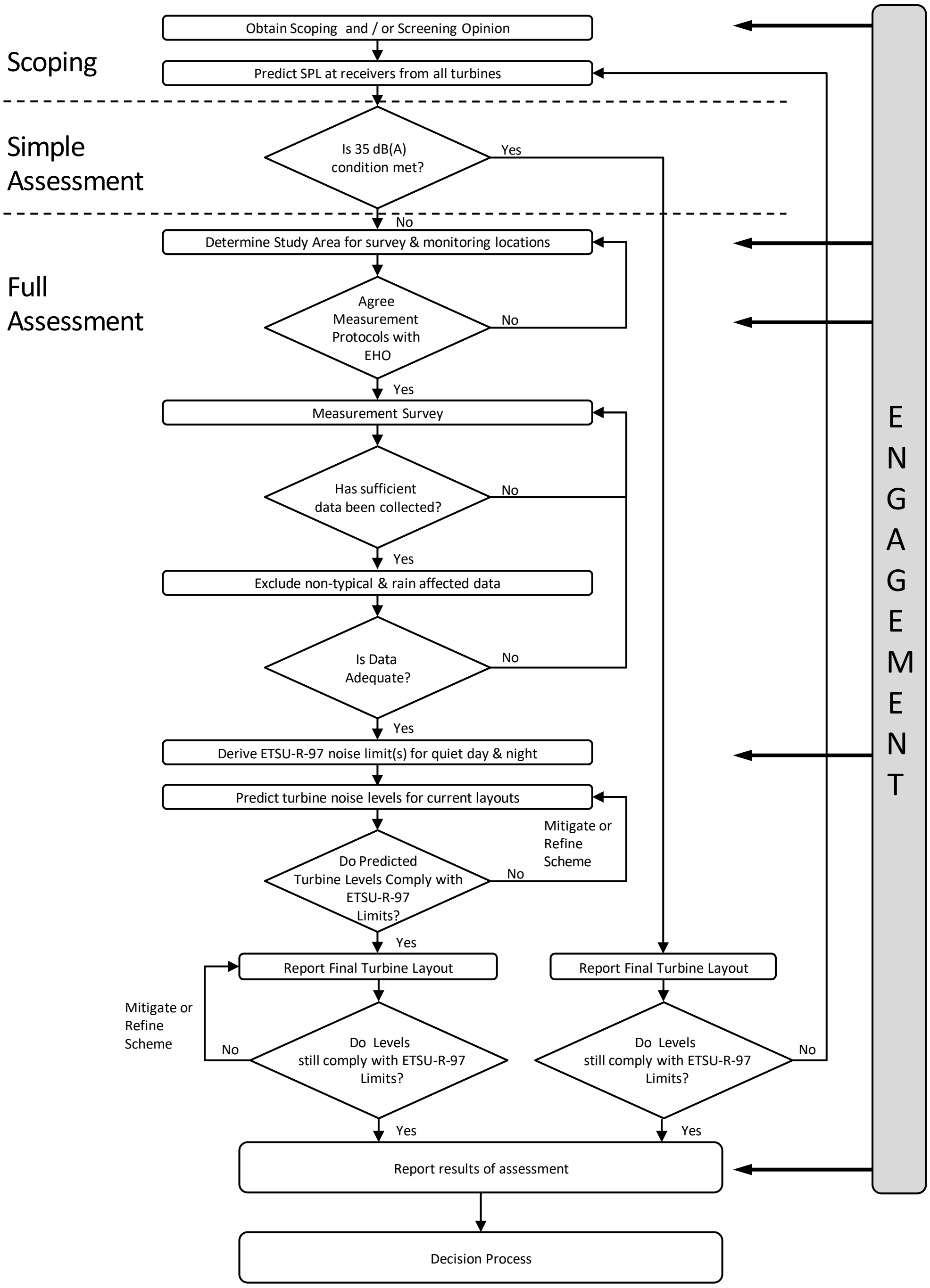


Figure 2-7: Summary flow chart of UK wind turbine noise assessment procedure at development planning stage

It can be seen from Figure 2-7 that, unless developments are predicted to meet a specified level of ≤35 dB $L_{AF90,10min}$ in the worst-case (the 'simple assessment'), the approach entails determining baseline conditions via a measurement survey. This usually comprises several weeks of monitoring existing (ie, non-wind turbine) background sound level and wind data, on the basis of which a set of wind-speed dependent noise limits are established using the ETSU-R-97 regime described in section 2.3.2. Figure 2-7 also illustrates that the ETSU-R-97 noise limits are applied as a pass/fail system of acceptability vs unacceptability, and the cycle of assessment, mitigation and prediction continues until the development is predicted to meet the limits.

The basic assessment time interval in the current guidance is 10 minutes: ETSU-R-97 confirms that this selection was made primarily because it was conventional practice to measure wind data in 10-minute intervals. However, it is also noted that 10 minutes is considered a useful interval for establishing a relationship between background sound and wind speed at the turbines, due to the typical distances involved – ETSU-R-97 highlights that shorter or longer intervals are likely to obscure this relationship[116].

A recommended method for predicting wind turbine sound is not defined in ETSU-R-97, but was introduced in the IOA GPG, which applies an international standard engineering method (ISO 9613-2:1996[117]), along with parametric inputs considered likely to result in conservative predictions.

One of the most important aspects of wind turbine sound addressed by the IOA GPG is the effect of wind shear, which describes the vertical profile of wind speed change with height. In typical atmospheric conditions, wind shear is positive, and the wind speed at the turbine hub and blade heights is greater than the wind speed at the height of receptors near to the ground. When turbine sound power levels are tested, it is common practice to express the values relative to a wind speed 'standardised to 10 m height', which is determined using the hub height wind speed, extrapolated down to 10 m height using a standard wind shear profile. This enables the sound emissions from turbines with different physical heights to be compared directly at standardised 10 m height wind speeds.

Prior to the publication of a proposed approach to addressing wind shear in wind turbine assessment[118] (which was later expanded on and formalised in the IOA GPG), it was common practice to undertake background sound level measurements alongside wind speed measurements made directly at 10 m height. This created a situation in which predictions of wind turbine sound (based on sound power level test data) were referenced to 10 m standardised wind speed, while background sound levels (and the noise limiting values derived from them) were referenced to 10 m measured wind speed, which in general are not the same, due to wind shear. The IOA GPG confirmed the recommended approach to address this difference, which involves determining the standardised 10 m height wind speeds during background sound measurements, so that wind turbine sound predictions and background sound data are effectively scaled to the same wind speed referencing system.

[116] ETSU-R-97, section 6, pages 56-57
[117] ISO, 1996. *ISO 9613-2:1996 Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation*. International Organization for Standardization. [URL]
[118] Bowdler, D, Bullmore, A, Davis, B, Hayes, M, Jiggins, M, Leventhall, G, McKenzie, A, 2009. Prediction and assessment of wind turbine noise. *Acoustics Bulletin*, 34 (2), 35-37 [URL]

2.3.2 NOISE LIMITS

ETSU-R-97 defines a noise limit regime that employs a combined absolute and relative limit approach (see section 2.1.4). The absolute part of the regime comprises a minimum limit[119], which takes different values for day or night periods, or otherwise if a receptor is considered as having 'some financial involvement' in the wind farm development being assessed.

The considerations underpinning the ETSU-R-97 limits are discussed in section 6.2.1, however it is important to understand one of the underlying assumptions that justified the choice of sound level index, the 10th percentile sound level $L_{AF90,10min}$. ETSU-R-97 advises that energy time-averaged sound levels $L_{Aeq,10min}$ measured for wind turbine sound can generally be expected to be approximately 1.5-2.5 dB higher than measured using $L_{AF90,10min}$. On this basis, the middle value of 2 dB is used in ETSU-R-97 to convert between the sleep disturbance threshold value that was identified in the literature review (defined as L_{Aeq}) into the preferred sound level measurement index L_{AF90}. The implications and validity of this assumption are explored in the evidence review in section 3, and discussed further in section 6.2.1.

The absolute part of the regime is as follows:

- Daytime (0700-2300 hrs), no financial involvement:
  - A value within the range 35 – 40 dB $L_{AF90,10min}$[120], to be determined on consideration of:
    - the number of dwellings in the neighbourhood of the wind farm
    - the effect of noise limits on the energy generation capacity of the wind farm
    - the duration and level of exposure

  In this report, this absolute limit is referred to as the '**ETSU-R-97 daytime minimum limit**', and the values at either end of the range are referred to as the '**lower/upper bound of the daytime minimum limit**'.
- Night-time (2300-0700 hrs), no financial involvement:
  - 43 dB $L_{AF90,10min}$

  In this report, this absolute limit is referred to as the '**ETSU-R-97 night-time minimum limit**'.
- Day or night-time, no financial involvement:
  - ETSU-R-97 also advises that in situations in which the developer and the local authority are in agreement that day or night background levels do not vary significantly, a single day and night minimum limit in the range 35-40 dB $L_{AF90,10min}$ can be imposed.
- Financially involved receptors, day or night-time:
  - 45 dB $L_{AF90,10min}$

  In this report, this absolute limit is referred to as the '**ETSU-R-97 financial involvement minimum limit**'.
- The 'simplified' limit:

[119] The term 'lower fixed limit' is used in ETSU-R-97; however, this term has the potential for confusion due to the flexibility available in the daytime limit, which can take a value from a range within lower and upper bounds
[120] The 10th percentile (ie, 90% exceeded) sound level – see section 2.1.2

- ETSU-R-97 also allows a ‘simplified’ assessment approach to be adopted in cases in which sound immissions are not expected to exceed 35 dB $L_{AF90,10min}$: in these cases, a single maximum limit of 35 dB $L_{AF90,10min}$ can be imposed, and there is no requirement to undertake measurements of background sound levels at receptors.

The relative part of the regime is as follows:

- No financial involvement (day or night at any time):
  - The wind turbine sound level $L_{AF90,10min}$ is limited to 5 dB above the background sound level $L_{AF90,10min}$.

  In this report, this relative limit is referred to as the ‘**ETSU-R-97 relative limit**’.
- Financial involvement (day or night at any time):
  - Consideration may be given to increasing the relative limit to a margin greater than 5 dB above the background sound level[121].

The ETSU-R-97 limit regime as applicable to properties with no financial involvement is illustrated by the examples in Figure 2-8.

[121] Exercising this flexibility does not appear to be common practice; in our experience, relative limits are invariably set at the margin of 5 dB

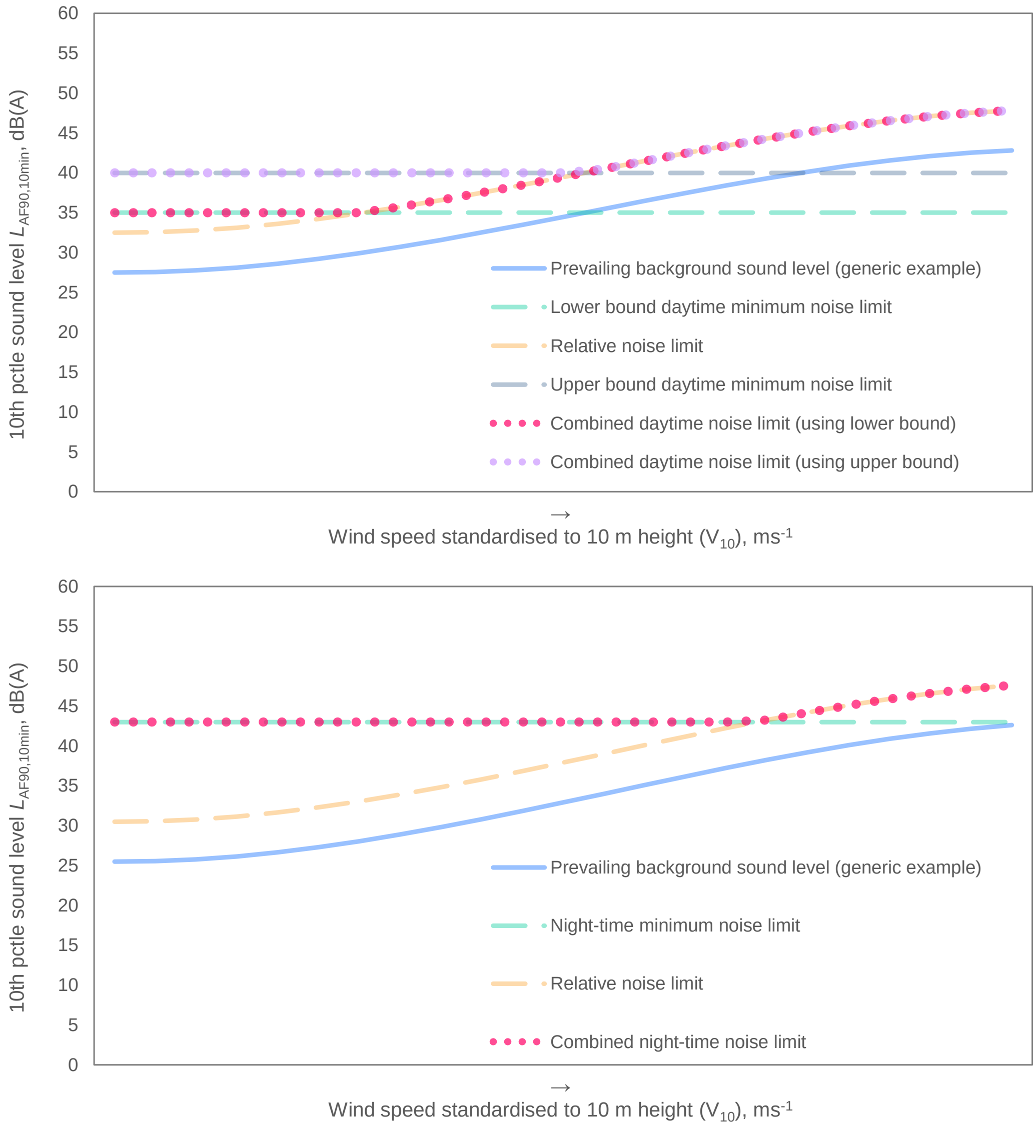


Figure 2-8: Example of ETSU-R-97 noise limit regime for properties with no financial involvement (top: daytime, bottom: night-time)

2.4 WIND TURBINE SOUND

2.4.1 FUNDAMENTALS

This study addresses the sound from onshore horizontal axis wind turbines. These are configured so that the rotor, which usually comprises three blades, rotates around a vertical plane in a clockwise direction, as illustrated in Figure 2-9.

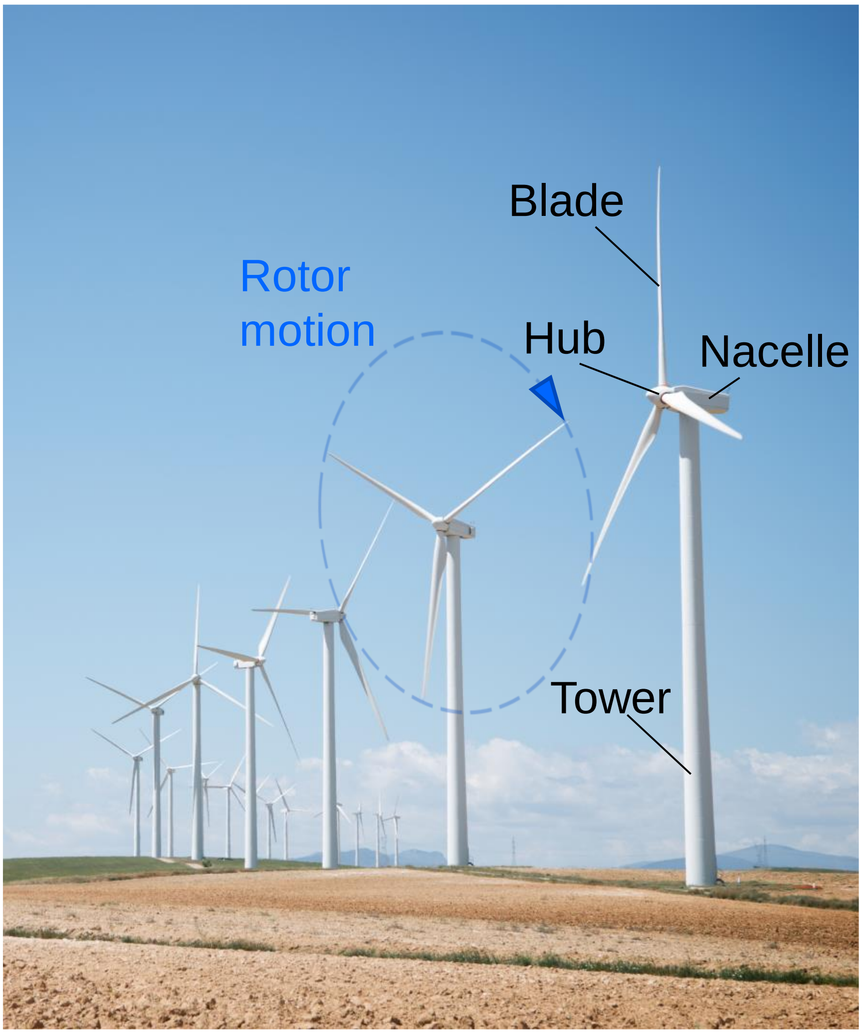


Figure 2-9: Main components of horizontal axis wind turbines

The rotor plane is orientated to be perpendicular to the incoming wind, which, when combined with the flow over the blade generated by the rotation, generates a lift force that maintains the rotation and imposes a torque on the shaft, which is connected via a gearbox to the electrical generator.

As shown in Figure 2-10, wind turbine blades comprise an aerofoil that has a smooth leading edge and a sharp trailing edge. The side of the blade facing the incoming wind is called the pressure side, and the opposite side is the suction side. The effective flow velocity of air at the leading edge is the combination of the incoming wind velocity and the flow velocity generated by the blade rotation. The angle between the effective flow velocity and the blade chord line is called the angle of attack (AoA), denoted α, and the angle between the rotor plane and the chord line is the pitch angle, denoted β.

Modern turbines are pitch regulated, which means the pitch angle is directly controlled. The control of the pitch angle provides a degree of control over the AoA, although comparison of Figure 2-10 and Figure 2-11 illustrates that, because the AoA is also affected by the wind velocity, it is only partially dependent on the pitch angle. The lift force (and the generating torque) is normally proportional to the AoA, and so is the aerodynamic sound energy emitted by the turbine blade – a larger AoA normally results in greater torque, increased power generation, and increased sound emissions. The AoA is also important in determining occurrences of AM at long ranges, as discussed further below.

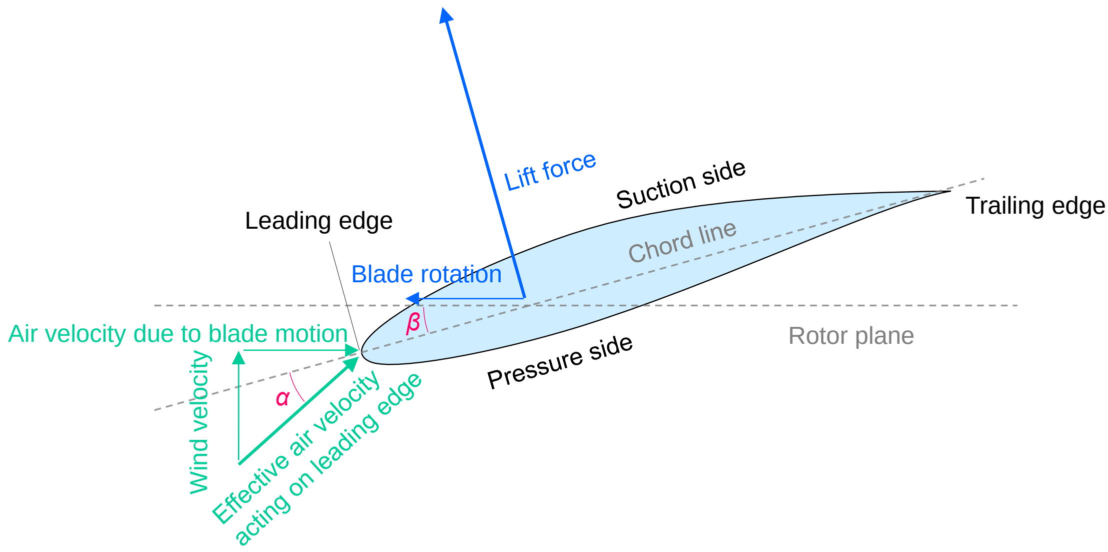


Figure 2-10: Example illustration of wind turbine blade cross-section, indicating relationship between wind velocity, turbine blade 'angle of attack' *α*, and 'pitch angle' *β* (low incoming wind velocity)

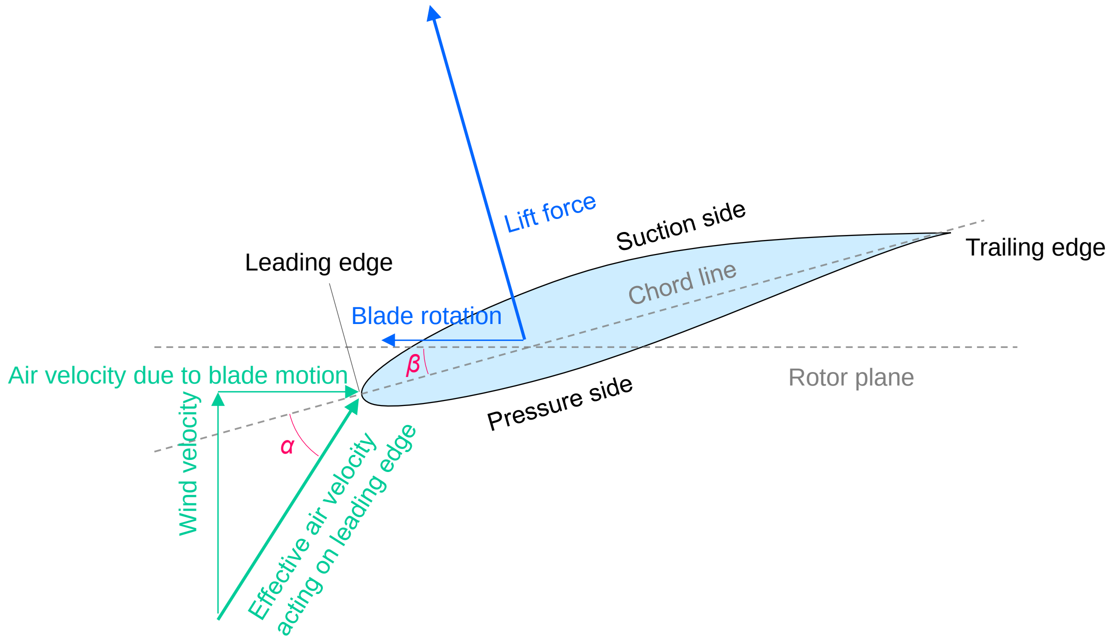


Figure 2-11: Example illustration of wind turbine blade cross-section, indicating relationship between wind velocity, turbine blade 'angle of attack' *α*, and 'pitch angle' *β* (high incoming wind velocity)

2.4.2 AERODYNAMIC SOUND SOURCE MECHANISMS

Sound is emitted by wind turbines from the mechanical and electrical components, and by the aerodynamic mechanisms associated with the rotation of the blades. In modern turbines, it is normally the aerodynamic mechanisms that dominate the sound emissions. Figure 2-12 illustrates the main mechanisms involved in aerodynamic sound generation from a wind turbine blade.

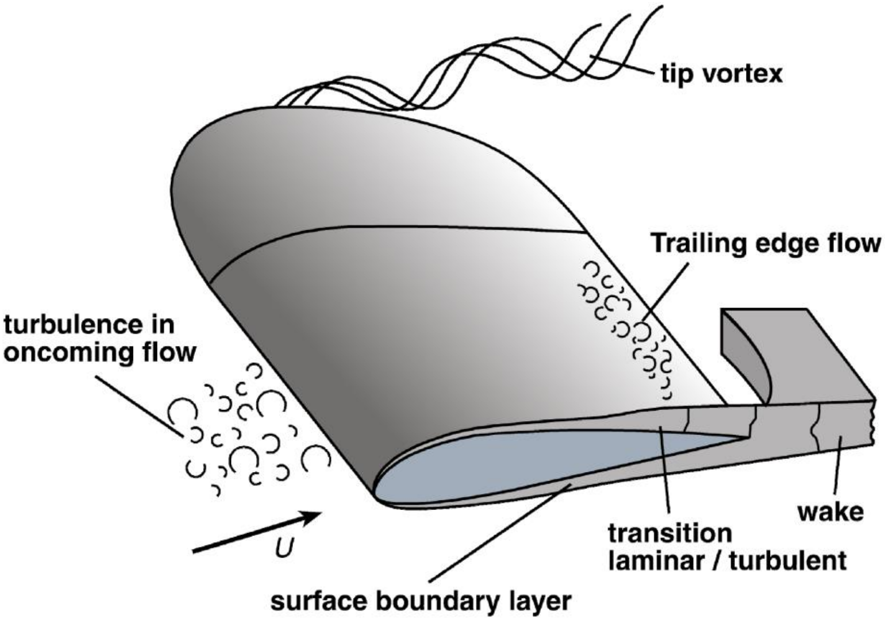


Figure 2-12: Illustration of aerodynamic mechanisms involved in sound emission from a wind turbine blade (shown in cross-section; '*U*' indicates incoming air flow velocity; figure from Oerlemans, 2009[122]; image © S. Oerlemans)

Of the aerodynamic mechanisms, the most important for determining the typical wind turbine sound signature in the far-field (at receptor locations) are normally:

1. inflow turbulence, which is the interaction of turbulence in the incoming airflow with the leading edge and surface of the blade, and
2. trailing edge sound, which is caused by the scattering of turbulent eddies in the boundary layer as they reach the trailing edge of the blade.

These sources have different characteristic sound spectra: inflow turbulence generates broadband sound concentrated in the lower end of the frequency range (the spectral energy varies according to the flow speed and the size of the turbulent eddies in the incoming flow), while trailing edge turbulence scattering generates broadband sound more toward the upper end of the frequency spectrum.

These mechanisms also have different characteristic directivity patterns (which means they radiate more sound in certain outward directions relative to the blade cross-section). The inflow turbulence sources emit most of the sound outwards from the blade side surfaces, resulting in a 'figure-of-eight' radiation pattern around the blade cross section. Trailing edge sound is focussed predominantly forwards in the direction of the leading edge and the blade rotation. This trailing edge directivity has

[122] Oerlemans, S, 2009. *Detection of aeroacoustic sound sources on aircraft and wind turbines*. Doctoral thesis. University of Twente. [URL]

an important implication for the characteristic of the sound emission, which is that a greater proportion of the trailing edge sound is directed towards a listener or sensor located on the ground during the downward sweep of the blade than during the upward sweep (and vice versa). This directivity, along with the convective amplification effects intrinsic to any moving sound source[123], results in an asymmetric source distribution pattern that is noticeable at locations relatively close to turbines. An example of this pattern is shown in Figure 2-13, which shows a sound source visualisation superimposed over a turbine, as captured from a sensor array on the ground at a distance of 58 m. In considering Figure 2-13 it should be noted that the blades constantly emit sound energy throughout the rotation; it is the stationary measurement position and the particular acoustic source behaviour of the rotating blades that results in the observed asymmetric pattern – at a different measurement position, the pattern visualisation would be shifted around the rotor). Figure 2-13 also shows that most of the sound energy is generated by the outer portion of the blades, which is because the rotation speed increases with distance along the blade away from the hub.

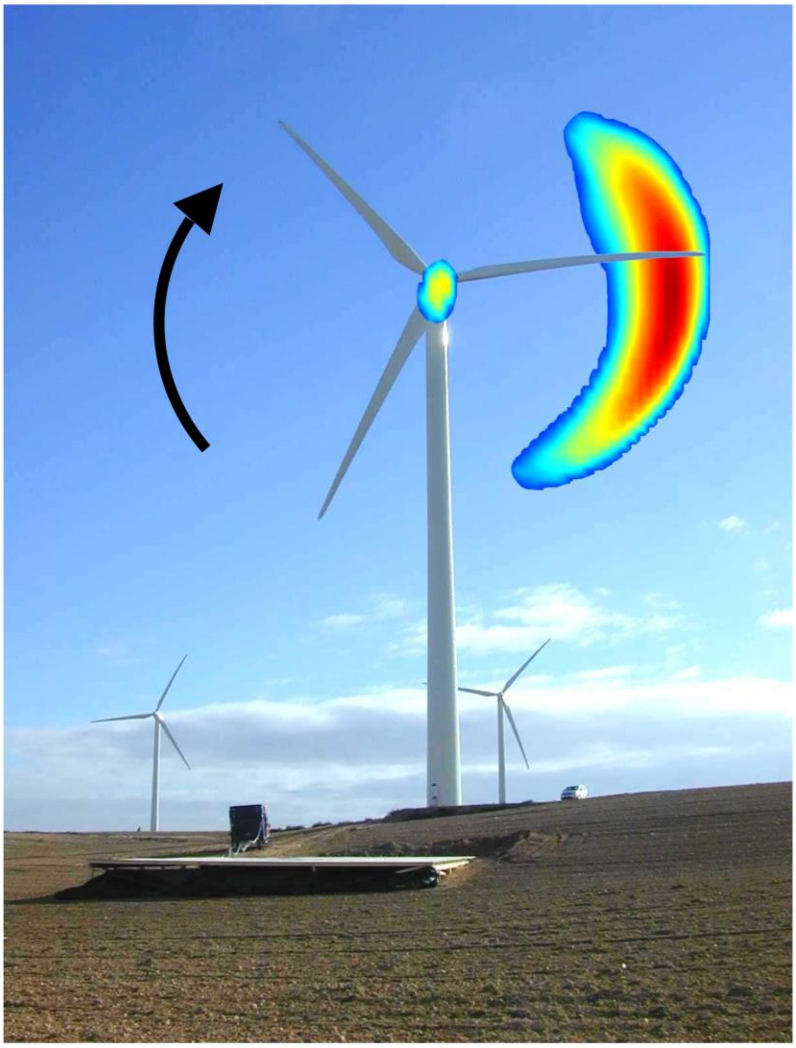


Figure 2-13: Example wind turbine sound source distribution over rotor (figure from Oerlemans, 2009[122]; image © S. Oerlemans)

[123] The 'Doppler effect' on moving source amplification is a component of the broader definition of 'convective amplification'

2.4.3 AMPLITUDE MODULATION OF WIND TURBINE AERODYNAMIC SOUND

The blade source behaviour outlined above is the cause of a characteristic of wind turbine sound known as 'blade swish', which is a form of amplitude modulation (AM) of the aerodynamic sound. This form of AM is dependent on the trailing edge directivity and convective amplification of the blade sources[124], and in this report is referred to as 'TEDCAR-AM' (trailing edge directivity and convective amplification-related AM). TEDCAR-AM is most prominent at close ranges (1-2 rotor diameters), and in a plane parallel with the rotor plane (within which the blade motion relative to a stationary observation point is greatest); it is inherently less prominent upwind or downwind of a turbine, and at longer ranges. Because TEDCAR-AM is primarily modulation of the trailing edge sound, it is also associated with modulation within the upper range of aerodynamic wind turbine sound frequencies (eg, 500-1500 Hz).

Another form of AM, which is not caused by the effects of trailing edge directivity and convective amplification, is also associated with wind turbine sound. This 'non-TEDCAR-AM' form has a lower frequency sound character, and can be present at longer ranges and over different directions from turbines compared with 'blade swish'. Non-TEDCAR-AM has also been linked with reported noise disturbances, and is sometimes described as 'whoomphing'.

One potential cause of non-TEDCAR-AM is transient blade stall[125]. As illustrated in Figure 2-14, stall of an aerofoil occurs when the turbulent boundary layer becomes detached from the aerofoil surface, generating larger-scale turbulent eddies and a rapid loss of lift force. The stall turbulence causes an increase in the sound emitted by the aerofoil, which is more prevalent in lower frequencies, due to the larger scales of the turbulent eddies. Figure 2-14b shows that stall occurrence depends on the blade AoA, which is in turn affected by the wind speed (and wind shear), and the pitch angle. Wind turbine blades also have 'twist' so that the pitch angle varies over the blade length. These factors combine with the effect that part of the blade could be in stall while other parts of the blade are not. Stall sound is associated with a different directivity to the trailing edge sound, which could explain why non-TEDCAR-AM is connected with different spatial patterns to TEDCAR-AM.

[124] Oerlemans, S, 2009. Prediction of wind turbine noise and validation against experiment. *International Journal of Aeroacoustics*, 8 (6), 555-584. [URL]
[125] Oerlemans, S, 2015. Effect of wind shear on amplitude modulation of wind turbine noise. *International Journal of Aeroacoustics*, 14 (5-6), 715-728. [URL]

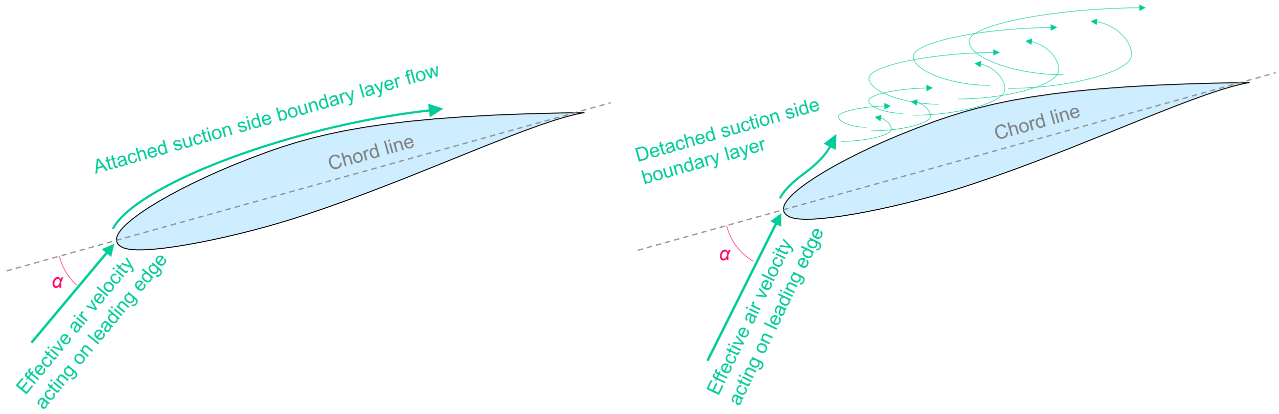


Figure 2-14: Illustration of blade stall occurrence; a (left): attached suction side boundary layer, steady flow; b (right): separated suction side boundary layer, blade stall

Variations in inflow turbulence have also been potentially connected with non-TEDCAR-AM[126], which also would be consistent with the lower frequency range and the directional characteristics associated with non-TEDCAR-AM.

Other potential causal mechanisms and contributory factors associated with non-TEDCAR-AM are outlined in section 3.5.1, based on further evidence reviewed during this study.

To summarise, amplitude modulation of the aerodynamic sound from wind turbines has been identified as being separable into two categories:

1. 'blade swish' AM:
   - which is a relatively well understood phenomenon, and is associated with:
     - the directivity of the trailing edge sound generation mechanisms
     - the convective amplification intrinsic to a moving source relative to a stationary observation position

     Due to these causal mechanisms, 'blade swish' can be described as 'trailing edge directivity and convective amplification-related' AM (TEDCAR-AM). It is also commonly described as 'normal' AM.
   - has a character that emphasises the mid and upper frequency ranges ('swish')
   - exhibits a modulation depth that is greatest in the crosswind directions, along which the relative variation in position of the rotating blades is maximal
   - is less prominent in the up or downwind directions, except at relatively close ranges (1-2 rotor diameters)
2. AM that does not exhibit the characteristics of 'blade swish', is connected with a different range of causal mechanisms and contributing factors, and could be described as 'whoomph':
   - AM that is not associated with the trailing edge directivity and convective amplification (non-TEDCAR-AM) is also commonly described as 'other', or 'enhanced', or 'abnormal' AM.

[126] Smith, MG, 2013. Work package A2: Fundamental research into possible causes of amplitude modulation. *Wind turbine amplitude modulation: Research to improve understanding as to its cause and effect*. RenewableUK. [URL]

- This AM can be prominent at longer ranges, may have a lower frequency character, and may be prominent over varying wind directions.
- Plausible causal mechanisms for non-TEDCAR-AM include transient blade stall and variations in inflow turbulence; these and other contributing factors identified in the research literature are discussed in section 3.5.1. Increased risk of blade stall occurrence is associated with increasing AoA.

2.4.4 WIND TURBINE INFRASOUND

The interaction of wind turbine blades with the supporting tower generates sound pressure in the very low frequency range, including <20 Hz, a range that is often termed 'infrasound'. This mechanism is associated with energy at the blade-passage frequency (typically ~0.5-1.5 Hz for 3-bladed turbines), and its harmonics.

Blade-tower interaction sound has been associated more strongly with downwind-rotor designs of turbine, since in that case, the blade interacts with the disrupted flow field downstream of the tower. Some experimental downwind-rotor turbines tested in the US were found to exhibit a very low frequency 'thumping' sound and 'pulsing' airborne vibrations that were associated with disturbances at nearby dwellings[127].

For upwind-rotor designs (which is the dominant design type in commercial onshore wind farms), the effect of the tower on the upstream flow is relatively insignificant, and, although disturbances have been reported as being connected with wind turbine infrasound, 'thumping', 'pulsing' etc, the scientific evidence currently indicates that wind turbine infrasound generated by modern, upwind-rotor turbines at typical receptor distances is unlikely to be perceptible, and has not been robustly associated with any adverse effects (see section 3.5.1).

Recent research on upwind rotor turbines outlined in section 3.5.1 has also indicated that the pressure fluctuations acting on the tower during a blade pass are more dominant in the generation of blade-tower interaction sound than the forces acting on the blades.

2.4.5 TONALITY IN WIND TURBINE SOUND

There are aerodynamic mechanisms that can be responsible for generating tonal content in wind turbine sound, such as vortex shedding caused by bluntness of the blade trailing edge. However, these can be addressed by good design. Damaged or dirty blades could also be a cause of tonality in the aerodynamic sound, which can be addressed by suitable maintenance or repairs.

Tonality in wind turbine sound is more commonly associated with mechanical or electrical sources in the nacelle, including the gears, generator etc. Gear meshing generates tonal sound at the meshing frequencies, harmonics and sidebands, which depend on the rotation speed and number of gear teeth, and the imperfections of the gear geometries. Any other defects present in the gears (eg, due to gear degradation), could generate additional tones.

In generators, vibrations are excited by the electromagnetic forces caused by interaction of the rotor and stator. The vibration from mechanical or electrical sources can be transmitted via the component mountings into the turbine structure, and radiated as sound. If the vibrations coincide with natural frequencies in the structure, the sound radiation will be especially efficient. However,

127 Kelley, ND, McKenna, HE, Hemphill, RR, Etter, CL, Garrelts, RL and Linn, NC, 1985. *Acoustic noise associated with the MOD-1 wind turbine: Its source, impact and control*. Solar Energy Research Institute, US Department of Energy. [URL]

sound generated by mechanical or electrical components is generally less important than that from aerodynamic sources in modern commercial wind turbines.

3

EVIDENCE REVIEW

3 EVIDENCE REVIEW

3.1 INTRODUCTION

The evidence review scope and methodology is based on the Defra/NERC guidance on developing a 'Quick Scoping Review' (QSR)[128]. According to the guidance, a QSR is defined as

> *A type of evidence review that aims to provide an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to a question.*

QSR is distinguished from the more rigorous Rapid Evidence Assessment (REA) and Systematic Review in that a critical appraisal of the relevance and robustness (accuracy and risk of bias) of the evidence is not part of conducting a QSR. A QSR has been selected for this project for consistency with the project scope and aims, and because it provides a robust, systematic basis for further evidence review work (eg, if it is desired to advance the QSR to a more rigorous REA or Systematic Review in the future). Part of the QSR involves the production of a 'systematic map', comprising a database of publications identified during the evidence review, and corresponding key information, including any relevant evidence extracted. The systematic map can provide a platform for further evidence review work addressing the same, or similar, research questions.

3.2 METHODOLOGY

3.2.1 RESEARCH QUESTIONS

Primary question

The evidence review is primarily intended to address the following research question:

- **1**: Does the evidence indicate that the ETSU-R-97 guidance, when considered alongside the government-endorsed IOA best practice application guidance, requires updating to be consistent with the aims and objectives of current government policy and regulatory frameworks, and if so which aspects of it should be revised?

Secondary questions

The Defra/NERC guidance states that[128]:

> *Secondary questions can also be investigated by the evidence review, these are typically more 'open', non-impact questions. They may also reflect the diverse issues surrounding the primary question, for example concerns and aspirations of stakeholders related to the assessment of the effectiveness of a policy driven intervention. The potential list of secondary questions should be carefully considered so that the analysis is realistic for the scope of the review (only 1 or 2 secondary questions should be used), ensuring the focus of the review is the primary question. Where secondary questions are investigated it should be noted that the main focus of the evidence review will be the primary question, secondary questions will only be addressed once the initial search for the primary question has been conducted.*

[128] Collins, A.M., Coughlin, D., Miller, J., Kirk, S. 2015. *The production of Quick Scoping Reviews and Rapid Evidence Assessments: A how to guide*. Department for Environment, Food & Rural Affairs / Natural Environment Research Council. [URL]

Leading from the primary question, the secondary questions that have been considered during the evidence review comprise:

- **2a**: What further evidence or information may need to be obtained to robustly support updates to the current guidance (if it does require updating)?
- **2b**: What evidence is there on the influence of turbine age and design on the sound emission characteristics?

3.2.2 SEARCH STRATEGY

Overview

Pilot searches were carried out using a broad range of topics relevant to wind turbine noise assessment guidance, which identified a volume of publications that was not feasible to screen within the project timescales. The rationale applied to optimise the review is outlined below.

The search strategy has taken a two-stage approach:

1. For stage 1, an initial search and screening has been aimed at identifying issues raised within the literature concerning the current guidance. This search included keywords relevant to UK wind turbine noise regulatory guidance and included evidence from black and grey literature sources (defined below).
2. In stage 2, the search focussed on two aspects that were highlighted as the priority from the stage 1 review presented in section 3.3.

The searches excluded publications:

- written in languages other than English
- published before the year 2000
- concerning only offshore turbines
- concerning only micro, building-mounted, or vertical-axis turbines

Publication classification

The identified evidence has been classified in the following way:

- Articles published in reputable, independently peer-reviewed journals, and conference papers published by recognised associations and institutions that are clearly identified as having been peer-reviewed have been classified as 'black literature'[129].
- Conference papers, government or non-governmental organisation research papers, reports, and guidance documents, and academic textbooks, have been classified as 'grey literature'[130].

Search sources

The review has included searches of the following sources:

- Black literature:
  - Web of Science citations database ('Core Collection')

[129] The evidence reviewed has included published corrections made to peer-reviewed articles, and published article response letters and comments that are relevant to the evidence in the original publication.
[130] In determining these classifications, it is acknowledged that government-funded research publications often also undergo forms of peer review.

- PubMed citations database (although PubMed is indexed by Web of Science, pilot searches identified that results found in PubMed searches are not always identified in Web of Science searches, which is likely to be due to differences in the database algorithms)

- Grey literature:
  - Conference proceedings:
    - INCE Europe International Conferences on Wind Turbine Noise 2005-2021
    - International INCE Inter-noise (via IngentaConnect platform)
    - International Congress on Acoustics
    - ICBEN conference proceedings 2003-2021
  - Institute of Acoustics e-library (including IOA conference proceedings and Acoustics Bulletin)
  - Overseas national wind turbine noise assessment standards and guidance documents

Other sources

The review has also considered publications known to the review team, or identified during the course of the review, and the stakeholder engagement exercise (which requested that respondents identify evidence).

Search keywords

The search keyword strings used in the database searches are shown in Table 3-1.

Due to the large volume of results obtained during pilot searches, the Web of Science stage 2 search employed additional exclusion logic and filtering criteria for publication classifiers, including database categories, research areas and document types – full details are found in the provided web links for each search.

Searches of grey literature sources varied, depending on the search facilities available. Due to the varied and relatively limited systems, this was a largely manual process, for example, scrolling through conference session titles and lists of abstracts. This process meant it was also necessary to apply screening at the point of searching for these publication types.

Table 3-1: Database search keyword strings

Stage	Database	Search date	Search string	No. of results
1	Web of Science[131]	02/08/2021	wind AND (turbine* OR farm*) AND (sound* OR nois*) AND (assess* OR manag* OR control* OR effect* OR affect* OR impact*) AND (regulat* OR etsu* OR ordinance* OR guid* OR legislat*)	225
	PubMed[132]			30
2	Web of Science[133]	21/09/2021	wind AND (turbine* OR farm*) NOT (offshore OR marine OR tidal OR hydro OR ocean OR fault OR crop OR vertical-axis OR micro) AND (infrasound* OR sound* OR nois*) AND ((modulat* OR fluctuat* OR "AM" OR "EAM" OR "OAM" OR "NAM" OR whoo* OR thump* OR swish* OR lash* OR tonal* OR hum* OR buzz* OR whin* OR dron* OR character* OR feature*) OR (control* OR mitigat* OR reduc* OR treat* OR threshold* OR limit*) OR (health* OR wellbeing OR "quality of life" OR annoy* OR sleep* OR psycholog* OR physiolog* OR percept* OR disease OR syndrome)	1095
	PubMed[134]		(wind AND (turbine* OR farm*) NOT (marine OR tidal OR hydro) AND (sound* OR nois*) AND ((modulat* OR fluctuat* OR "AM" OR "EAM" OR "OAM" OR "NAM" OR whoo* OR thump* OR swish* OR lash* OR tonal* OR hum OR humming OR hums OR buzz* OR whin* OR dron* OR character* OR feature*) OR (control* OR mitigat* OR reduc* OR treat* OR threshold* OR limit*) OR (health* OR wellbeing OR "quality of life" OR annoy* OR sleep* OR psycholog* OR physiolog* OR percept* OR disease OR syndrome)))	208
Notes: Boolean operators: AND, OR, NOT apply combinational logic Apostrophes are used to specify a term or phrase Asterisks are used to apply a 'wildcard' operator, to enable multiple string root and branch combinations				

Stage 1 screening and inclusion criteria

The stage 1 search results were screened using the following inclusion criteria:

- Evidence that directly raises or addresses issues with the current UK wind turbine noise assessment guidance in relation to the primary research question.
- Evidence that addresses overseas national or regional wind turbine noise assessment guidance or regulation that could be relevant to the primary research question.

131 Search URL
132 Search URL
133 Search URL
134 Search URL

Two phases were used for screening:

1. Title (marked ‘clearly relevant’/‘uncertain’/‘clearly irrelevant’)
2. Abstract or summary (marked ‘highly relevant’/‘partially relevant’/‘excluded’[135])

Exclusion criteria applied in the screening excluded studies that:

- do not address wind turbine sound or noise
- are limited to wind turbines with power ratings ≤50 kW[136]
- are limited to localised issues (for example, the local specifics of a national or regional legislative issue)
- report only a compliance test of a wind turbine
- are limited to the development of a turbine component or software routine (eg, fault diagnosis or structural health monitoring)
- are limited to the development of computational prediction models for a specific element of wind turbine sound
- are limited to turbine ground-borne vibration
- are limited to offshore turbines
- are limited to occupational sound exposure (ie, for wind farm workers)
- are limited to downwind rotor turbines
- are limited to non-human effects of wind turbine sound exposure
- have been formally retracted from the original publication

The systematic map includes all publications identified from the search phases, including publications excluded at screening, and the reasons for exclusions.

The relevance of records was marked ‘highly’/’partially’ according to whether the abstract directly addressed the inclusion criteria, or whether it addressed other aspects of wind turbine sound that could be relevant in developing guidance, respectively.

Following these phases, (from which 115 publications were marked as relevant, of which 94 were marked as ‘highly relevant’) an additional eligibility phase was applied to the database records, which comprised searching the text of the ‘highly relevant’ publications, and reviewing only those that specifically referred to ETSU-R-97 or the IOA GPG. This resulted in 46 publications identified for review in stage 1. The search and screening flow chart diagram for stage 1 (based on PRISMA 2020[137]) is shown in Figure 3-1.

[135] It was initially expected that the phase 2 screening classifications of ‘highly relevant’ or ‘partially relevant’ would be used to assign either ‘full text’ or ‘abstract/summary and conclusions’ reviews to each publication. Due to the project constraints and in view of the volume of literature identified from the search stages, it was agreed that only ‘highly relevant’ publications would proceed to review, with ‘partially relevant’ classifications retained in the systematic map to support potential future review exercises.
[136] It is acknowledged that, strictly-speaking, the ‘>50 kW’ applicability criterion specified in the IOA GPG (on which the exclusion criterion is based) applies to ‘wind turbine developments’ rather than individual ‘wind turbines’.
[137] Preferred Reporting Items for Systematic Reviews and Meta-Analyses [URL]

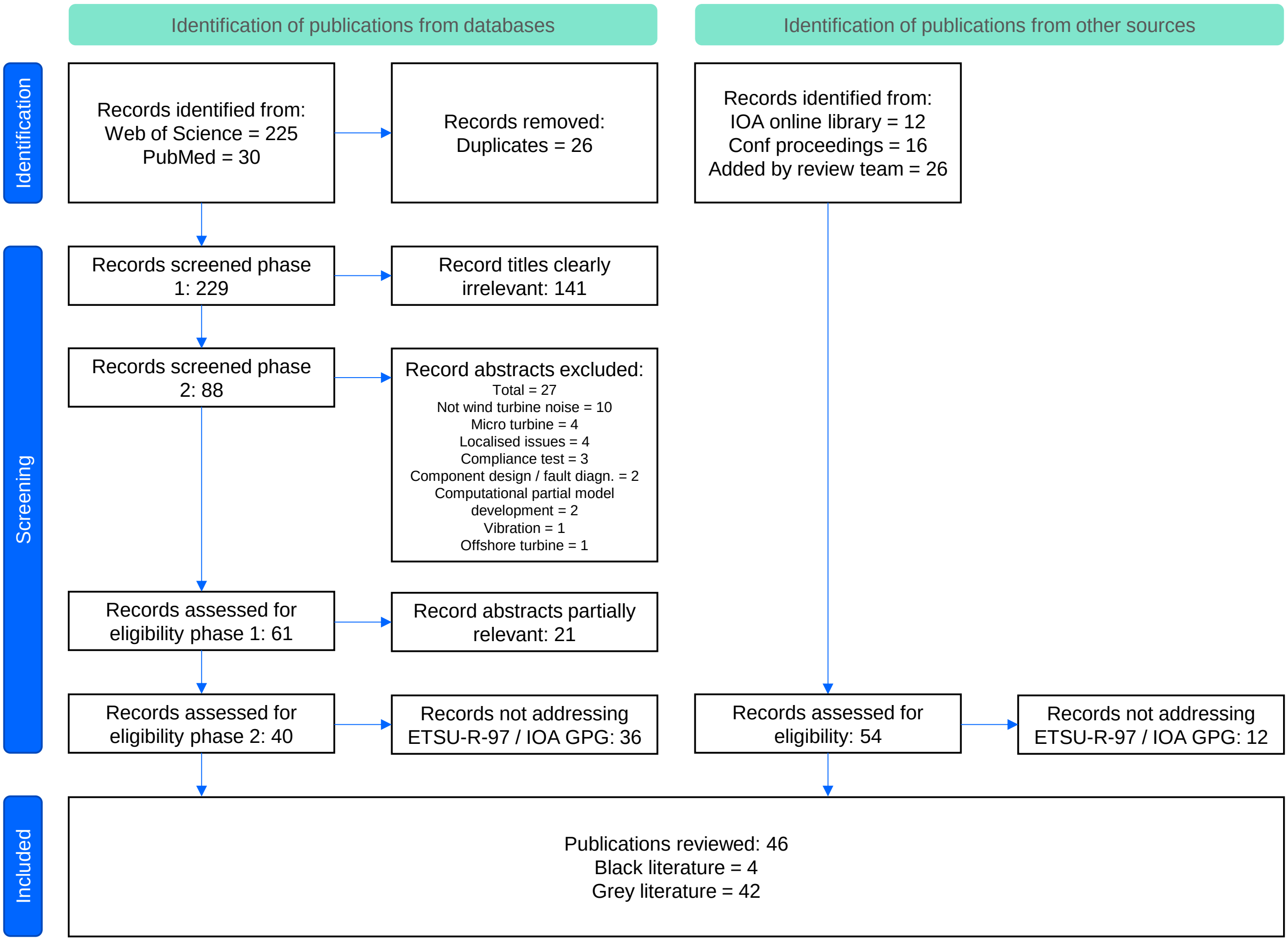


Figure 3-1: PRISMA-based flow diagram for stage 1 search and screening

Stage 2 screening and inclusion criteria

As discussed in section 3.3, the results of the stage 1 review identified two priority topics that formed the basis for the stage 2 inclusion criteria, which were defined as:

- Evidence directly addressing one of the two prioritised topics in relation to the primary research question:
  1. noise limits or effects thresholds
  2. amplitude modulation

Publications meeting these criteria were marked as 'highly' relevant, while publications addressing other aspects of wind turbine sound that could be relevant in developing guidance were marked as 'partially' relevant.

The stage 2 screening used the same two-phase approach as for stage 1, but also automatically included in the second-phase screening any publications marked as partially relevant or highly relevant in stage 1. The screening phase identified over 400 publications that were considered 'highly relevant' to the research questions, when considering only the two prioritised topics. In view of the project constraints, and to optimise the review towards the most reliable and up to date evidence, an additional eligibility phase was applied as described below:

- Publications eligible for review in stage 2 comprised:

- peer-reviewed publications published from 2015 that included (85 publications, of which 5 were also reviewed in stage 1):
  - evidence reviews (28 publications)
  - original studies that had not been included in existing peer-reviewed evidence reviews (57 publications, including 1 article erratum and 1 associated response letter)
- the 2015-16 IOA reports published from the study undertaken to develop a suitable metric for wind turbine AM measurement (2 publications)
- the WSP | Parsons Brinckerhoff 2016 report from the BEIS-published study undertaken to review subjective responses to wind turbine AM
- highly relevant conference papers published during 2021 (up to the date of the stage 2 search in September: 3 publications)

- This strategy was agreed on the basis that:
  - including almost exclusively peer-reviewed publications would enable the review to focus on evidence that had undergone this process of quality-checking, which would be expected to support more robust conclusions
  - including publications from 2015 recognised the fact that relevant publications prior to 2015 had been reviewed in:
    - the WHO systematic reviews of noise effects on health underpinning the 2018 ENGER
    - the IOA review of AM measurement metrics
    - the WSP | Parsons Brinckerhoff review of subjective responses to AM
  - including original studies that had not been reviewed in previous evidence reviews ensures that findings would not be overlooked

The search and screening flow chart diagram for stage 2 is shown in Figure 3-2.

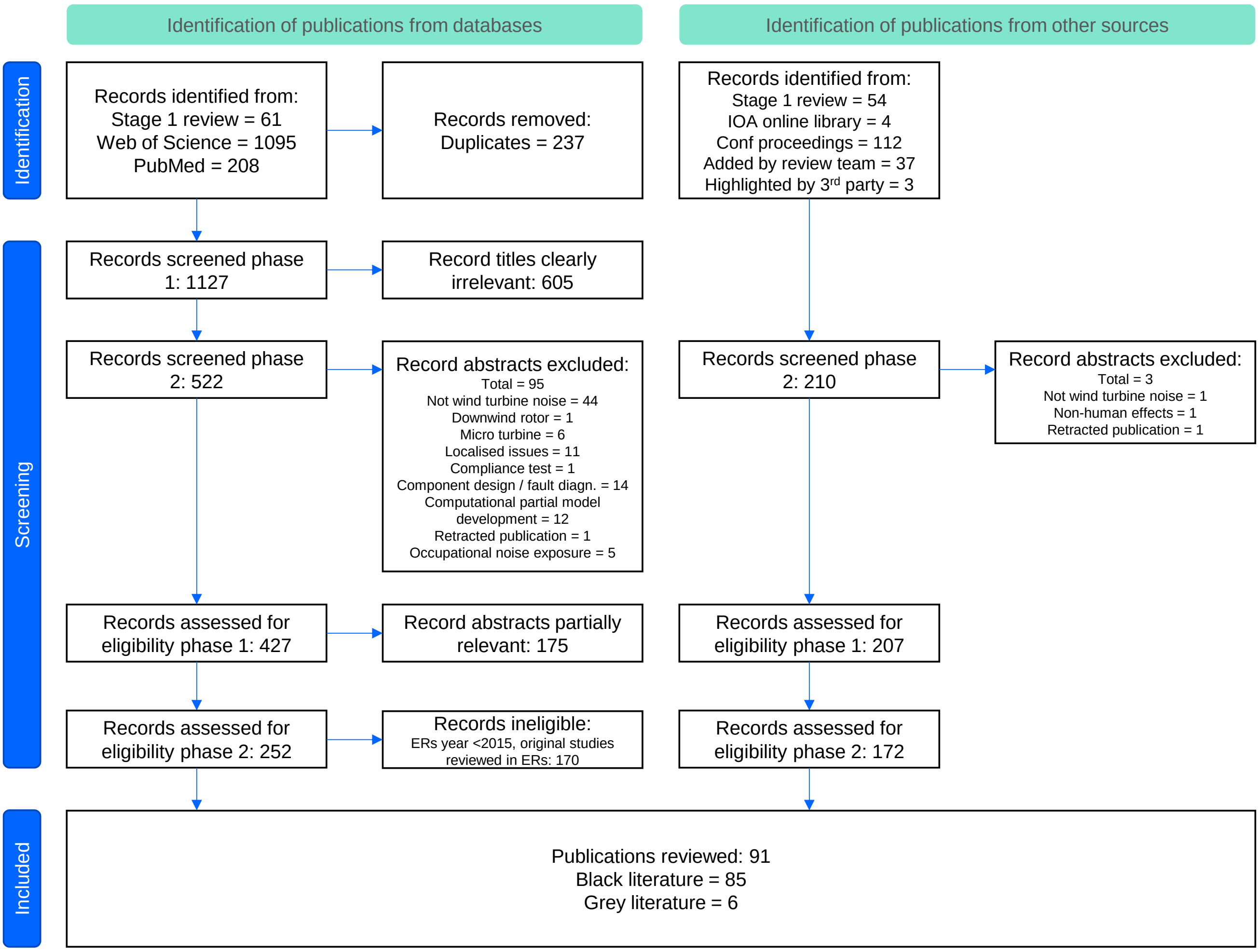


Figure 3-2: PRISMA-based flow diagram for stage 2 search and screening

In total, 132 publications have been reviewed during stages 1 and 2 of this evidence review. A random sample of 80 records from the systematic map was selected and the screening and classification decisions checked by two members of the team who had not been involved in the search or screening stages; these checks confirmed the decisions made during the process.

3.2.3 EVIDENCE EXTRACTION

The information extracted from each included publication is summarised in the systematic map outline in Table 3-2.

Table 3-2: Systematic map outline

Field	Coding / notes
ID	Unique project-specific identification number
Publication type	Peer-reviewed journal article Conference paper Conference paper (peer reviewed) Government report or research paper Official (government) guidance document Non-government guidance document (including industry standard)
Document title	Title of the document (main title only). For reports, this may include the report number
Publication title	If different to the document title (eg, journal or conference title)
Authors	Surname1, Initials1; Surname 2, Initials2; etc… or institutional/corporate name if no individual authors are identified
Publication year	The year of publication
Digital object identifier (DOI)	DOI number (eg, '10.1121/1.5051331')
Identification source	Database search Proceedings search IOA library search Added by review team Highlighted by third party
Screening phase 1 result	clearly relevant / uncertain / clearly irrelevant
Screening phase 2 result	highly relevant / partially relevant / excluded (or N/A if screened out in phase 1)
Screening exclusion reason	Offshore / Non-human only / Small/micro/building mounted/vertical axis / Component design/fault diagnosis / Partial model development / WT worker impacts / Does not address WT noise / Compliance test / Retracted / Localised issues / Downwind rotor / Seismic/vibration
Evidence review	Is the publication primarily a review of evidence from other research studies? Yes or no
Linked publications (multiple fields)	IDs of linked publications, ie studies reviewed by evidence reviews, journal article comment letters and errata

Field	Coding / notes
Full text obtained	Yes or no with reason
Abstract or summary	The text of the abstract or summary copied in full
Review type	Full text / abstract + conclusions / executive summary
Relevant topics	UK guidance/regulation/policy Overseas national guidance/regulation/policy Baseline determination Measurements of sound or meteorology Consideration of atmospheric, meteorological, or topographical influences on sound Evaluation of sound characteristics Sound predictions Noise impact assessment Noise controls Noise effects Compliance determination and enforcement Uncertainty Influence of wind farm or turbine design on sound emissions
Review questions addressed	1, 2a, 2b
Summary of relevant information and key evidence	Extract and summarise the main findings with relevance to the research questions
Web link	Link to the full text

3.3 IDENTIFICATION OF ISSUES WITH CURRENT GUIDANCE

Of the black literature sources identified during the first stage of the search, all four of those that directly address ETSU-R-97 or the IOA GPG stem from authors based in Australia. In part this is because, as noted by Davy et al[138] (2018), Australasian wind turbine noise regulations have historically been "*strongly influenced*" by ETSU-R-97. It also reflects the contemporary research interest in wind turbine noise in Australia, including two evidence reviews undertaken by the National Health and Medical Research Council, which led to the award of funding grants totalling approximately £1.75m for two fundamental research studies in 2016[139]. This has led to a series of publications in academic journals, the findings of which are discussed in the evidence synthesis section 3.5.

[138] Davy, JL, Burgemeister, K & Hillman, D, 2018. Wind turbine sound limits: current status and recommendations based on mitigating noise annoyance. *Applied Acoustics*, 140 (2018), 288-295. [URL]
[139] NHMRC, 2016. *Targeted call for research into wind farms and human health (wind farms TCR) for funding commencing in 2016*. [URL]

It is also noted that all the publications identified during this stage that appear to be from UK-based authors are in the grey literature category, some of which comprise reports undertaken on behalf of UK governmental departments.

The two most-discussed themes identified in the stage 1 review are outlined in sections 3.3.1 and 3.3.2, and comprise:

- the development, justifications, and appropriateness of the ETSU-R-97 system of noise controls (ie, noise limits and associated justifications of thresholds for adverse effects)
- the need for a specific control to address the potential impact of AM

Other issues concerning ETSU-R-97 identified in the stage 1 review, but to a lesser extent, are also presented in section 3.3.3.

See Appendix B, section 9.1 for the corresponding review summaries and further publication references.

3.3.1 NOISE LIMITS AND EFFECTS

Several authors in the black[138,140,141] and grey literature[142,143,144] have noted that the basis for the ETSU-R-97 night-time minimum noise limit was the 1980 WHO Environmental Health Criteria 12[145] report, which has been succeeded by the 1999 Guidelines for Community Noise (GCN)[146], the 2009 Night Noise Guidelines for Europe (NNGE)[147], and the 2018 ENGER[148].

It has also been observed that having a night-time limit higher than daytime is unusual[141,149], and this arrangement appears to be particular to regulations based on ETSU-R-97.

It has been argued in the grey literature by Bowdler[150] and Bullmore et al[151] (and echoed by others in the black literature[140]) that the ETSU-R-97 pass/fail system of noise limits, and the use of minimum noise limits, effectively precludes the assessment of noise *impact* (and effects).

Bowdler[150] and others[143,144] have also noted the basis for the ETSU-R-97 relative noise limit in BS 4142:1990[152] (now superseded by the current 2014 revision, as amended in 2019[153]). This standard advised that a rating level margin above background sound level of 'around 10 dB or more' indicated an expectation of 'complaints likely', while a margin or 'around 5 dB' was of 'marginal significance'; the ETSU-R-97 relative limit effectively enables typical wind turbine sound at levels falling in

[140] Cooper, S & Chan, S, 2020. Determination of Acoustic Compliance of Wind Farms. *Acoustics*, 2 (2), 416-450. [URL]
[141] Alamir, MA, Hansen, KL & Catcheside, P, 2021. Penalties applied to wind farm noise: Current allowable limits, influencing factors, and their development. *Journal of Cleaner Production*, 295 (2021). [URL]
[142] Hayes McKenzie Partnership, 2011. *Analysis of how noise impacts are considered in the determination of wind farm planning applications*. HM:2293/R1. Department of Energy & Climate Change. [URL]
[143] Walsh, U, 2015. Northern Ireland Assembly Committee for the Environment Wind Energy Inquiry: Specialist Advisor report. *Report on the Committee's Inquiry into Wind Energy* (volume 7). [URL]
[144] Hansen, CH, Doolan, CJ & Hansen, KL, 2017. Wind energy and noise. In: *Wind farm noise: measurement assessment and control* (chapter 1). John Wiley & Sons. [URL]
[145] WHO, 1980. *Environmental Health Criteria 12: Noise*. World Health Organization. [URL]
[146] WHO, 1999. *Guidelines for community noise*. World Health Organization. [URL]
[147] WHO Regional Office for Europe, 2009. *Night noise guidelines for Europe*. World Health Organization. [URL]
[148] World Health Organization Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region.* [URL]
[149] Bastasch, M, 2011. Criteria. In: Bowdler, D & Leventhall, G (eds). *Wind turbine noise* (Ch 8). Multi-Science Publishing.
[150] Bowdler, D, 2012. ETSU-R-97: An alternative view. *Acoustics Bulletin*, 37 (3), 32-34. [URL]
[151] Bullmore, A & McKenzie, A, 2015. What would an alternative to ETSU-R-97 look like? *Proceedings of the Institute of Acoustics*, 37 (2) 54-63. [URL]
[152] BSi, 1990. *BS 4142:1990 Method for rating industrial noise affecting mixed residential and industrial areas*. British Standards Institution. [URL]
[153] BSi, 2019. *BS 4142:2014+A1:2019 Methods for rating and assessing industrial and commercial sound*. British Standards Institution. [URL]

between these two values. Bowdler[150] and Hansen et al[144] argue this is an indication of an adverse impact (for which the ETSU-R-97 pass/fail system implies no mitigation is required).

A study aiming to compare experienced impacts of 390 survey respondents with those predicted in planning-stage assessments for sites in Scotland advised that a review of the derivation of the ETSU-R-97 noise limits should be undertaken, to consider whether an appropriate balance between protection, robustness and simplicity is achieved[154]. It was also noted that investigation of the potential effects of sound masking, and the merits of the relative limits versus absolute limits could be valuable.

The ETSU-R-97 approach to noise limits is based on the use of the 10th percentile ('90% exceeded') sound level index $L_{AF90,10min}$. It is more common in current general practice for controlling sound emissions from wind turbines to use the energy time-averaged sound level index L_{Aeq}[155], although the French regulations use the 50th percentile level index L_{A50} to control and measure wind turbine sound[156]. The approach in ETSU-R-97 is taken because the 90% exceeded sound level is a more convenient index for measurements of wind turbine sound (ie, for compliance tests), as it is much more resistant to contamination from other sources than L_{Aeq}, which is a common issue affecting wind turbine sound measurements. ETSU-R-97 asserts that the relationship for uncontaminated wind turbine sound levels quantified in 10-minute periods using each metric is relatively constant, varying by no more than ~1 dB (ie, the typical range for the level difference $L_{Aeq,10min}$-$L_{AF90,10min}$ for uncontaminated measurements is stated to be approximately 1.5-2.5 dB). This assumption underpins the use in the current guidance of the $L_{AF90,10min}$ sound level index for assessing wind turbine sound levels, and is used in the derivation of the ETSU-R-97 noise limits (for which the middle value of 2 dB is adopted from the approximate range). Some authors criticise or comment on this approach[157,158,159], noting this assumption may not hold in the presence of amplitude modulation.

3.3.2 AMPLITUDE MODULATION

The lack of a specific evaluation and control method within ETSU-R-97 (or the IOA GPG) for AM is highlighted in the black[155,159] and grey[158,160,161,162,163,164,165,166] literature. Some authors (eg, Large et al, 2017[165]) assert that a control should be placed on the frequency of occurrence of AM above a given threshold, while others (eg, Perkins[163]) argue that an AM character penalty is appropriate, in a

[154] SLR & Hoare Lea, 2015. *Wind Farm Impacts Study: Review of the visual, shadow flicker and noise impacts of onshore wind farms.* Final report: 405.04528.00001. ClimateXChange. [URL]
[155] Alamir, MA, Hansen, KL & Catcheside, P, 2021. Penalties applied to wind farm noise: Current allowable limits, influencing factors, and their development. *Journal of Cleaner Production*, 295 (2021). [URL]
[156] Goeme, A, 2015. *Comparative analysis of wind turbine noise assessment and rating procedures in the UK, France and the Netherlands*. Wind Turbine Noise 2015, 20-23 April, Glasgow. INCE-Europe.
[157] Hansen, C & Hansen, K, 2020. Recent advances in wind turbine noise research. *Acoustics*, 2 (1), 171-206. [URL]
[158] Walsh, U, 2015. Northern Ireland Assembly Committee for the Environment Wind Energy Inquiry: Specialist Advisor report. *Report on the Committee's Inquiry into Wind Energy* (volume 7). [URL]
[159] Cooper, S & Chan, S, 2020. Determination of Acoustic Compliance of Wind Farms. *Acoustics*, 2 (2), 416-450. [URL]
[160] Hayes McKenzie Partnership, 2006. *The measurement of low frequency noise at three UK wind farms*. Contract number: W/45/00656/00/00 URN number: 06/1412. Department of Trade & Industry. [URL]
[161] Hayes McKenzie Partnership, 2011. *Analysis of how noise impacts are considered in the determination of wind farm planning applications*. HM:2293/R1. Department of Energy & Climate Change. [URL]
[162] Bowdler, D, 2012. ETSU-R-97: An alternative view. *Acoustics Bulletin*, 37 (3), 32-34. [URL]
[163] Perkins, R, 2015. IOA windfarm guidance – where to next. *Proceedings of the Institute of Acoustics*, 37 (2), 1-3. [URL]
[164] Cox, R, Cowen, R, Gray, B, Hanning, C, Hulme, M, Sherman, T, Yelland, J & Large, S, 2015. INWG wind turbine amplitude modulation & planning control study. *Proceedings of the Institute of Acoustics*, 37 (2), 42-53. [URL]
[165] Large, S, Stigwood, D & Stigwood, M, 2017. *Cotton Farm Wind Farm long term community noise monitoring 4 years on: testing compliance and AM control methods*. Inter-noise 2017, 27-30 August, Hong Kong. I-INCE. [URL]
[166] Hansen, CH, Doolan, CJ & Hansen, KL, 2017. Wind energy and noise. In: *Wind farm noise: measurement assessment and control* (chapter 1). John Wiley & Sons. [URL]

similar manner as is already used in ETSU-R-97 for tonal sound (and in BS 4142 for a range of other sound characteristics).

3.3.3 OTHER ISSUES

Other issues identified in the literature are briefly outlined below.

Minimum 'set back' distances for noise control

Some authors argue that set back distances are required for noise control purposes[166,167], while others point out that there is a lack of evidence to support this approach, which could lead to either over- or underestimation of noise impacts[168,169].

Data aggregation and treatment of uncertainty

Some authors have argued that the use of statistical aggregation methods to derive either (i) the 'prevailing' background sound level (in turn used to derive relative limits for impact assessment), or (ii) the measured wind turbine sound level (in a compliance test) results in periods when experienced impacts could be under- or overestimated[170,171]. Others have noted that the potential for varying applications of statistical analysis in ETSU-R-97 assessments introduces uncertainty that is not adequately addressed[172].

Measurement instrumentation

Two specific issues are identified in the grey literature concerning sound measurement instruments used: (i) that guidance on suitable microphone wind shields may not be sufficiently prescriptive[173], and (ii) that there is no guidance on addressing sound level meter 'self-noise'[174] (beyond prescribing the performance specification class of the measurement instrument)[175]. In both cases, the concern is about ensuring accuracy of baseline survey measurements, which may be undertaken during high wind speeds, or in environments with low ambient sound levels.

Wind shear effects

The influence of wind shear on the relationship between wind speed-referenced wind turbine sound levels and background sound levels has been a contentious issue surrounding the use of ETSU-R-97. This has become more important over time as turbine heights have increased, and the influence of wind shear on the assessment of sound immissions relative to baseline measurement-derived limits became stronger. This was addressed in the IOA GPG by formalising and expanding on a proposal (made in a 2009 industry periodical article by Bowdler et al, 2009[176]) to standardise wind

167 Davy, JL, Burgemeister, K, Hillman, D & Carlile, S, 2020. (Davy, Burgemeister, Hillman, & Carlile, A review of the potential impacts of wind turbine noise in the Australian context, 2020). *Acoustics Australia*, 48, 181-197. [URL]
168 Marshall Day Acoustics, 2013. *Examination of the significance of noise in relation to onshore wind farms.* Sustainable Energy Authority of Ireland. [URL]
169 Walsh, U, 2015. Northern Ireland Assembly Committee for the Environment Wind Energy Inquiry: Specialist Advisor report. *Report on the Committee's Inquiry into Wind Energy* (volume 7). [URL]
170 Hansen, KL, Zajamsek, B, & Hansen, CH, 2018. Wind farm noise uncertainty: Prediction, measurement and compliance assessment. *Acoustics Australia,* 46, 59-67. [URL]
171 Hansen, C & Hansen, K, 2020. Recent advances in wind turbine noise research. *Acoustics*, 2 (1), 171-206. [URL]
172 Greenough, R & Unwin, D, 2013. A neglected source of uncertainty in potential wind farm noise assessment using the ETSU-R-97 process. *Acoustics Bulletin*, 38 (3), 36-42. [URL]
173 Perkins, R, 2015. IOA windfarm guidance – where to next. *Proceedings of the Institute of Acoustics*, 37 (2), 1-3. [URL]
174 The instrumentation electrical, mechanical, and digital noise 'floor' generated by the measurement system and components, which imposes a lower bound on the level of sounds that can be reliably measured using the instrument in quiet environments.
175 Hansen, CH, Doolan, CJ & Hansen, KL, 2017. Wind energy and noise. In: *Wind farm noise: measurement assessment and control* (chapter 1). John Wiley & Sons. [URL]
176 Bowdler, D, Bullmore, A, Davis, B, Hayes, M, Jiggins, M, Leventhall, G, McKenzie, A, 2009. Prediction and assessment of wind turbine noise. *Acoustics Bulletin*, 34 (2), 35-37 [URL]

speed references used for both predictions and measurements. This meant that the wind speed axis would then be based on the same effective referencing scale, whereas previous assessments had usually been based on a comparison of noise limits referenced to wind speeds *measured* at 10 m height, and sound immissions referenced to wind speeds *standardised* to 10 m height (using the standard logarithmic wind shear profile that applies to neutral atmospheric conditions). A relatively small number of the included publications in the period after the publication of the IOA GPG raise comments on this approach to addressing wind shear.

The concerns raised about the IOA GPG approach to wind shear are focussed on two issues: (i) that the standardisation of wind speeds to 10 m height during baseline measurements effectively results in an 'averaged' wind shear over the survey period[177], and (ii) that the process is unnecessarily complicated, and could be simplified by referencing all wind speeds to turbine hub height rather than 10 m[178]. A related issue was noted in relation to cumulative assessments, in which differences in turbine heights or ground heights on separate sites make determining cumulative immissions more complicated[179], which may benefit from further guidance.

Compliance assessments and cumulative impacts

Authors in the grey literature have highlighted the complexities of assessing compliance, and that this is made even more difficult when the cumulative impacts of multiple developments have to be considered[179,180]. It has been noted that there can be considerable difficulties involved in demonstrating compliance with the ETSU-R-97 'simplified' limit due to the low wind turbine sound levels, and that proxy measurement locations could be used to address this[181].

The benefits of proxy locations have also been considered for more general compliance testing applications, and it is noted that, although this could be used to overcome the issue of low wind turbine sound levels, the evaluation of sound characteristics would still require measurements to be made at receptor locations[182].

Turbine technology

Some implications of changes in the typical design of commercial wind turbines since ETSU-R-97 have been highlighted[183], primarily the larger size of turbines, entailing greater separation distances, which may mean that the sound immissions could have a somewhat lower-frequency character at long ranges.

Fixed speed and stall regulated turbines have been superseded by variable speed, pitch regulated models, which enables greater control flexibility. Bullmore et al (2015)[183] suggest this may enable operators to maximise power generation (and sound emissions) while staying within noise limits, which could impart more sustained impact than would previously have been possible.

[177] Bowdler, D, 2013. Wind turbine noise Good Practice Guide - 'the good and the bad'. *Acoustics Bulletin,* 38 (5), 36-37. [URL]
[178] Coulon, M, 2014. The complex wind speed referencing system in wind farm noise assessment. *Acoustics Bulletin,* 39 (4), pp. 30-35. [URL]
[179] Summers, S & Parry, G, 2021. *Further experience of reviewing noise assessments for wind farms in Scotland and the implementation of the IOA Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise.* Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe.
[180] Bullmore, A & McKenzie, A, 2015. What would an alternative to ETSU-R-97 look like? *Proceedings of the Institute of Acoustics*, 37 (2) 54-63. [URL]
[181] Sutherland, C, 2014. Practical challenges with post completion measurements of the ETSU-R-97 simplified 35dB(A) planning condition for wind turbines. *Acoustics Bulletin*, 39 (5), 34-38. [URL]
[182] Mackay, J, Coulon, m & Baldwin, J, 2016. The use of proxy measurements to determine wind farm noise compliance, what are the options, is there a need for further guidance? *Proceedings of the Institute of Acoustics*, 38 (1), 245-251. [URL]
[183] Bullmore, A & McKenzie, A, 2015. What would an alternative to ETSU-R-97 look like? *Proceedings of the Institute of Acoustics*, 37 (2) 54-63. [URL]

3.3.4 STAGE 1 REVIEW OUTCOME

The stage 1 review indicates that the two most prevalent issues identified in the literature concerning the ETSU-R-97 approach are:

1. the formulation of the limiting values (especially the night-time minimum limit) in relation to considerations of the likely noise effects, specifically that:
   - the underlying guidance used to support the limits has been superseded
   - it is unusual for night-time limits to be higher (less stringent) than for daytime
   - the application of the limits as pass/fail criteria precludes the assessment of impact
   - the sound level index employed in the limits is technically questionable
   - the balance between protection, robustness and simplicity should be reviewed
   - the different merits of relative and absolute limits in the context of wind turbine sound should also be reviewed
2. the guidance on the presence, character and control of AM:
   - that a specific control for AM is needed, over and above the consideration in ETSU-R-97
   - the most effective form of control should be established, ie, either a character penalty scheme, or a limit on occurrences of AM exceeding a given threshold

Accordingly, these two themes were carried forwards to use in the criteria for screening studies identified in the stage 2 search.

3.4 EVIDENCE CHARACTERISTICS

This section provides a broad overview of general characteristics identified from the evidence. The evidence review summaries supporting the discussion in this section can be found in Appendix B.

3.4.1 METADATA ANALYSIS

An overview of the numbers of publications identified by year during the search and screening process is shown in Figure 3-3.

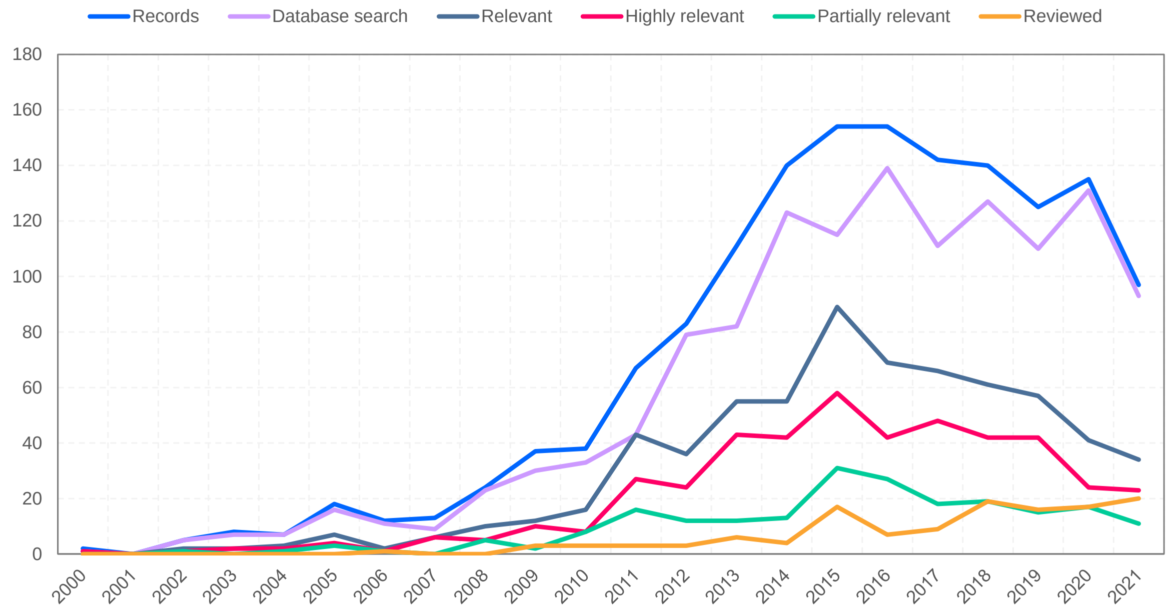


Figure 3-3: Overview of identified evidence by publication year

Figure 3-3 shows that the quantity of evidence identified remains relatively small until 2011, when a steep rise in the volume of publications is observed, which is consistent with the analysis of a previous scoping review[184]. This increase continues at a very similar rate until 2015, when the annual publication rate appears to peak, and then starts to drop gradually. Figure 3-3 also indicates that the evidence base for wind turbine sound and noise research is now considerable, and future reviews will need to carefully consider the effort involved in thoroughly investigating the available evidence.

The publication types in the evidence identified as 'highly relevant' are shown by publication year in Figure 3-4 (ie, the publication type breakdown of the 'highly relevant' line plotted in Figure 3-3). A similar pattern is observed, although it can be seen that the number of peer-reviewed journal articles has remained relatively high over the 2018-21 period compared with conference papers.

The publication types in the evidence reviewed is shown by publication year in Figure 3-5. Figure 3-5 illustrates the strategy employed in the screening process, which emphasises peer-reviewed evidence, and evidence published from 2015.

[184] Freiberg, A, Schefter, C, Girbig, M, Murta, VC & Seidler, A, 2019. Health effects of wind turbines on humans in residential settings: results of a scoping review. *Environmental Research*, 169, 446-463 [URL]

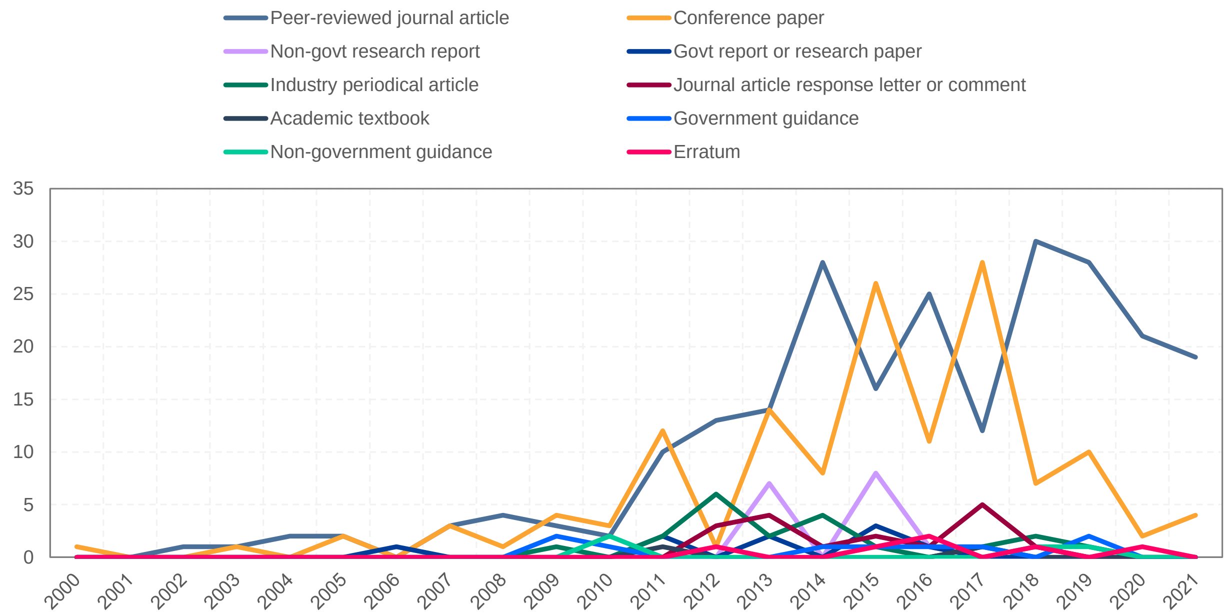


Figure 3-4: Publication types of 'highly relevant' evidence by publication year

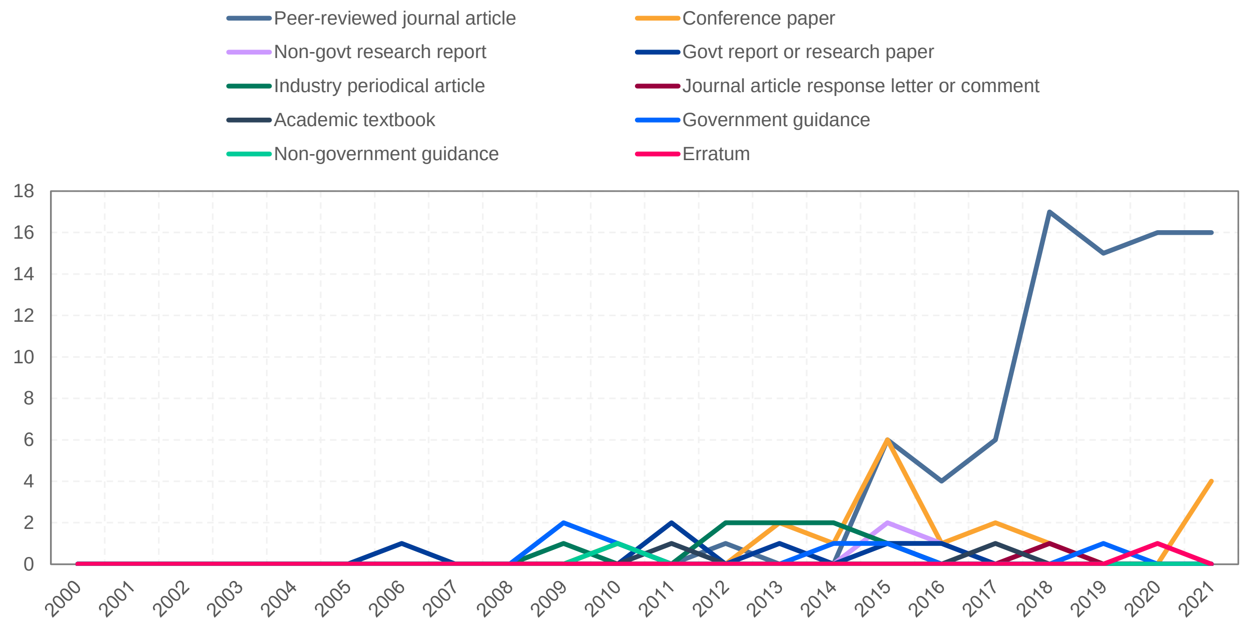


Figure 3-5: Publication types of reviewed evidence by publication year

3.4.2 OBSERVATIONAL STUDIES OF HEALTH EFFECTS

There have now been several large-scale epidemiological observational field studies undertaken around the world investigating the potential effects on people of wind turbine sound exposure. Some studies are so commonly cited that it is often convenient to refer to their results in shorthand by specifying the country. For clarity, the shorthand references to specific observational studies in the evidence review are summarised alongside the key publications in Table 3-3.

Table 3-3: Observational studies of health effects associated with wind turbine sound (non-exhaustive)

Study shorthand ref	Respondent sample size	Turbine powers	Effects studied (measurement indicator: s=subjective; o=objective)	Key publications
First Sweden study	351	500-650 kW	Annoyance; sleep quality (s)	Pedersen et al, 2004[185]
Second Sweden study	754	500 kW -1.5 MW	Annoyance; sleep quality (s); general health & wellbeing (s)	Pedersen et al, 2007[186]
Netherlands study	725	500 kW -2.5 MW	Annoyance; sleep quality (s); psychological distress (s)	Pedersen et al, 2009[187] Bakker et al, 2012[188]
Pooled Sweden and Netherlands studies	1755	500 kW-2.5 MW	Annoyance	Janssen et al, 2011[189]
New Zealand study	197	2.3 MW	Health-related quality of life (HRQoL)	Shepherd et al, 2011[190]
Japan study	1079	400 kW-3 MW	Annoyance; sleep quality (s); general health (s)	Kuwano et al, 2014[191] Kageyama et al, 2016[192]
First Poland study	156	150 kW-2 MW	Annoyance; general health (s)	Pawlaczyk-Łuszczyńska et al, 2014[193]
Second Poland study	361	100 kW-2.5 MW	Annoyance; general health (s)	Pawlaczyk-Łuszczyńska et al, 2014[194]

[185] Pedersen, E & Persson Waye, K, 2004. Perception and annoyance due to wind turbine noise—a dose-response relationship. *Journal of the Acoustical Society of America*, 116 (6), 3460-3470. [URL]
[186] Pedersen, E & Persson Waye, K, 2007. Wind turbine noise, annoyance and self-reported health and well-being in different living environments. *Occupational & Environmental Medicine*, 64 (7), 480-486. [URL]
[187] Pedersen, E, van den Berg, F, Bakker, R & Bouma, J, 2009. Response to noise from modern wind farms in The Netherlands. *Journal of the Acoustical Society of America*, 126 (2), 634-643. [URL]
[188] Bakker, RH, Pedersen, E, van den Berg, GP, Stewart, RE, Lok, W & Bouma, J, 2012. Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. *Science of the Total Environment*, 425, 42-51. [URL]
[189] Janssen, SA, Vos, H, Eisses, AR & Pedersen, E, 2011. A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. *Journal of the Acoustical Society of America*, 130 (6), 3746- 3753. [URL]
[190] Shepherd, D, McBride, D, Welch, D, Dirks, KN & Hill, EM, 2011. Evaluating the impact of wind turbine noise on health-related quality of life. *Noise & Health*, 13 (54), 333-339. [URL]
[191] Kuwano, S, Yano, T, Kageyama, T, Sueoka, S & Tachibana, H, 2014. Social survey on wind turbine noise in Japan. *Noise Control Engineering Journal*, 62 (6), 503-520. [URL]
[192] Kageyama, T, Yano, T, Kuwano, S, Sueoka, S & Tachibana, H, 2016. Exposure-response relationship of wind turbine noise with self-reported symptoms of sleep and health problems: A nationwide socioacoustic survey in Japan. *Noise & Health*, 18 (81), 53-61. [URL]
[193] Pawlaczyk-Łuszczyńska, M, Dudarewicz, A, Zaborowski, K, Zamojska-Daniszewska, M & Waszkowska, M, 2014. Evaluation of annoyance from the wind turbine noise: A pilot study. *International Journal of Occupational Medicine and Environmental Health*, 27 (3), 364-388. [URL]
[194] Pawlaczyk-Łuszczyńska, M, Dudarewicz, A, Zaborowski, K, Zamojska-Daniszewska, M & Waszkowska, M, 2014. Annoyance related to wind turbine noise. *Archives of Acoustics*, 39 (1), 89-102. [URL]

Study shorthand ref	Respondent sample size	Turbine powers	Effects studied (measurement indicator: s=subjective; o=objective)	Key publications
Third Poland study	517	100 kW-2.5 MW	Annoyance; general health (s) and specific symptoms (s)	Pawlaczyk-Łuszczyńska et al, 2018[195]
Health Canada study	1238	660 kW-3 MW	Annoyance; sleep quality (o+s); stress (o+s); general health (s) and specific symptoms (o+s)	Michaud et al, 2016[196,197,198,199] Michaud et al, 2018[200,201] Michaud et al, 2021[202]
China study	227	2 MW	Annoyance; sleep quality (s); general health (s)	Song et al, 2016
Finland study	429	3-5 MW	Annoyance; sleep quality (s); general health (s)	Hongisto et al, 2017[203] Radun et al, 2019[204]

[195] Pawlaczyk-Łuszczyńska, M, Zaborowski, K, Dudarewicz, A, Zamojska-Daniszewska, M & Waszkowska, M, 2018. Response to noise emitted by wind farms in people living in nearby areas. *International Journal of Environmental Research and Public Health*, 15 (8), 1575. [URL]
[196] Michaud, DS, Feder, K, Keith, SE, Voicescu, SA, Marro, L, Than, J, Guay, M, Denning, A, McGuire, D, Bower, T, Lavigne, E, Murray, BJ, Weiss, SK & van den Berg, F, 2016. Exposure to wind turbine noise: Perceptual responses and reported health effects. *Journal of the Acoustical Society of America*, 139 (3), 1443-1454. [URL]
[197] Michaud, DS, Feder, K, Keith, SE, Voicescu, SA, Marro, L, Than, J, Guay, M, Denning, A, Murray, BJ, Weiss, SK, Villeneuve, PJ, van den Berg, F & Bower, T, 2016. Effects of wind turbine noise on self-reported and objective measures of sleep. *Sleep*, 39 (1), 97-109. [URL]
[198] Michaud, DS, Keith, SE, Feder, K, Voicescu, SA, Marro, L, Than, J, Guay, M, Bower, T, Denning, A, Lavigne, E, Whelan, C, Janssen, SA, Leroux, T & van den Berg, F, 2016. Personal and situational variables associated with wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1455-1466. [URL]
[199] Michaud, DS, Feder, K, Keith, SE, Voicescu, SA, Marro, L, Than, J, Guay, M, Denning, A, Bower, T, Villeneuve, PJ, Russell, E, Koren, G & van den Berg, F, 2016. Self-reported and measured stress related responses associated with exposure to wind turbine noise. *Journal of the Acoustical Society of America*,
[200] Michaud, DS, Marro, L & McNamee, J, 2018. Derivation and application of a composite annoyance reaction construct based on multiple wind turbine features. *Canadian Journal of Public Health*, 109, 242-251. [URL]
[201] Michaud, DS, Marro, L & McNamee, J, 2018. The association between self-reported and objective measures of health and aggregate annoyance scores toward wind turbine installations. *Canadian Journal of Public Health*, 109, 252-260. [URL]
[202] Michaud, DS, Keith, ST, Guay, M, Voicescu, S, Denning, A, McNamee, JP, 2021. Sleep actigraphy time-synchronized with wind turbine output. *Sleep*, 44 (9), zsab070. [URL]
[203] Hongisto, V, Oliva, D & Keränen, J, 2017. Indoor noise annoyance due to 3-5 megawatt wind turbines – An exposure–response relationship. *Journal of the Acoustical Society of America*, 142 (4), 2185-2196. [URL]
[204] Radun, J, Hongisto, V & Suokas, M, 2019. Variables associated with wind turbine noise annoyance and sleep disturbance, Building and Environment, 150, 339-348. [URL]

Study shorthand ref	Respondent sample size	Turbine powers	Effects studied (measurement indicator: s=subjective; o=objective)	Key publications
Danish nationwide (case-crossover / cohort) study	National Danish population health register	All wind turbines installed in Denmark up to 2013 (≤ 6 MW)	Hypertension (o); adverse birth outcomes (o); myocardial infarction (o); stroke (o); sleep quality (o); depression (o)	Poulsen et al, 2018[205,206,207,208] Poulsen et al, 2019[209,210]
Danish nurse cohort study	Danish Nurse Organization (linked to national Danish population health register)	All wind turbines installed in Denmark up to 2013 (≤ 6 MW)	Myocardial infarction (heart attack), stroke, atrial fibrillation (heart contractions)	Bräuner et al 2018[211] Bräuner et al 2019[212,213]
US Dept of Energy (DoE) study	1043	1.5-2.5 MW	Annoyance	Haac et al 2019[214]
UK study	359	2.3-3.4 MW	Annoyance; sleep disturbance (s); general health (s) and specific symptoms (s)	Qu et al, 2021[215]

205 Poulsen, AH, Raaschou-Nielsen, O, Peña, A, Hahmann, AN, Nordsborg, RB, Ketzel, M, Brandt, J & Sørensen, M, 2018. Short-term nighttime wind turbine noise and cardiovascular events: A nationwide case-crossover study from Denmark. *Environment International*, 114, 160-166. [URL]

206 Poulsen, AH, Raaschou-Nielsen, O, Peña, A, Hahmann, AN, Nordsborg, RB, Ketzel, M, Brandt, J & Sørensen, M, 2018. Long-term exposure to wind turbine noise and redemption of antihypertensive medication: A nationwide cohort study. *Environment International*, 121 (1), 207-215. [URL]

207 Poulsen, AH, Raaschou-Nielsen, O, Peña, A, Hahmann, AN, Nordsborg, RB, Ketzel, M, Brandt, J & Sørensen, M, 2018. Long-term exposure to wind turbine noise at night and risk for diabetes: A nationwide cohort study. *Environmental Research*, 165, 40-45. [URL]

208 Poulsen, AH, Raaschou-Nielsen, O, Peña, A, Hahmann, AN, Nordsborg, RB, Ketzel, M, Brandt, J & Sørensen, M, 2018. Pregnancy exposure to wind turbine noise and adverse birth outcomes: A nationwide cohort study. *Environmental Research*, 167, 770-775. [URL]

209 Poulsen, AH, Raaschou-Nielsen, O, Peña, A, Hahmann, AN, Nordsborg, RB, Ketzel, M, Brandt, J & Sørensen, M, 2019. Long-term exposure to wind turbine noise and risk for myocardial infarction and stroke: A nationwide cohort study. *Environmental Health Perspectives*, 127 (3), 037004. [URL]

210 Poulsen, AH, Raaschou-Nielsen, O, Peña, A, Hahmann, AN, Nordsborg, RB, Ketzel, M, Brandt, J & Sørensen, M, 2019. Impact of long-term exposure to wind turbine noise on redemption of sleep medication and antidepressants: A nationwide cohort study. *Environmental Health Perspectives*, 127 (3), 037005. [URL]

211 Bräuner, EV, Jørgensen, JT, Duun-Henriksen, AK, Backalarz, C, Laursen, JE, Pedersen, TH, Simonsen, MK & Andersen, ZJ, 2018. Long-term wind turbine noise exposure and incidence of myocardial infarction in the Danish nurse cohort. *Environment International*, 121 (1), 794-802. [URL]

212 Bräuner, EV, Jørgensen, JT, Duun-Henriksen, AK, Backalarz, C, Laursen, JE, Pedersen, TH, Simonsen, MK & Andersen, ZJ, 2019. Long-term wind turbine noise exposure and the risk of incident atrial fibrillation in the Danish Nurse cohort. *Environment International*, 130, 104915. [URL]

213 Bräuner, EV, Jørgensen, JT, Duun-Henriksen, AK, Backalarz, C, Laursen, JE, Pedersen, TH, Simonsen, MK & Andersen, ZJ, 2019. Association between long-term exposure to wind turbine noise and the risk of stroke: Data from the Danish nurse cohort. *Journal of the American Heart Association*, 8 (14), e013157. [URL]

214 Haac, TR, Kaliski, K & Landis, M, 2019. Wind turbine audibility and noise annoyance in a national U.S. survey: Individual perception and influencing factors. *Journal of the Acoustical Society of America*, 146 (2), 1124-1141. [URL]

215 Qu, F, & Tsuchiya, A, 2021. Perceptions of wind turbine noise and self-reported health in suburban residential areas. *Frontiers in Psychology, 12*, 3357. [URL]

Exposure estimation

Levels of sound exposure in the studies have been quantified using a variety of methods. The most common approach is to use standard engineering models (such as ISO 9613-2[216]) to estimate 'worst-case' sound exposure. Commonly, this is defined as immissions downwind of turbines at a wind speed of 8 ms^{-1} (determined at a height of 10 m), which typically corresponds with modern turbines' maximum rated power output[217]. Many studies also apply adjustments to the L_{Aeq} exposure estimates to produce estimated long-term period-weighted annual average day-evening-night levels (L_{den}), in line with the EU 'Environmental Noise Directive'[218] index – as discussed further below, the adjustments applied vary between studies.

Some studies have used measurements to validate the modelling, usually at ranges closer than the study respondent locations. Uniquely, the Japan study took night-time measurement data from multiple locations around the target wind farm sites and used extrapolation or interpolation of the measurements to estimate the corresponding night-time levels at respondent locations.

The varying approaches used to quantify the exposure levels, including parametric inputs used in prediction models, make direct cross-study comparisons uncertain, which is discussed further in section 6.2.1.

Response estimation

Indicators of noise annoyance

Annoyance responses in wind turbine noise studies are typically obtained using numerical and descriptive scales, such as those in ISO 15666[219], which adopts 11-point numerical (0-10, 'not at all'-'extremely') or 5-point verbal ('not at all'-'slightly'-'moderately'-'very'-'extremely') scales. It is common for studies to analyse such response data by combining scoring categories to quantify binary outcomes such as 'percentage highly annoyed' (%HA) or 'percentage annoyed' (%A) within the population. The way in which different response scales have been employed and combined to form binary outcomes has some influence on the results, and makes direct comparisons between the results of varying published studies on wind turbine noise annoyance more complicated[220].

There are various methods that have been commonly employed in wind turbine noise effects research to derive exposure-response functions that map levels of sound exposure to noise annoyance outcomes. These include:

- the model described by Miedema et al, 2001[221] (applied to wind turbine sound by, eg, Janssen et al, 2011[222])

[216] ISO, 1996. *ISO 9613-2:1996 Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation*. International Organization for Standardization. [URL]
[217] As turbines increase in size, the maximum rated power (and maximum sound emission) can be realised at lower standardised 10 m height wind speeds, however the studies reviewed typically use model-specific turbine sound data to estimate the worst-case immissions
[218] *Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise - Declaration by the Commission in the Conciliation Committee on the Directive relating to the assessment and management of environmental noise* [URL]
[219] ISO, 2021, *ISO/TS 15666:2021. Acoustics – Assessment of noise annoyance by means of social and socio-acoustic surveys.* International Organization for Standardization. [URL] (NB: the studies cited in this report generally make use of the previous 2003 version)
[220] Klæboe, R & Sundfør, HB, 2016. Windmill noise annoyance, visual aesthetics, and attitudes towards renewable energy sources. *International Journal of Environmental Research and Public Health*, 13 (8), 746. [URL]
[221] Miedema, HME & Oudshoorn, CGM, 2001. Annoyance from transportation noise: Relationships with exposure metrics DNL and DENL and their confidence intervals. *Environmental Health Perspectives*, 109 (4), 409-416. [URL]
[222] Janssen, SA, Vos, H, Eisses, AR & Pedersen, E, 2011. A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. *Journal of the Acoustical Society America*, 130 (6), 3746-3753. [URL]

- the 'community tolerance level' (CTL) model (described by Fidell et al[223], and applied to wind turbine sound by, eg, Michaud et al, 2016[224])
- binary logistic regression (applied to wind turbine noise annoyance by, eg, Kuwano et al, 2014[225])
- ordinal logistic regression (applied to wind turbine noise annoyance by, eg, Klæboe et al, 2016[220])

One characteristic these models have in common is that they all describe an 'S-shaped' (sigmoidal) response outcome curve, as illustrated in Figure 3-6. However, the differences in the assumptions underlying the models mean that there will be variability in exposure-response functions that are related to the choice of model. In particular, the growth rate of the sigmoidal function varies between models; the CTL model assumes that annoyance increases in proportion to the standard loudness power law relationship (see section 2.1.2), with the result that the varying gradient of the exposure-response relationship always follows the same curve. Other models do not make this assumption, so that the fitted relationships can have varying growth rates.

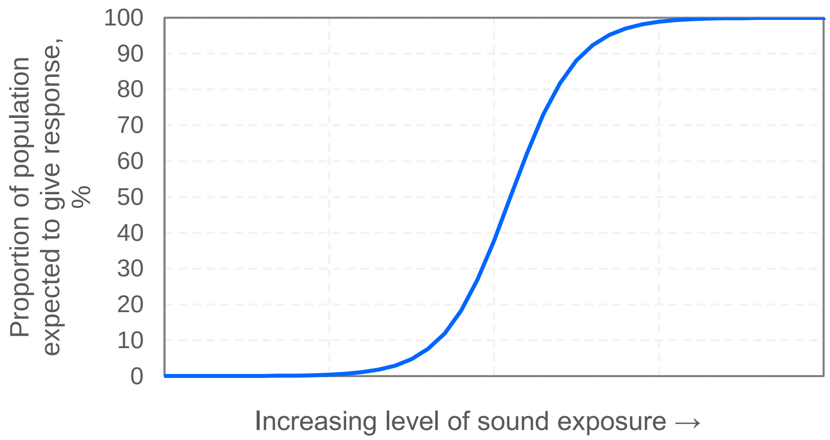


Figure 3-6: Generic example of exposure-response relationship model

The potential implications of these differences are demonstrated in Figure 3-7, which shows the resulting curves of two different models (that of Miedema et al[221], and the 'community tolerance level'[223] model) based on the same underlying exposure-response data (from the Finland study[226]). Figure 3-7 illustrates that the choice of model could potentially have a non-trivial influence on conclusions drawn from the data, and consequently on decisions made about relevant effects thresholds.

One of the main advantages of applying logistic regression models (or other forms of multiple regression analyses) is that the models can account for potential confounding variables (eg, 'personal and contextual factors', discussed further in this section below) where these have been investigated in the study. This means that response relationships can be expressed as a function of

[223] Fidell, S, Mestre, V, Schomer, P, Berry, B, Gjestland, T, Vallet, M & Reid, T, 2011. A first-principles model for estimating the prevalence of annoyance with aircraft noise exposure. *Journal of the Acoustical Society of America*, 130 (2), 791-806. [URL]
[224] Michaud, DS, Keith, SE, Feder, K, Voicescu, SA, Marro, L, Than, J, Guay, M, Bower, T, Denning, A, Lavigne, E, Whelan, C, Janssen, SA, Leroux, T & van den Berg, F, 2016. Personal and situational variables associated with wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1455-1466. [URL]
[225] Kuwano, S, Yano, T, Kageyama, T, Sueoka, S & Tachibana, H, 2014. Social survey on wind turbine noise in Japan. *Noise Control Engineering Journal*, 62 (6), 503-520. [URL]
[226] Hongisto, V, Oliva, D & Keränen, J, 2017. Indoor noise annoyance due to 3-5 megawatt wind turbines – An exposure–response relationship. *Journal of the Acoustical Society of America*, 142 (4), 2185-2196. [URL]

a sound exposure indicator while ‘controlling for’ (ie, holding constant) the influence of other variables that could otherwise affect (confound) the relationship.

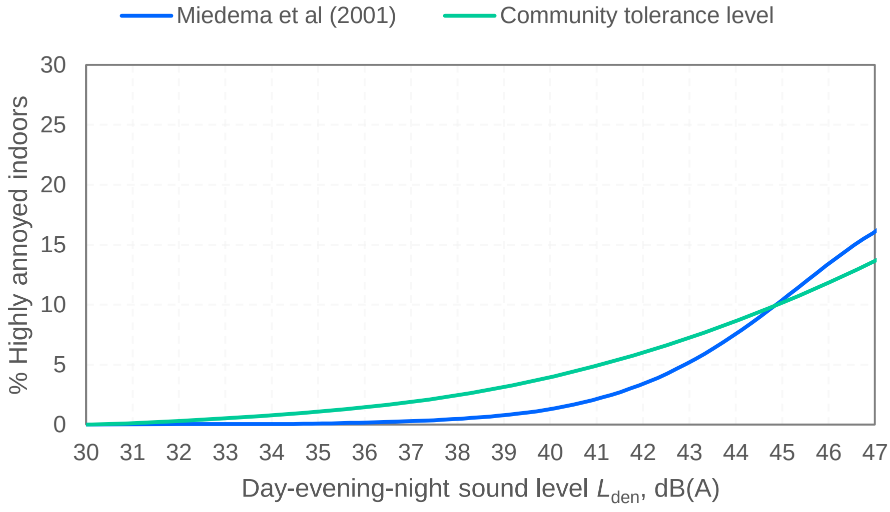


Figure 3-7: Example of influence from exposure-response model selection on derived exposure-response relationship (data from Hongisto et al, 2017[226])

It has been shown that uncertainty in the estimation of individual sound exposure has an influence on response curves derived using statistical models[228]. This includes uncertainty due to exposure modelling procedures, and also due to exposure interval categorisation (ie, sound level ‘binning’). This effect results in a smoothing of the sigmoid shape, such that responses at lower exposures (ie, below the mid-point of the curve shown in Figure 3-6) tend to be overestimated, while responses at higher exposures (above the mid-point of the curve) tend to be underestimated. In relation to wind turbine sound, since high levels of sound exposure are uncommon, this suggests that modelled responses may typically be overestimated, with the degree of overestimation linked to the magnitude of uncertainty in the exposure estimation.

Another form of response indicator commonly derived in wind turbine noise annoyance research analysis is the odds ratio (derived from binary logistic regression models), which represents the odds[229] of a specified response (eg, ‘highly annoyed’) corresponding with a given change in the level of sound exposure. Therefore, odds ratios (and similar quotient-based indicators, such as hazard ratios) must be specified relative to the baseline comparison level (or exposure category).

Personal and contextual factors

Personal and contextual factors are variables that are not an acoustic component of the sound source of interest[230] but could influence subjective responses to sound exposure. These have been categorised by van Kamp et al (2018)[231] as follows:

[228] Horonjeff, RD, 2021. An examination of dose uncertainty and dose distribution effects on community noise attitudinal survey outcomes. *Journal of the Acoustical Society of America*, 150 (3), 1691-1701. [URL]
[229] The ratio of the likelihood of an outcome and the likelihood the outcome will not occur.
[230] Sometimes described as ‘non-acoustic’ factors, but this description would not cover some factors that are considered here, such as the existing sound environment.
[231] van Kamp, I & van den Berg, F, 2018. Health effects related to wind turbine sound, including low-frequency sound and infrasound. *Acoustics Australia*, 46, 31-57 [URL]

- Situational, eg:
  - visual perception and impact of turbines
  - the general character of the area and the acoustic environment (in the absence of wind turbine sound)
- Demographic, eg:
  - age
  - socioeconomic status
- Personal, eg:
  - individual sensitivities to noise or other environmental stressors
  - economic benefits or financial involvement in wind energy developments
- Social, eg:
  - individual attitudes to wind turbines or wind energy, and how these can be influenced by messaging (eg, in the media)
  - trust in planning authorities, community involvement, and the perception of fairness in the wind farm development planning process

Many studies investigate these factors as potential confounding variables in statistical analyses.

Indicators of sleep disturbance

Sleep quality indicators used to investigate possible links between wind turbine sound exposure and disturbed sleep include subjective (ie, self-reporting) and objective measures, which are distinguished in the review below.

The first peer-reviewed observational studies to report objectively measured indicators of sleep quality in wind turbine research were published in 2016. Objective indicators of sleep quality used in the studies reviewed include:

- polysomnography (PSG), which monitors electrical activity in the brain (among other physiological processes) and involves attaching several electrodes to the subject
- actigraphy, which monitors motor activity using a single wrist-worn device

PSG is considered the most accurate way of monitoring sleep patterns but is more invasive, complicated, and costly, while actigraphy is simpler and cheaper, but is less accurate in distinguishing wake periods from sleep periods.

Indicators of other effects on health and quality of life

A wide range of other effects of wind turbine sound (and infrasound) exposure on psychological and physiological health and quality of life (QoL) have been investigated, but to a lesser extent than noise annoyance or sleep disturbance. Commonly, these investigations have comprised subjective self-assessment responses to survey questionnaires, but more recently, examples of objective indicators, such as stress hormone measurements, medication redemption and clinical diagnoses have been employed.

Clinical health outcomes due to wind turbine sound exposure are evaluated statistically using odds ratios, relative risk (ratio of outcome probabilities between different exposure groups), hazard ratios (ratio of outcome hazards between different exposure groups – similar to relative risk, but specific to time-limited conditions) or incidence rate ratios (ratio of incidence rates between different exposure groups). All of these measures express a form of proportional change in the outcome occurrences at a given exposure relative to a baseline – therefore, to hold meaning, the baseline exposure must be specified.

3.4.3 EXPERIMENTAL STUDIES

Exposure estimation

Many of the experimental studies reviewed address AM in wind turbine sound. Methods used to estimate AM depths of experimental sound stimuli vary between studies, which makes inter-study comparisons uncertain. Typically, the modulation depth is estimated from the 'peak-trough' level difference in the A-weighted sound level determined over very short intervals (eg, 1/10 to 1/8 second). The way in which this estimation is calculated, and the way in which the sound level time-series is determined, both influence the magnitude of the AM depth estimation. One study described in section 3.5.1 has systematically investigated this issue by reanalysing the sound samples used in published experiments with a consistent AM metric, to enable direct comparisons of the study results to be made[232] – among other things, the investigation indicated that differences in AM exposure estimations used across the various studies are often non-trivial, and can influence the conclusions. This observation was also a finding in the 2013 RenewableUK-funded AM study, which cautioned that:

> "*When discussing the effects of the modulation of signals it is therefore crucial to be consistent in the definition of the metric and the normalisation that is adopted. This point cannot be emphasised strongly enough.*"[233] [original authors' emphasis]

Response estimation

The most commonly studied effect of wind turbine sound in experiments is its contribution to noise annoyance. Typically, this is measured by presenting a sound with prescribed characteristics, and having the participants assign an annoyance rating (using a scale such as the IOS/TS 15666 11-point numerical scale) – this kind of approach is known as 'magnitude estimation'.

One study[234] employed the inverse procedure known as 'magnitude production', in which participants were asked to adjust the level of a sound until they judged it to match a prescribed annoyance rating.

Another form of experimental response scale is 'paired comparison', in which participants adjust a parameter (eg, sound level) of one sound to match another 'paired' sound in some subjective parameter, such as annoyance.

Other studies have addressed audibility of wind turbine sound when combined with other residual sounds, by having participants indicate when they felt they could detect wind turbine sound (eg[235]).

[232] Lotinga, M, & Lewis, T, 2021. *Subjective responses to wind turbine noise amplitude modulation: Pooled analysis of laboratory listening studies and synthesis of an AM character rating penalty*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe: INCE-Europe. [URL]
[233] Bullmore, A & Cand, M, 2013. Work package F: Collation of work package reports and final reporting. *Wind turbine amplitude modulation: research to improve understanding as to its cause & effect*. RenewableUK. [URL]
[234] Johansson, A, Bolin, K, & Alvarsson, J, 2019. Annoyance and partial masking of wind turbine noise from ambient sources. *Acta Acustica united with Acustica*, 105 (6), 1035-1041. [URL]
[235] Dutilleux, G, & Fosset, J, 2020. Comparing sound emergence and sound pressure level as predictors of short-term annoyance from wind turbine noise. *Acta Acustica*, 3 (4), 10. [URL]

3.5 EVIDENCE SYNTHESIS

The evidence review summaries and the full references supporting the synthesis in this section can be found in Appendix B.

3.5.1 PRIMARY RESEARCH QUESTION 1

- *Does the evidence indicate that the ETSU-R-97 guidance, when considered alongside the government-endorsed IOA best practice application guidance, requires updating to be consistent with the aims and objectives of current government policy and regulatory frameworks, and if so which aspects of it should be revised?*

Prioritised theme 1: Noise limits and effects

Noise limits

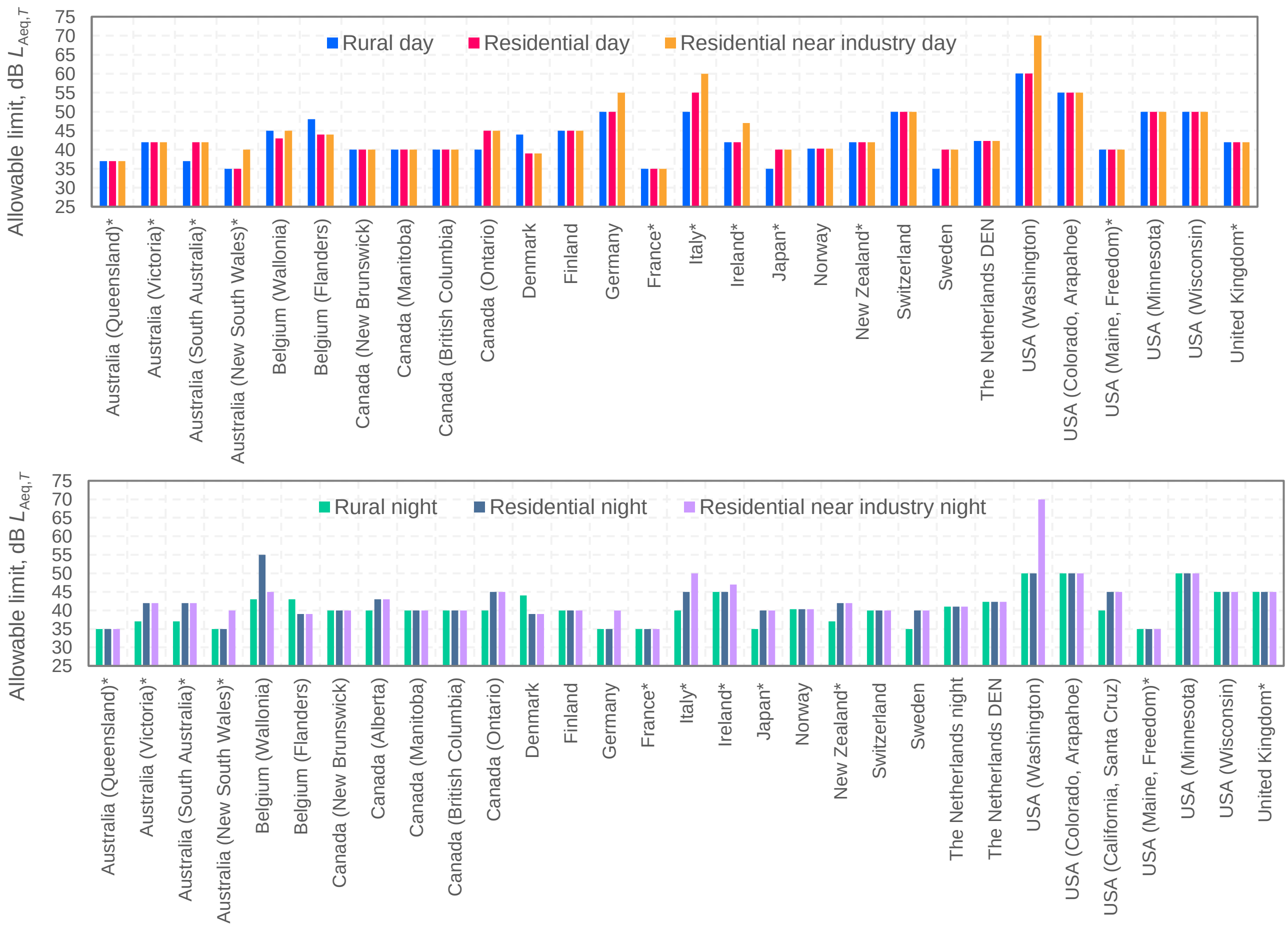
National and regional guidelines and regulations

A summary comparison of wind turbine noise limits imposed under several countries in Europe, Australasia and the US is presented by Alamir et al (2021)[236]. The regulations in Japan[237] are also relevant, since these were introduced following an extensive research programme, incorporating an observational field study of the effects of wind turbine sound exposure, and experimental work investigating the effects of AM, tonality and low-frequency sound associated with wind turbines[238]. The absolute limits from the corresponding territories are presented in Figure 3-8. It should be noted that in this comparison, adjustments have been applied to ensure broadly consistent sound level indices – it is acknowledged that there are technical issues with 'converting' between different sound level indices (as discussed further in section 6.2.1). The guidance in South Australia is complicated due to its specification of minimum noise limits in terms of $L_{Aeq,10min}$, while enabling compliance to be demonstrated by measurement using $L_{A90,10min}$, but without including any adjustment for the use of different measurement indices (see section 3.3.1 – the typical adjustment is expected to be ~2 dB). This means that turbine sound levels would be predicted at the development planning stage in terms of L_{Aeq}, but any compliance testing would effectively allow a more relaxed $L_{AF90,10min}$ target to be used as demonstration of compliance. This apparent anomaly has been highlighted in the literature[239], yet has been retained in a proposed update to the guidance, as published for consultation in 2019[240].

It is also important to note that the time bases employed in the limit values do vary between territories. Some of the limits displayed are referenced to 10-minute aggregation intervals (consistent with the ETSU-R-97 approach), ie, the short-term levels within the longer day or night periods. However, other approaches impose controls using longer averaging times, which means that short-term exceedances of the numerical values may still be compliant, if averaged with lower levels during the overall period. For example, the limits for Belgium are specified over 1 hour, the values for Switzerland are over 12 hours (day or night), the limits in Germany are 16-hour daytime and 1-hour night-time averages, values for Italy are over 16 hours daytime and 8 hours night, while

[236] Alamir, MA, Hansen, KL & Catcheside, P, 2021. Penalties applied to wind farm noise: Current allowable limits, influencing factors, and their development. *Journal of Cleaner Production*, 295 (2021). [URL]
[237] Shimada, A & Nameki, M, 2017. *Evaluation of wind turbine noise in Japan*. ICBEN 2017, 18-22 June, Zurich. International Commission on Biological Effects of Noise. [URL]
[238] Tachibana, H, Yano, H, Fukushima, A & Sueoka, S, 2014. Nationwide field measurements of wind turbine noise in Japan. *Noise Control Engineering Journal*, 62 (2), 90-101. [URL]
[239] Hansen, KL, Zajamsek, B, & Hansen, CH, 2018. Wind farm noise uncertainty: Prediction, measurement and compliance assessment. *Acoustics Australia,* 46, 59-67. [URL]
[240] Environment Protection Agency (State of South Australia), 2019. *Wind farms environmental noise guidelines 2019 – draft for consultation*. [URL]

the Netherlands and Norway limits refer to 24-hour (L_{den}) or 8-hour (L_{night}) averaging periods. Intercomparison of the values across differing time bases should therefore be viewed as broadly indicative only, and further work is advisable to consider these aggregation period discrepancies in greater detail. It is also noteworthy that Ireland is in the process of revising its guidance, the proposals for which[241] would also result in more stringent limits than those currently in place, which are based on the ETSU-R-97 limits (see Appendix B section 9.1.1).



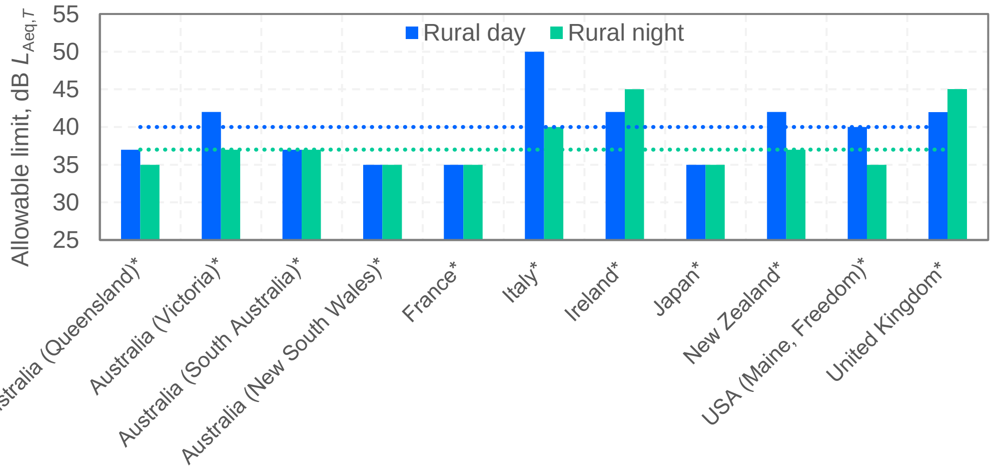
NB: for comparison purposes the following adjustments have been made: limit ranges have been displayed using the upper (least stringent) numeric value in any ranges; L_{AF90} values have been converted to estimated L_{Aeq} assuming a +2 dB difference (based on ETSU-R-97 and later evidence discussed in section 6.2.1); L_{den} values for the Netherlands and Norway have been converted to estimated L_{Aeq} assuming a -4.7 dB difference (based on van den Berg, 2008 - see section 6.2.1 for discussion on caution in converting index values)

Figure 3-8: Comparison of overseas national or regional wind turbine absolute noise limits (based on data in Alamir et al, 2021[236], supplemented with Shimada et al, 2017[237] and Ministry of the Environment, Finland, 2015[242]); a, top: daytime; b, bottom: night-time; L_{den} adjustment based on van den Berg, 2008[243]; *indicates territories that use some form of relative limit alongside absolute limits

[241] Government of Ireland, 2019. *Draft revised wind energy development guidelines.* [URL]
[242] Ministry of the Environment, Finland, 2015. *Valtioneuvoston asetus tuulivoimaloiden ulkomelutason ohjearvoista (1107/2015)* [Government Decree on guideline values for the outdoor noise level of wind turbines]. [URL]
[243] van den Berg, F, 2008. *Criteria for wind farm noise: Lmax and Lden*, Acoustics '08, 29 June – 4 July, Paris.

The comparison in Figure 3-8 indicates that, according to values provided in the cited references[236,237], the daytime ETSU-R-97 upper minimum limit (ie, 40 dB $L_{AF90,10min}$, which is roughly equivalent to 42 dB $L_{Aeq,10min}$) is comparable with or slightly below the majority of those of the other territories presented. On the other hand, the ETSU-R-97 minimum night-time limit (ie, 43 dB $L_{AF90,10min}$, roughly equivalent to 45 dB $L_{Aeq,10min}$) is comparable with, but slightly above the majority of those of the other territories presented.

It is also important to recognise that, as well as absolute limits, several of the nations and regions combine these with a form of relative limit. For those countries with regulations similar to ETSU-R-97 (Australia, Ireland, New Zealand and Japan), the relative limits are in the form of a margin above the background sound level. In Italy and France, the relative limits are in the form of 'sound emergence', which is a different concept of relative impact, defined in ISO 1996-1[244] as the level difference between the residual sound level and the ambient sound level (ie, the total L_{Aeq} including the residual sound *and* the wind turbine sound). In one US locality (Freedom, Maine), a relative limit is set on audible wind turbine sound relative to the pre-construction ambient sound, which is similar to sound emergence. A sub-set of the comparison of absolute limits focussing on the territories that also impose relative limits is shown in Figure 3-9. The comparison in Figure 3-9 also indicates that the ETSU-R-97 upper minimum daytime limit is comparable with those for the other territories presented, and is near the middle of the distribution of values. The ETSU-R-97 night-time minimum limit has the highest value (alongside Ireland). It is also notable that the only regulations with a night-time minimum limit that is higher (less stringent) than for daytime are those of the UK and Ireland (which based its guidelines on ETSU-R-97).

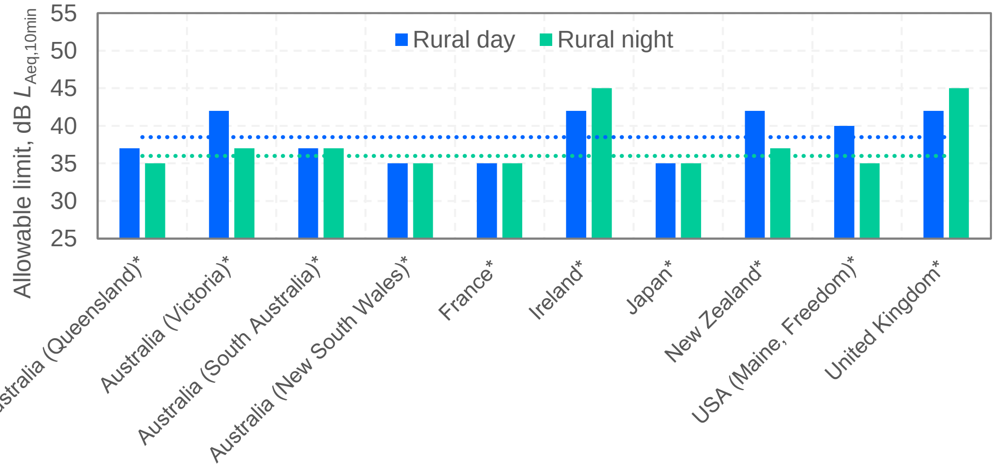


NB: for comparison purposes, the following adjustments have been made: limit ranges have been displayed using the upper (least stringent) numeric value in any ranges; L_{AF90} values have been converted to estimated L_{Aeq} assuming a +2 dB difference (based on ETSU-R-97 and later evidence discussed in section 6.2.1)

Figure 3-9: Comparison of overseas national or regional wind turbine minimum (upper) noise limits for territories with a limiting regime incorporating relative limits (based on data in Alamir et al, 2021[236], supplemented with Shimada et al, 2017[237]); dotted lines indicate median values

[244] ISO, 2016. *ISO 1996-1:2016 Acoustics – Description, measurement and assessment of environmental noise – Part 1: Basic quantities and assessment procedures.* International Organization for Standardization. [URL]

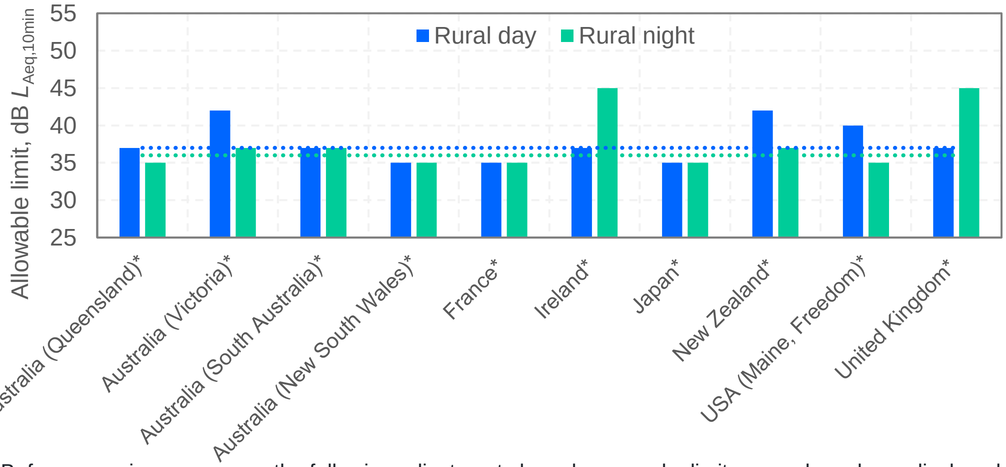
As discussed, aggregation intervals that differ from the 10-minute period used in ETSU-R-97 are employed among some of the defined limits. The limits for overseas territories that *are* defined using a 10-minute aggregation period are shown Figure 3-10.



NB: for comparison purposes, the following adjustments have been made: limit ranges have been displayed using the upper (least stringent) numeric value in any ranges; L_{AF90} values have been converted to estimated L_{Aeq} assuming a +2 dB difference (based on ETSU-R-97 and later evidence discussed in section 6.2.1)

Figure 3-10: Comparison of overseas national or regional wind turbine minimum (upper) noise limits for territories with a 10-minute aggregation period (based on data in Alamir et al, 2021[236], supplemented with Shimada et al, 2017[237]); dotted lines indicate median values

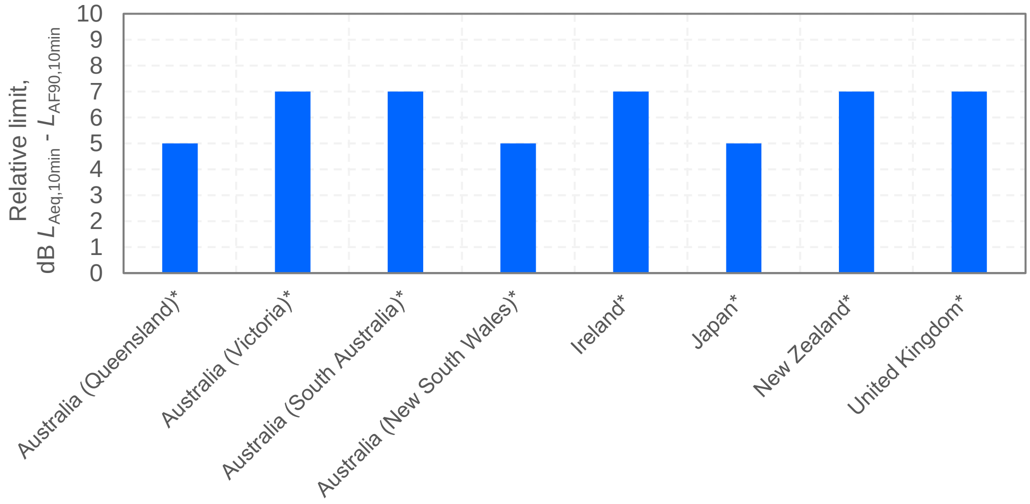
Here, both the ETSU-R-97 daytime minimum limit and the night-time minimum limit are equal to the highest values in each range. However, it should be noted that this analysis so far disregards the potential for a lower daytime minimum limit in the range 35-40 dB $L_{AF90,10min}$ to be specified in accordance with ETSU-R-97. If, instead of taking the *upper* minimum limit values, the analysis takes the *lower* values (for both the UK and overseas territories), the ETSU-R-97 daytime minimum limit is in the middle of the distribution, as shown in Figure 3-11.



NB: for comparison purposes, the following adjustments have been made: limit ranges have been displayed using the lower (most stringent) numeric value in any ranges; L_{AF90} values have been converted to estimated L_{Aeq} assuming a +2 dB difference (based on ETSU-R-97 and later evidence discussed in section 6.2.1)

Figure 3-11: Comparison of overseas national or regional wind turbine minimum (lower) noise limits for territories with a 10-minute aggregation period (based on data in Alamir et al, 2021[236], supplemented with Shimada et al, 2017[237]); dotted lines indicate median values

The relative limits in place vary slightly: territories with a 'margin above background sound level' relative limit are compared in Figure 3-12. This shows that some Australian states and Japan have a relative limit that is 2 dB more stringent than that imposed in the UK, Ireland and New Zealand. This difference also coincides with the choice of sound level index used to define the relevant controlling values: in the UK, Ireland, New Zealand and the states of South Australia and Victoria, this is the $L_{AF90,10min}$; in Japan and the states of New South Wales and Queensland, the $L_{Aeq,10min}$ is used to define the relative limits for turbine sound levels (relative to background sound levels $L_{AF90,10min}$).



NB: for comparison purposes the following adjustments have been made: L_{AF90}(wind turbine)-L_{AF90}(background) values have been converted to estimated L_{Aeq}(wind turbine)-L_{AF90}(background) assuming a +2 dB difference (based on ETSU-R-97 and later evidence discussed in section 6.2.1)

Figure 3-12: Comparison of overseas national or regional wind turbine relative noise limits for territories with a 'margin above background sound level' regime

This analysis of overseas national and regional noise limits supports the notion that the ETSU-R-97 daytime minimum noise limits are comparable with other territories, while the night-time minimum noise limit tends to be less stringent. It should be noted that this analysis has been based mainly on secondary literature sources, and should be considered indicative only; further review is recommended to confirm the information identified, review any updated information, and to consider the comparability of limits defined using different aggregation periods.

Alongside the UK, overseas nations or regions that also allow a less stringent limit to be applied to properties with financial involvement in the wind turbine development include Ireland, and the Australian states of Queensland, Victoria and South Australia (NB: this aspect has only been briefly considered in this review, and further investigation using primary literature sources would be necessary to confirm the approach taken in other territories).

Outdoor-indoor attenuation assumptions

In devising the night-time minimum noise limit, ETSU-R-97 assumes that the attenuation of (A-weighted) wind turbine sound from outdoors to indoors provided by a building envelope with its windows open is 10 dB. Evidence from the Health Canada study[245] indicates that typical open

[245] Keith, SE, Michaud, DS, Feder, KP, Soukhovtsev, V, Voicescu, SA, Denning, AR, Tsang, J, Broner, N & Richarz, WG, 2019. Wind turbine audibility calculations inside dwellings. *Journal of the Acoustical Society of America*, 145 (4), 2435-2444. [URL]

windows[246] achieve ~14 dB measured attenuation (standard deviation: ~3 dB) for outdoor free-field wind turbine sound levels to indoor levels (in a furnished bedroom). Further evidence from studies in which similar estimations of building envelope attenuation of wind turbine sound (with windows open) have been obtained from measurements is discussed in section 6.2.1.

Low frequency noise limits

The wind turbine sound regulation in Denmark includes a specific limit for A-weighted indoor low frequency sound levels in the range 10-160 Hz, which is 25 dB $L_{\mathrm{Aeq(10\text{-}160Hz)}}$ during the day and 20 dB $L_{\mathrm{Aeq(10\text{-}160Hz)}}$ at night.

A review undertaken for the Australian government concluded that there is insufficient evidence on the effects of low frequency sound and infrasound (discussed further below) to recommend any limits[247].

Another review showed that C-weighted wind turbine sound levels are unlikely to exceed criteria for low frequency noise disturbance while A-weighted levels are below ~48 dB L_{Aeq}, and concluded that no specific low frequency limits are necessary to control wind turbine sound beyond limits on A-weighted levels[248] (which have been shown in controlled experiments to provide a reliable estimator for the perceived loudness of wind turbine sound[249]).

Community tolerance-based limits

Davy et al (2018)[250] proposed noise limits for wind turbine sound based on limiting expected 'high annoyance' to ≤10%. To inform this, Davy et al used results presented by Michaud et al (2016)[251], who applied the Community Tolerance Level (CTL) model of responses to derive CTL values for each of six sets of noise annoyance exposure-response data, comprising the two regions included in the Health Canada study (which showed different results for each region), the first and second Sweden studies, the Netherlands study, and the Japan study (see Table 3-3 for key references). Davy et al converted the corresponding CTL curves from day-night sound level L_{dn} into $L_{\mathrm{AF90,10min}}$ using a series of assumptions, including the distribution of sound levels within different daytime periods. The converted curves were averaged to produce a single exposure-response function, and it was suggested that a limit based on mitigating annoyance could be taken from the curve at 10% highly annoyed. As shown in Figure 3-13, this resulted in a proposed limit of 35 dB $L_{\mathrm{AF90,10min}}$. In comparison with the national and regional regulations shown in Figure 3-8, it can be seen that this value (equivalent to ~37 dB $L_{\mathrm{Aeq,10min}}$) would fall towards the lower end of the range of limits imposed. The validity of the assumptions made by Davy et al in deriving the function shown in Figure 3-13, and the effect of adopting alternative assumptions, are discussed further in section 6.2.1.

[246] Although the measurements were undertaken on Canadian housing stock (which uses predominantly timber-framed construction), the attenuation with windows open would be largely dictated by the opening, which was set to give a window gap of 100-150 mm.
[247] Davy, JL, Burgemeister, K, Hillman, D & Carlile, S, 2020. A review of the potential impacts of wind turbine noise in the Australian context. *Acoustics Australia*, 48 (2), 181-197. [URL]
[248] Hessler, G, Leventhall, G, Schomer, P, & Walker, B, 2017. Health effects from wind turbine low frequency noise & infrasound: Do wind turbines make people sick? That is the issue. *Sound and Vibration*, 51 (1), 34-44. [URL]
[249] Yokoyama, S, Sakamoto, S, Tsujimura, S, Kobayashi, T & Tachibana, H, 2015. Loudness experiment on general environmental noises considering low-frequency components down to infrasound. *Acoustical Science and Technology*, 36 (1), 24-30. [URL]
[250] Davy, JL, Burgemeister, K & Hillman, D, 2018. Wind turbine sound limits: current status and recommendations based on mitigating noise annoyance. *Applied Acoustics*, 140 (2018), 288-295. [URL]
[251] Michaud, DS, Keith, SE, Feder, K, Voicescu, SA, Marro, L, Than, J, Guay, M, Bower, T, Denning, A, Lavigne, E, Whelan, C, Janssen, SA, Leroux, T & van den Berg, F, 2016. Personal and situational variables associated with wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1455-1466. [URL]

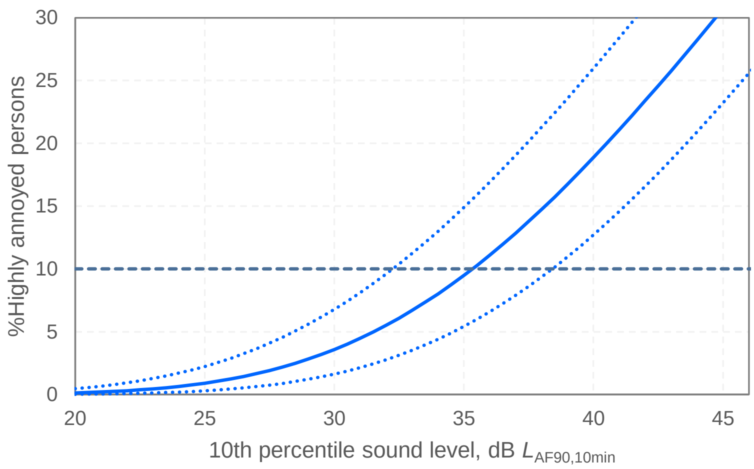


Figure 3-13: Community Tolerance Level model-based limits for mitigating annoyance at 10% HA, proposed by Davy et al (2018)[250]; solid line: mean CTL curve; dotted lines: mean CTL curve ±1 standard deviation; dashed line: 10% HA mark

Effects of noise

Noise annoyance

The evidence reviewed (see Appendix B) indicates that noise annoyance is by far the most investigated and consistently identified adverse effect of wind turbine sound exposure, and is systematically associated with wind turbine sound levels:

- Exposure-response relationships for wind turbine noise annoyance have been determined in numerous studies, as discussed further below.
- Several studies indicate that:
  - at (worst-case) exposure levels of around 35 dB L_{Aeq} or lower, relatively insignificant proportions (typically ≤5%) of the participants in the areas studied tend to report feeling 'highly annoyed'[252] (eg[253,254,255,256,257,258])

[252] Here, 'highly annoyed' has been determined using the approach described by Miedema, HME & Oudshoorn, CGM, 2001. Annoyance from transportation noise: Relationships with exposure metrics DNL and DENL and their confidence intervals. *Environmental Health Perspectives*, 109 (4), 409-416. [URL]: the different response scales used in the studies have first been transformed to a 0-100 scale. The transformed scales are then used to define 'highly annoyed' as either a) the top 40% of the scale – this is the selection made in the Health Canada study, which enables comparison with the published data from the six selected studies, or b) the top 28% of the scale (the selection used in many previous noise effect studies – this selection precludes the use of the Health Canada data, which has not been published in a form that would enable this transformation). The differences in response scalings are expected to have influenced the annoyance prevalence results, and the analysis presented here should therefore be interpreted as indicative only.
[253] Pedersen, E & Persson Waye, K, 2004. Perception and annoyance due to wind turbine noise – a dose-response relationship. *Journal of the Acoustical Society of America*, 116 (6), 3460-3470. [URL]
[254] Bakker, RH, Pedersen, E, van den Berg, GP, Stewart, RE, Lok, W & Bouma, J, 2012. Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. *Science of the Total Environment*, 425, 42-51. [URL]
[255] Michaud, DS, Feder, K, Keith, SE, Voicescu, SA, Marro, L, Than, J, Guay, M, Denning, A, McGuire, D, Bower, T, Lavigne, E, Murray, BJ, Weiss, SK & van den Berg, F, 2016. Exposure to wind turbine noise: Perceptual responses and reported health effects. *Journal of the Acoustical Society of America*, 139 (3), 1443-1454. [URL]
[256] Hongisto, V, Oliva, D & Keränen, J, 2017. Indoor noise annoyance due to 3-5 megawatt wind turbines – An exposure–response relationship. *Journal of the Acoustical Society of America*, 142 (4), 2185-2196. [URL]
[257] Haac, TR, Kaliski, K, Landis, M, Hoen, B, Rand, J, Firestone, J, Elliott, D, Hübner, G & Pohl, J, 2019. Wind turbine audibility and noise annoyance in a national U.S. survey: Individual perception and influencing factors. *Journal of the Acoustical Society of America*, 146 (2), 1124-1141. [URL]
[258] Qu, F, & Tsuchiya, A, 2021. Perceptions of wind turbine noise and self-reported health in suburban residential areas. *Frontiers in Psychology, 12*, 3357. [URL]

- at levels exceeding 35 dB L_{Aeq}, the inter-study variation in annoyance responses tends to increase – for example, see Figure 3-14 and Figure 3-15, which present annoyance prevalence data from six major field studies in Europe and North America[259] (NB: the response scales used in these studies varied, so the data shown in Figure 3-14 and Figure 3-15 has been transformed using a common approach[252], and should be interpreted as broadly indicative and illustrative only). In the UK study included in Figure 3-14 and Figure 3-15, it was noted that annoyance tended to be somewhat lower than in previous studies. This was thought to be due to the localities investigated, which comprised suburban areas, as well as relatively positive attitudes to wind energy identified among respondents. This study and its results are discussed in more detail below.
- it is common for the proportions of study participant samples in each sound exposure category to vary considerably: there are typically smaller numbers of participants in the highest (and sometimes lowest) exposure categories, which implies greater uncertainty in the responses at the exposure extrema

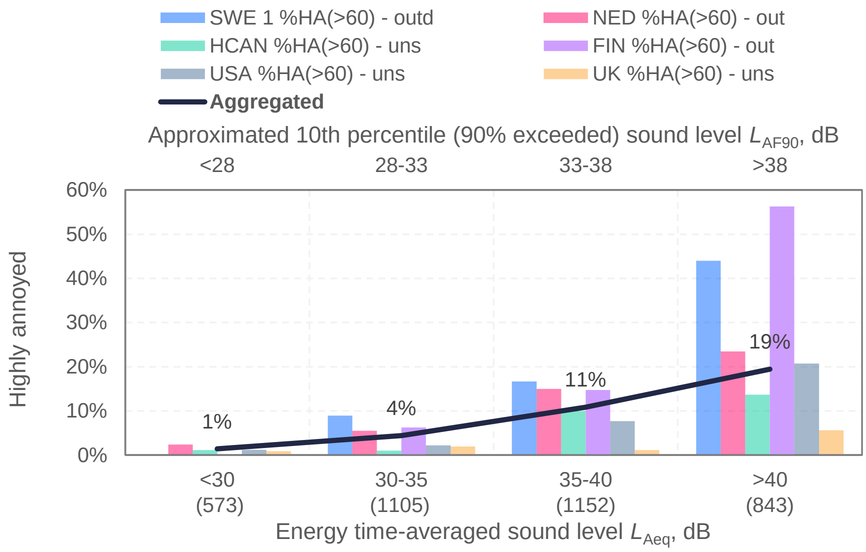


Figure 3-14: Illustrative comparison of annoyance prevalence data for six observational studies[260] (aggregate sample size *N*: 3673); response transformed to common scale with a >60% 'highly annoyed' cutoff value[252], along with specified response location (outdoors, or unspecified) ; participant numbers in each category shown in brackets

[259] These studies have been selected according to the availability of data and relative similarity in exposure and response variables.
[260] SWE 1 = 1st Sweden study, NED = Netherlands study, HCAN = Health Canada study, FIN = Finland study, USA = US DoE study, UK = UK study; see Table 3-3

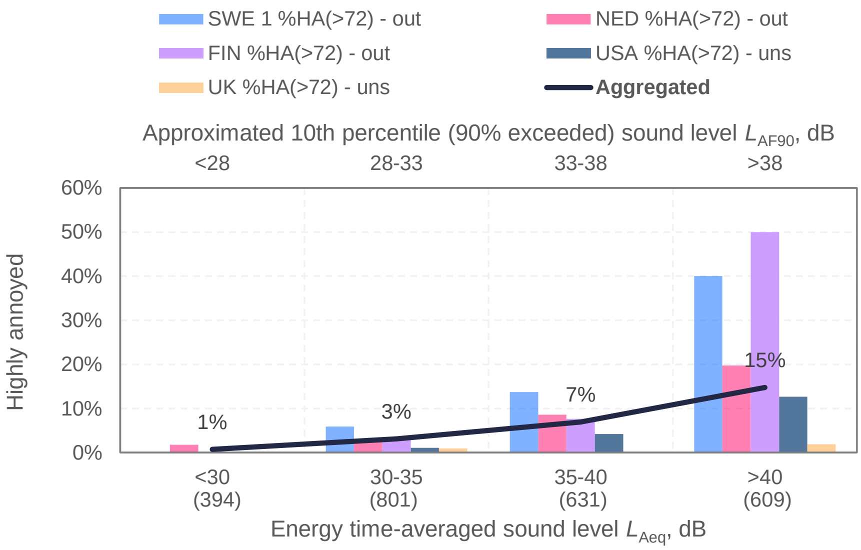


Figure 3-15: Illustrative comparison of annoyance prevalence data for five observational studies[260] (aggregate sample size *N*: 2435); response transformed to common scale with a >72% 'highly annoyed' cutoff value[252], along with specified response location (outdoors, or unspecified) ; participant numbers in each category shown in brackets

The UK observational study[261] investigated the effects of wind turbine sound exposure in suburban communities around three commercial wind turbine sites. The sites studied were small, comprising only one or two turbines, and the generalisability of the study is limited by the localities and demographics involved. Sound exposure was quantified as a worst-case estimate using predictive modelling. Noise annoyance prevalence and sound perception data from the study are shown in Figure 3-16 and Figure 3-17, for two different sets of exposure categories[262,263].

The set of categories in Figure 3-16 corresponds with the original categories used in the study (and those shown in Figure 3-14 and Figure 3-15). By contrast, the exposure categories in Figure 3-17 are shifted by +2 dB, to correspond more closely with the ETSU-R-97 noise limit values (in terms of L_{AF90}). Figure 3-17 indicates that for levels of sound exposure exceeding 42 dB L_{Aeq} (~40 dB L_{AF90}), prevalence of high annoyance increased to 16%, which can be compared with only 6% for the upper exposure category >40 dB L_{Aeq} (~38 dB L_{AF90}) shown in Figure 3-16. However, the numbers of participants in the highest exposure categories were relatively small (~5% of the total sample were in the >42 dB L_{Aeq} category, while ~15% were in the >40 dB L_{Aeq} category), so this observation must be treated with caution. For exposure categories below 42 dB L_{Aeq} (~40 dB L_{AF90}), which comprised ~95% of the sample, prevalence of high annoyance was ~0-2%. As noted above, the authors highlighted that these results are unlikely to be representative for other communities, such as those living in rural areas.

261 Qu, F, & Tsuchiya, A, 2021. Perceptions of wind turbine noise and self-reported health in suburban residential areas. *Frontiers in Psychology, 12*, 3357. [URL]
262 Qu, F, 2021. Personal communication.
263 The response scaling in the figures represents >60% HA scaling – see footnote 252 for details

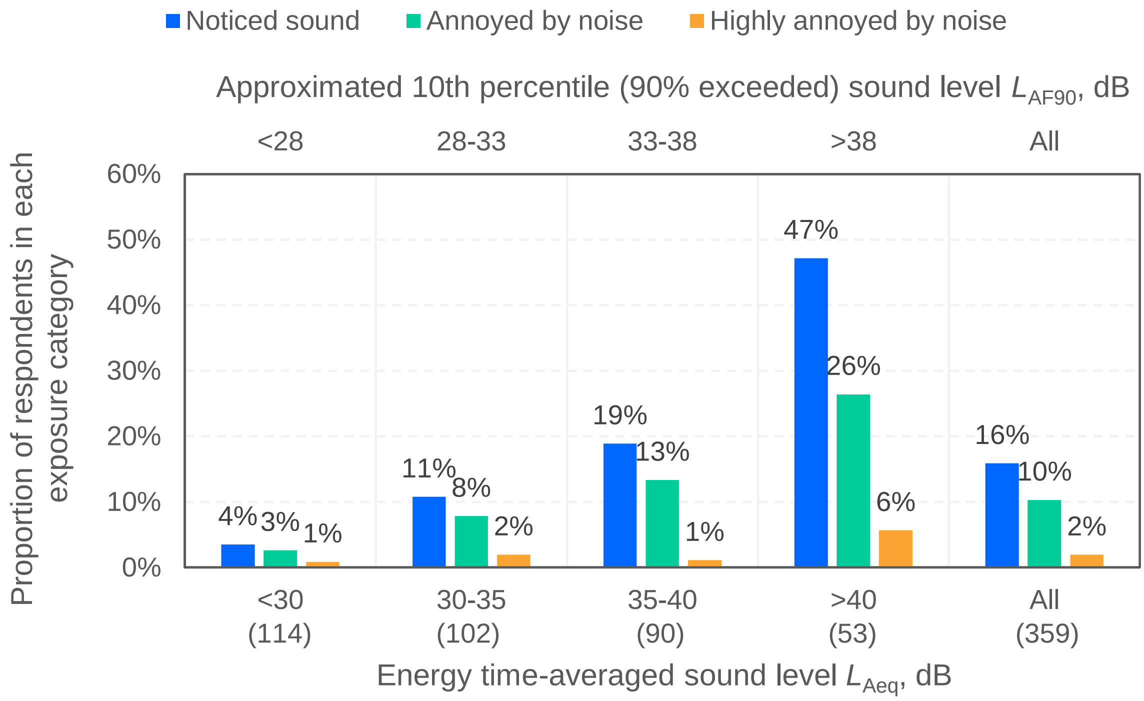


Figure 3-16: Noise annoyance and sound perception prevalence results for 359 UK respondents in suburban communities (data provided by Qu, 2021[262]); participant numbers in each category shown in brackets

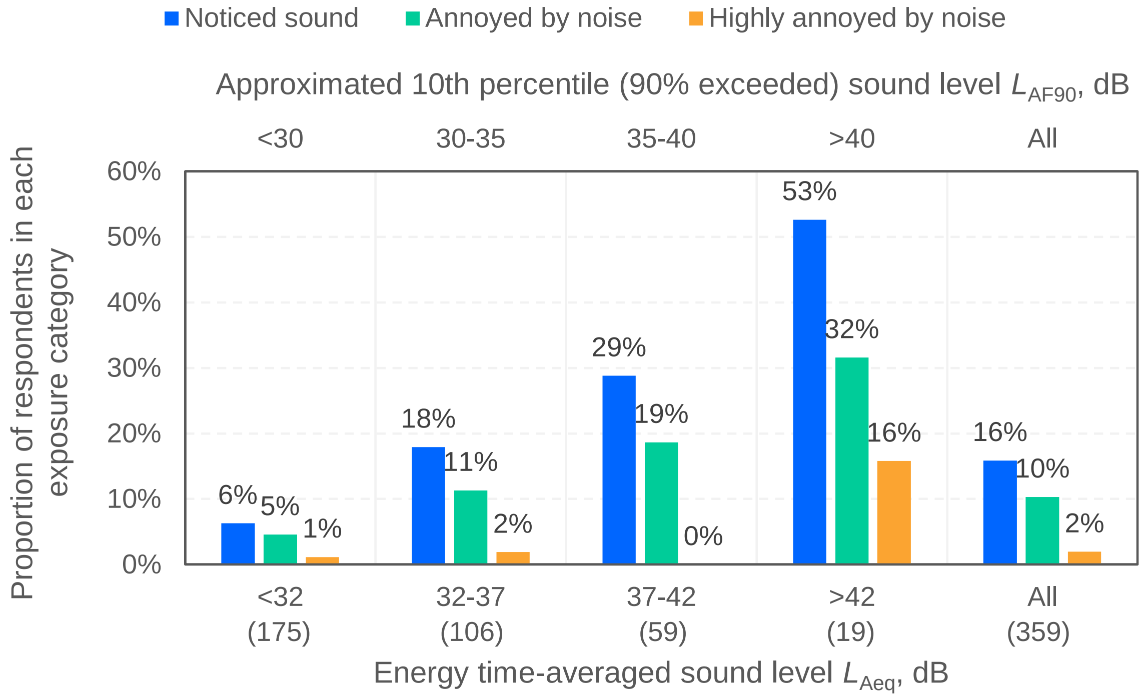


Figure 3-17: Noise annoyance and sound perception prevalence results for 359 UK respondents in suburban communities (data provided by Qu, 2021[262]); participant numbers in each category shown in brackets – exposure categories adjusted by +2 dB (compared with Figure 3-16)

Studies have also shown that noise annoyance associated with wind turbine sound tends to be greater than for other common sources of environmental sound, such as transportation:

- For example, the results of some observational and experimental studies have indicated that equivalent noise annoyance responses to wind turbine sound may be expected to occur at levels of sound exposure that are around 4-18 dB lower than those that produce the same annoyance responses to road traffic sound[264,265,266,267].
- Estimates of the differences vary between studies, comparisons of which are complicated by the use of different exposure metrics and varying models for quantifying noise annoyance responses.

The evidence indicates that noise annoyance can be aggravated by sound characteristics, including AM (examined further below), and can be strongly influenced by various personal and contextual factors, including (eg[268,269,270,271]):

- visual impacts of turbines (associated with increased annoyance)
- individual attitudes to wind turbines or wind energy, and how these can be influenced by messaging (negative attitudes associated with increased annoyance)
- individual sensitivity to noise (heightened sensitivity associated with increased annoyance)
- economic benefits or financial involvement in wind energy developments (benefits or involvement associated with reduced annoyance)
- the character of the area and the acoustic environment in the absence of wind turbine sound (some evidence indicates greater annoyance in quieter, rural environments)
- long-term duration of exposure (some evidence suggests possible sensitisation to wind turbine sound, ie, increasing duration associated with increased annoyance)
- trust in planning authorities, community involvement, and the perception of fairness in the wind farm development planning process (perception of unfairness, lack of trust and lack of community involvement associated with increased annoyance)

The influence of personal and contextual factors can result in widely varying responses to noise, as exemplified in an exposure-response relationship developed using the data collected from 517 respondents in the 3rd Poland study[272], as shown in Figure 3-18. Figure 3-18 shows that, at an estimated (worst-case downwind) exposure level of 42 dB L_{Aeq}, the %HA predicted by the regression model varied from around 0.3%-90%, depending on individual attitudes to wind turbines, ranging from 'very positive' to 'very negative'; for people with 'no opinion' the %HA at 42 dB L_{Aeq} predicted by

[264] Janssen, SA, Vos, H, Eisses, AR & Pedersen, E, 2011. A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. *Journal of the Acoustical Society America*, 130 (6), 3746-3753 [URL]
[265] Michaud, DS, Keith, SE, Feder, K, Voicescu, SA, Marro, L, Than, J, Guay, M, Bower, T, Denning, A, Lavigne, E, Whelan, C, Janssen, SA, Leroux, T & van den Berg, F, 2016. Personal and situational variables associated with wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1455-1466. [URL]
[266] Schäffer, B, Schlittmeier, SJ, Pieren, R, Heutschi, K, Brink, M, Graf, R, & Hellbrück, J, 2016. Short-term annoyance reactions to stationary and time-varying wind turbine and road traffic noise: A laboratory study. *Journal of the Acoustical Society of America*, 139 (5), 2949-2963. [URL]
[267] Klæboe, R & Sundfør, HB, 2016. Windmill noise annoyance, visual aesthetics, and attitudes towards renewable energy sources. *International Journal of Environmental Research and Public Health*, 13 (8), 746. [URL]
[268] Onakpoya, IJ, O'Sullivan, J, Thompson, MJ & Heneghan, CJ, 2015. The effect of wind turbine noise on sleep and quality of life: a systematic review and meta-analysis of observational studies. *Environment International*, 82, 1-9 [URL]
[269] van Kamp, I & van den Berg, F, 2018. Health effects related to wind turbine sound, including low-frequency sound and infrasound. *Acoustics Australia*, 46, 31-57 [URL]
[270] Freiberg, A, Schefter, C, Girbig, M, Murta, VC & Seidler, A, 2019. Health effects of wind turbines on humans in residential settings: results of a scoping review. *Environmental Research*, 169, 446-463 [URL]
[271] van Kamp, I, & van den Berg, F, 2021. Health effects related to wind turbine sound: An update. *International Journal of Environmental Research and Public Health*, 18 (17), 9133. [URL]
[272] Pawlaczyk-Łuszczyńska, M, Zaborowski, K, Dudarewicz, A, Zamojska-Daniszewska, m & Waszkowska, M, 2018. Response to noise emitted by wind farms in people living in nearby areas. *International Journal of Environmental Research and Public Health*, 15 (8), 1575. [URL]

the model is ~17%. This example illustrates the very wide range in subjective responses to wind turbine sound, as well as the potentially strong influence of personal factors. It also indicates that finding ways to encourage people to have a more positive attitude towards wind turbines could have a considerable beneficial effect on reducing noise annoyance.

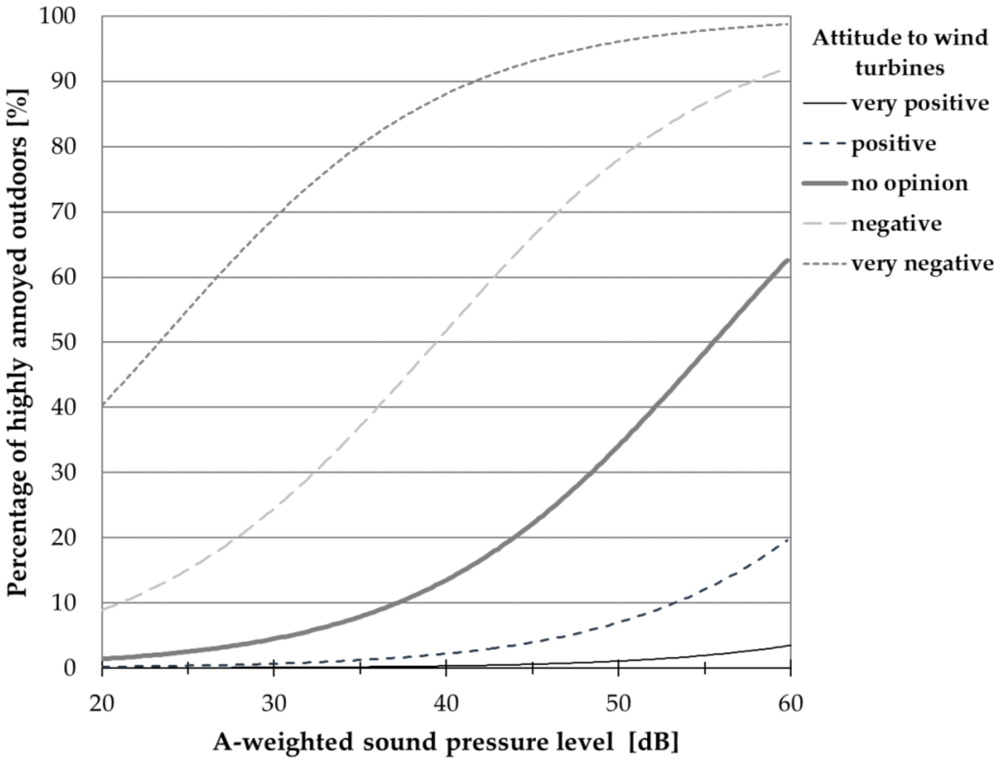


Figure 3-18: Exposure-response relationship example illustrating the variation in response depending on individual attitudes to wind energy (figure from Pawlaczyk-Łuszczynska et al, 2018[272]; image used under Creative Commons Attribution (CC BY) licence)

The UK study[273] also demonstrated that responses (for noise annoyance and for other self-reported health symptoms) can be influenced by the design of questionnaires used to investigate wind turbine sound. Specifically, drawing attention to wind turbines as a particular focus had a significant effect on responses, compared with an alternative questionnaire design that applied masking of the study intent. The authors speculated that this effect is likely to depend on personal attitudes towards wind energy, which in the UK study were relatively positive (and adverse responses to wind turbine sound in the main study group were found to be lesser than those in the 'masked intent' control group).

Noise annoyance associated with wind turbine sound:

- is often connected as a mediating pathway with adverse effects on subjective sleep quality[274]

[273] Qu, F, & Tsuchiya, A, 2021. Perceptions of wind turbine noise and self-reported health in suburban residential areas. *Frontiers in Psychology, 12*, 3357. [URL]
[274] Klæboe, R & Sundfør, HB, 2016. Windmill noise annoyance, visual aesthetics, and attitudes towards renewable energy sources. *International Journal of Environmental Research and Public Health*, 13 (8), 746. [URL]

- is inconsistently connected with increased self-reported stress and reduced quality of life; earlier and lower quality studies tend to identify associations, while later and higher quality studies tend to find no associations[275,276]

Sleep disturbance

Evidence on sleep disturbance associated with wind turbine sound exposure is inconsistent, with some studies indicating an effect and others not. In many cases, the analysis shows that noise annoyance is a stronger predictor of subjective sleep disturbance than levels of wind turbine sound exposure, while studies investigating sleep using objective indicators remain relatively few in number:

- In a detailed scoping review, it was noted that lower quality studies tended to indicate a significant association, while higher quality studies produced non-significant results[276].
- The UK study found that self-reported sleep disturbance was associated with noise annoyance, but not with levels of sound exposure, which is consistent with several previous studies[277].
- The Finland study identified a significant association between wind turbine sound and self-reported sleep disturbance[278], which, in contrast with many other studies, had been rated in response to a question specifically asking participants about sleep disturbance that they associated with wind turbine sound – the authors noted that drawing attention to the study intent in this way may have influenced the outcomes obtained, which differ from those in other studies.
- The small number of observational studies that have used objective indicators to directly assess sleep quality have tended not to identify statistically significant effects from wind turbine sound exposure.
- The results from the Danish nationwide study, which took a 'big data' approach and employed an objective, but indirect, measure of sleep disturbance (redemption of sleep medication) suggest that any direct effect that might be detectable is relatively small, and limited to population groups inherently more predisposed to reduced sleep quality. Respondents in the ≥65 years age group within the exposure category ≥42 dB $L_{Aeq,2200\text{-}0700h}$ (estimated as a 5-year average value) were found to be more likely to have redeemed sleep medication prescriptions than the same age group within the lowest exposure category <24 dB $L_{Aeq,2200\text{-}0700h}$; considered across the whole participant sample, this relationship was weaker (and non-significant).
- The Health Canada study found no significant association of wind turbine sound exposure up to 46 dB L_{Aeq} on subjective or objective (actigraphy) indicators of sleep quality among the study populations (1238 participants for the subjective assessment; 707 for the objective measurements)[279]. Further analysis of a subset of 343 participants in the Health Canada study that lived within 1 km of wind turbines enabled examination of synchronised sleep actigraphy data with modelled levels of wind turbine sound exposure (based on turbine SCADA[280] data) at a

[275] van Kamp, I & van den Berg, F, 2018. Health effects related to wind turbine sound, including low-frequency sound and infrasound. *Acoustics Australia*, 46, 31-57 [URL]
[276] Freiberg, A, Schefter, C, Girbig, M, Murta, VC & Seidler, A, 2019. Health effects of wind turbines on humans in residential settings: results of a scoping review. *Environmental Research*, 169, 446-463 [URL]
[277] Qu, F, & Tsuchiya, A, 2021. Perceptions of wind turbine noise and self-reported health in suburban residential areas. *Frontiers in Psychology, 12*, 3357. [URL]
[278] Radun, J, Hongisto, V & Suokas, M, 2019. Variables associated with wind turbine noise annoyance and sleep disturbance. *Building and Environment*, 150, 339-348. [URL]
[279] Michaud, DS, Feder, K, Keith, SE, Voicescu, SA, Marro, L, Than, J, Guay, M, Denning, A, Murray, BJ, Weiss, SK, Villeneuve, PJ, van den Berg, F & Bower, T, 2016. Effects of wind turbine noise on self-reported and objective measures of sleep. *Sleep*, 39 (1), 97-109. [URL]
[280] Supervisory control and data acquisition: the operational control and monitoring system for turbines

resolution of 10-minute intervals[281]. The estimated night-time outdoor exposure levels ranged up to 45 dB $L_{Aeq,10min}$ (ie, approximately 43 dB $L_{AF90,10min}$, which corresponds with the ETSU-R-97 night-time minimum limit), and 32 dB $L_{Aeq,10min}$ indoors[282]. No significant association was found between the night-time 9-hour average levels of sound exposure and the measured objective sleep quality indicators. However, a significant association *was* found when the sound exposure data was analysed further to produce a value for the level difference between the 10-minute level and the 9-hour average level. This association indicated that an effect on both actigraphy 'awakenings' and motility could be detected when short-term (10-minute) levels varied from the nightly average (9-hour) level. Nonetheless, the authors stressed that the effects observed were extremely small, representing increases of around 42 seconds in actigraphy 'awakenings' per night, and 60 seconds increase in motility. They concluded that, considered alongside the other Health Canada study findings on sleep disturbance, the results do not provide any compelling evidence for an association between wind turbine sound exposure and serious sleep disturbance.

- Experimental studies have shown that some effects on objective sleep indicators can be induced with controlled exposures to wind turbine sound (for example, reductions in duration of specific sleep stages, or inductions of specific brain electrical patterns indicating some neural response to sound during sleep). However, at present, the overall effects on individual sleep quality are not fully understood:

  - One study found observable effects on some aspects of sleep structure corresponding with external levels of 45 dB $L_{Aeq,8h}$ (indoor levels at the sleeping position of 32 dB $L_{Aeq,8h}$)[283]. The effect on self-reported sleep quality was stronger, with a range of measures of self-reported sleep disturbance associated with night-time exposure to wind turbine sound (compared with a quiet control night).
  - Further research addressing effects of wind turbine sound exposure on sleep in controlled conditions is emerging, and new results from studies are expected. Preliminary results emerging from the National Health and Medical Research Council (NHMRC) studies in Australia have indicated that:

    – Sensitive objective brain pattern indicators of sleep structure ('K-complexes') can be induced or affected by short exposures to wind turbine sound (and road traffic sounds) at levels of 33 dB $L_{Aeq,20s}$ or higher (ie, indoors at the sleeping position)[284]. The wind turbine sounds were either steady ('no AM'), or included AM (either upper-frequency broadband 'swish' or low frequency tonal at 46 Hz), and was alternated with short periods of quiet ambient sound at 23 dB $L_{Aeq,20s}$. The road traffic sounds included long range and short range variants. It was noted from the statistical analysis that the type of sound did not have a significant influence on the observed effects.
    – Another sensitive brain pattern indicator ('electroencephalographic power spectrum') also showed changes in brain activity during exposure to wind turbine sound and road traffic

[281] Michaud, DS, Keith, ST, Guay, M, Voicescu, S, Denning, A, McNamee, JP, 2021. Sleep actigraphy time-synchronized with wind turbine output. *Sleep*, 44 (9), zsab070. [URL]
[282] Indoor levels were estimated using sound insulation measurement data obtained for building envelopes corresponding with typical Canadian housing stock, along with participants' individual sleep diary data indicating whether windows were open or closed at night
[283] Smith, MG, Ogren, M, Thorsson, P, Hussain-Alkhateeb, L, Pedersen, E, Forssen, J, Ageborg Morsing, J & Persson Waye, K, 2020. A laboratory study on the effects of wind turbine noise on sleep: Results of the polysomnographic WiTNES study. *Sleep*, 43 (9), zsaa046. [URL]
[284] Lechat, B, Hansen, K, Micic, G, Decup, F, Dunbar, C, Liebich, T, Catcheside, P & Zajamsek, B, 2021. K-complexes are a sensitive marker of noise-related sensory processing during sleep: A pilot study. *Sleep*, 44 (9), zsab065. [URL]

sound at levels of 33 dB $L_{Aeq,3min}$ and higher[285]. The wind turbine sound recordings included an AM low frequency tone at 46 Hz. In this case, it was noted that the sounds elicited subtly different effects: the road traffic sound tended to stimulate greater changes in brain activity at higher sound levels across several sleep stages, while the wind turbine sound at the lowest presentation level affected sleep stage N2[286] more than the road traffic sound. The authors noted the effects observed were subtle and had little impact on conventionally PSG-scored sleep quality.

- Objective and subjective indicators of sleep latency (delay in sleep onset) were unaffected by exposure to wind turbine sound at levels of 33 dB L_{Aeq} (indoors at the sleeping position, exposure duration varied according to the individual onset of deeper sleep)[287], which again included an AM low frequency tone at 46 Hz, described as 'rumbling'.
- Exposure to wind turbine sound levels of 25 dB L_{Aeq} (indoors at the sleeping position) did not appear to induce any significant effect on objective indicators of sleep quality[288].
- Exposure to wind turbine sound was not associated with increased prevalence of self-reported sleep disturbance when compared with control groups in areas exposed to road traffic sound, or in quiet rural areas[289].

It appears likely that the results observed in the field reflect a situation in which exposure to wind turbine sound at levels generally expected at dwellings (within the study populations considered) is typically too low to have any substantial, direct effect on sleep quality. However, the most recent results indicate that some subtle effects on sleep structure are detectable using objective measures at indoor sound levels of around 32-33 dB L_{Aeq} – at present, it is not known what outcomes these measurable effects may imply for individual and long-term sleep quality.

Relative impacts

The evidence on noise effects from observational studies is almost exclusively based on absolute levels of sound exposure. A few, mainly experimental, studies have considered or investigated the perception or response to relative impacts from wind turbine sound:

- It has been noted in reviews that the results of experimental and observational studies have indicated some influence of residual sound environments on noise annoyance associated with wind turbine sound, although findings are inconsistent, and the influence has yet to be reliably established[290,291,292]. Where findings are detected, the tendency is for lesser annoyance when residual sounds are higher, which would suggest some sound masking, or a psychological effect connected with attitudes or local expectations of the acoustic environment.

[285] Dunbar, C, Catcheside, P, Lechat, B, Hansen, K, Zajamsek, B, Liebich, T, Nguyen, DP, Scott, H, Lack, Decup, F, Vakulin, A & Micic, G, 2021. EEG power spectral responses to wind farm compared with road traffic noise during sleep: A laboratory study. *Journal of Sleep Research*, 00, e13517. [URL]
[286] Sleep stage N2 is the 'slow wave' onset stage preceding the 'deep sleep' stage N3 during non-REM (non-rapid eye movement) sleep
[287] Liebich, T, Lack, L, Micic, G, Hansen, K, Zajamšek, B, Dunbar, C, Lechat, B, Scott, H, Lovato, N, Decup, F, Nguyen, D & Catcheside, P, 2021. The effect of wind turbine noise on polysomnographically measured and self-reported sleep latency in wind turbine noise naïve participants. *Sleep*, 45 (1), zsab283. [URL]
[288] Liebich, T, Lack, L, Micic, G, Hansen, K, Zajamsek, B, Dunbar, C, Lechat, B, Nguyen, D, Scott, H & Catcheside, P, 2021. O003 The impact of wind farm noise in a laboratory setting on objective and subjective sleep efficiency. *SLEEP Advances*, 2 (1), A1-A2. [URL]
[289] Rawson, G, Catcheside, P, Zajamšek, B, Hansen, K, Lack, L, Vakulin, A, Lovato, N, Bruck, D, Taylor, A, Gill, T, Toson, B, Dal Grande, L, Scott, H & Micic, G, 2021. P118 The prevalence of self-reported sleep difficulties in wind farm noise, urban road traffic noise and quiet rural exposure areas in South Australia. *SLEEP Advances*, 2 (1), A59-A60. [URL]
[290] Onakpoya, IJ, O'Sullivan, J, Thompson, MJ & Heneghan, CJ, 2015. The effect of wind turbine noise on sleep and quality of life: a systematic review and meta-analysis of observational studies. *Environment International*, 82, 1-9 [URL]
[291] Freiberg, A, Schefter, C, Girbig, M, Murta, VC & Seidler, A, 2019. Health effects of wind turbines on humans in residential settings: results of a scoping review. *Environmental Research*, 169, 446-463 [URL]
[292] Hansen, C & Hansen, K, 2020. Recent advances in wind turbine noise research. *Acoustics*, 2 (1), 171-206. [URL]

- The results of one experimental study examining the effects of presenting a range of residual sounds alongside wind turbine sound exhibited a positive correlation between the signal-noise-ratio (SNR) and annoyance[293] – in other words, the presence of residual sound was found to reduce annoyance, and the less prominent the wind turbine sound was within the residual sound, the lower the annoyance. The residual sounds tested included wind-vegetation interaction, motorway sound, and urban street activity; differences between the results for each residual sound type were significant, and it was found that wind-vegetation sounds provided the poorest annoyance-reducing effect, while urban street sounds provided the greatest annoyance reduction. It was also noted, with reference to a previous study examining audibility, that the apparent onset for increases in noise annoyance roughly coincided with audibility thresholds, indicating that almost as soon as wind turbine sound is detected within residual sound, it may start to become annoying.
- Another experimental study examined the relationship between the 'sound emergence'[294] of wind turbine sound and noise annoyance. This study found only a weak correlation between this relative impact measure and annoyance, which was more strongly associated with the total ambient sound level alone (ie, the combined level of the wind turbine sound and the residual sound). Data from the 32 participants in this study are presented in Figure 3-19 and Figure 3-20. In Figure 3-19, the median annoyance ratings are plotted for two relative impact metrics, (i) sound emergence[294], and (ii) the level difference between the 'specific' sound level (comprising wind turbine sound), and the 'background' sound level, the latter representing the 'margin above background' approach taken in ETSU-R-97 (and in BS 4142[295]).

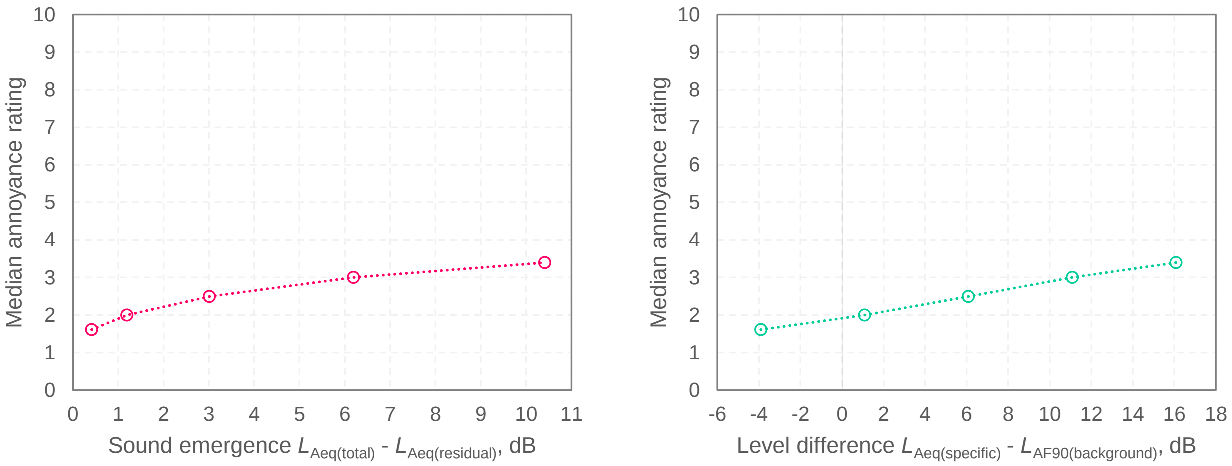


Figure 3-19: Example of experimental relative impact exposure-response relationships for wind turbine sound (data from Dutilleux et al[296], and provided by Dutilleux[297]); a, left: 'sound

[293] Johansson, A, Bolin, K, & Alvarsson, J, 2019. Annoyance and partial masking of wind turbine noise from ambient sources. *Acta Acustica united with Acustica,* 105 (6), 1035-1041. [URL]
[294] A relative impact concept defined in ISO 1996-1:2016 and employed in wind turbine noise regulations in France and Italy.
[295] BSi, 2019. *BS 4142:2014+A1:2019 Methods for rating and assessing industrial and commercial sound*. British Standards Institution. [URL]
[296] Dutilleux, G, & Fosset, J, 2020. Comparing sound emergence and sound pressure level as predictors of short-term annoyance from wind turbine noise. *Acta Acustica*, 3 (4), 10. [URL]
[297] Dutilleux, G, 2022. Personal communication.

emergence'[294]; b, right: 'margin above background', representing ETSU-R-97 assessment approach[298]

Both relative impact metrics plotted in Figure 3-19 are observed to have an apparent, but relatively weak, trend with the measured annoyance responses.

By contrast, the annoyance ratings are plotted with the absolute total sound level in Figure 3-20. This shows that the responses grouped by total sound level exhibit a more pronounced association with annoyance than shown for the relative impact measures (which was a conclusion of the study).

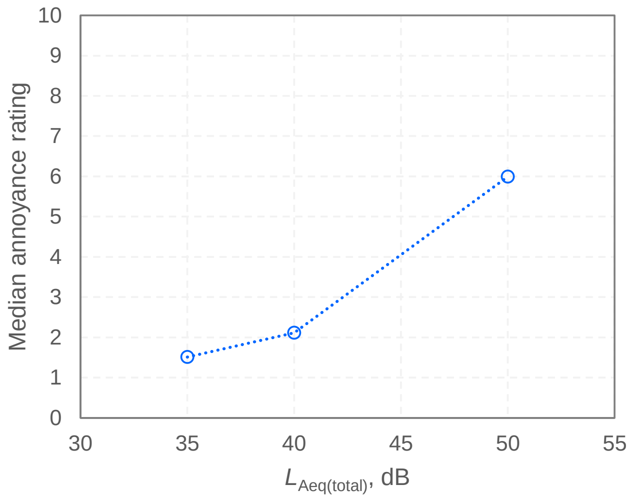


Figure 3-20: Absolute sound level exposure-response relationship for wind turbine sound corresponding with experimental data in Figure 3-19 (data from Dutilleux et al[296])

Taken together, these results indicate that there is some effect of the residual sound environment to be expected in moderating responses to wind turbine sound, but the effect may not be very strong. However, systematic investigations of the effects of residual sounds on wind turbine noise responses only appear to be emerging recently.

Clinical health effects or symptoms

The evidence base on other ('clinically apparent') adverse health effects or symptoms of exposure to sound in the auditory range is relatively small, and inconsistent:

- Several reviews have concluded that evidence concerning associations between wind turbine sound exposure and adverse health effects is inconsistent, and tends to be relatively low quality.

[298] It is acknowledged that the time base used to calculate the sound level indices shown is limited to the duration of the relatively short 30-second samples employed in the study, while noise assessments would normally be undertaken on considerably longer signals (eg, ETSU-R-97 would require 10 minutes). However, this would not affect the calculated values of the indices that would be obtained if the same sounds effectively persisted over a longer duration. To our knowledge (at the time of preparing this report), these experimental results represent the first quantified wind turbine sound exposure-response relationships for the ETSU-R-97 form of relative impact index derived from the results of a published peer-reviewed study under controlled laboratory conditions, albeit for a relatively small sample.

Reported symptoms may possibly be connected with psychogenic stress (which may be linked with individual feelings about wind energy developments)[299,300,301,302].

- The UK study found an association ($p<0.05$)[303] between levels of wind turbine sound exposure and self-reported nausea, and some evidence of a possible association with self-reported headache ($0.05<p<0.08$) and ear discomfort ($0.05<p<0.06$). The authors noted that this appeared to be a novel finding in comparison with previous wind turbine studies. However, it was also noted that these findings were limited to a subset of the total sample (97 respondents from a sample of 359), which suggests that these observations would need to be replicated at a larger scale.
- Evidence from the Danish nationwide study has provided some further insights based on long-term and large-scale analysis of health records for the Danish population:
  - No strong evidence was found for associations between higher levels of wind turbine sound exposure and increased risks of:
    - heart attack
    - stroke
    - hypertension
    - diabetes
    - adverse birth outcomes
  - Some evidence was found for an association between higher night-time wind turbine sound and increased risk of clinical depression (redemption of antidepressant prescription) – this was based on comparing the highest exposure group (≥42 dB $L_{Aeq,2200\text{-}0700h}$) to the lowest exposure group (<24 dB $L_{Aeq,2200\text{-}0700h}$), and stratification by sex showed that this effect was stronger among males than females.
- Evidence from the Danish nurse cohort study (which used the same exposure estimation methods as the Danish nationwide study) has also found:
  - No strong evidence for an association between higher wind turbine sound exposure and increased risks of:
    - heart attack
    - stroke
  - Some evidence was found for an association between higher levels of long-term night-time exposure and increased risk of atrial fibrillation when comparing exposure to ≥20 dB $L_{Aeq,2200\text{-}0700}$ (calculated as an 11-year average) with <20 dB $L_{Aeq,2200\text{-}0700}$. The authors advised that "*this*

[299] van Kamp, I & van den Berg, F, 2018. Health effects related to wind turbine sound, including low-frequency sound and infrasound. *Acoustics Australia*, 46, 31-57 [URL]
[300] Simos, J, Cantoreggi, N, Christie, D, & Forbat, J, 2019. Wind turbines and health: A review with suggested recommendations. *Environnement, Risques & Santé,* 18 (2), 149-159. [URL]
[301] Clark, C, Crumpler, C, & Notley, H, 2020. Evidence for environmental noise effects on health for the United Kingdom policy context: A systematic review of the effects of environmental noise on mental health, wellbeing, quality of life, cancer dementia, birth, reproductive outcomes, and cognition. *International Journal of Environmental Research and Public Health,* 17*,* 393. [URL]
[302] van Kamp, I, & van den Berg, F, 2021. Health effects related to wind turbine sound: An update. *International Journal of Environmental Research and Public Health*, 18 (17), 9133. [URL]
[303] See Appendix A for description of *p*-values and statistical significance

should be interpreted with caution as levels of [wind turbine sound] *exposure were low and direct auditory effects leading to AF are not expected.*"[304]

- A study undertaken in Taiwan investigated heart variability during sound exposure, which claimed to demonstrate that low frequency sound from wind turbines is associated with changes in heart rate variability[305]. We have reviewed this study, and have identified areas of methodological concern that cast doubt on the robustness of the study conclusions (see Appendix B section 9.2.1). Furthermore, the exposure distance used in the experiment (20 m to the nearest turbine) was far closer than receptors would be likely to be relative to commercial turbines in the UK. In summary, there is insufficient evidence provided in the study to robustly demonstrate that any changes in heart rate variability are systematically associated with wind turbine sound exposure at typical receptor distances.

WHO 2017-18 Systematic Reviews of noise effects

The stage 1 review highlighted that several authors noted the updated WHO guidelines published since ETSU-R-97 (see section 3.3.1). The systematic reviews undertaken on behalf of the WHO and published in 2017-18 in support of the WHO 2018 ENGER are discussed below.

Of the published reviews, four identified evidence on effects from wind turbine sound exposure:

- Guski et al (2017)[306] reviewed evidence on noise annoyance, including publications up to the end of 2014. Two publications covering four observational studies (the two Sweden studies, the Netherlands study, and the Japan study) were retained following screening. A meta-analysis of correlations between levels of sound exposure and annoyance identified a significant correlation with a 'moderate'[307] quality of evidence. The authors also directly compared the exposure-response relationships derived for the %HA according to sound exposure determined as day-evening-night level (L_{den}). In making this comparison, Guski et al concluded that the evidence was inconsistent and graded it as 'low'[306] quality. They stated that the evidence showed levels of wind turbine sound exposure are related to noise annoyance, including at levels <40 dB L_{den}. The comparative analysis of the exposure-response functions was later used as the basis of the WHO ENGER recommendation (with a 'conditional' strength[308]) for wind turbine noise control. However, it is important to recognise that the two exposure-response functions that were compared used different exposure quantification and response modelling methods:
  - Janssen et al (2011)[309] modelled worst-case L_{Aeq} sound levels and applied a +4.7 dB adjustment to 'convert' to L_{den}, a value that was established from an earlier analysis of long-term wind statistics at two sites in the Netherlands[310]. They modelled annoyance responses using the Miedema et al model (see section 3.4.2).

[304] Bräuner, EV, Jørgensen, JT, Duun-Henriksen, AK, Backalarz, C, Laursen, JE, Pedersen, TH, Simonsen, MK & Andersen, ZJ, 2019. Long-term wind turbine noise exposure and the risk of incident atrial fibrillation in the Danish Nurse cohort. *Environment International*, 130, 104915. [URL]
[305] Chiu, C-H, Lung, S-CC, Chen, N, Hwang, J-S & Tsou, M-CM, 2021. Effects of low-frequency noise from wind turbines on heart rate variability in healthy individuals. *Scientific Reports*, 11, 17817. [URL]
[306] Guski, R, Schreckenberg, D & Schuemer, R, 2017. WHO Environmental Noise Guidelines for the European Region: a systematic review on environmental noise and annoyance. *International Journal of Environmental Research and Public Health*, 14 (12), 1539 [URL]
[307] Rated according to the GRADE system employed by the WHO Regional Office for Europe [URL]
[308] Indicating the quality of evidence reviewed was low, there is less certainty about the about the effectiveness of the recommendation, and the burden on health is considered to be low, due to the relatively small number of people affected.
[309] Janssen, SA, Vos, H, Eisses, AR & Pedersen, E, 2011. A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. *Journal of the Acoustical Society America*, 130 (6), 3746-3753. [URL]
[310] van den Berg, F, 2008. *Criteria for wind farm noise: Lmax and Lden*. Acoustics '08, Paris, 29 June – 4 July.

- Kuwano et al (2014)[311] on the other hand, took measured 8-hour night-time energy time-averaged $L_{Aeq,2200\text{-}0600}$ sound levels, interpolated or extrapolated these to the respondent locations by fitting a curve to the data, and then applied a +6 dB adjustment to convert to L_{den}. They used binary logistic regression to model annoyance responses.
- As discussed in sections 3.4.2 and 6.2.1, the differences between these approaches to quantifying sound exposure and response modelling suggest that direct comparison of the exposure-response functions, which effectively use different scales, could produce misleading results.

- Basner et al (2018)[312] reviewed evidence on sleep disturbance, including publications up to 1 December 2015. Eight publications covering six studies were retained following screening. One of the studies included objective sleep quality indicators, while the rest addressed self-reported sleep disturbance. They conducted a meta-analysis of five of the studies, which yielded a non-significant pooled odds ratio for the risk of subjective sleep disturbance. The quality of the evidence was rated as 'very low'.
- Clark et al (2018)[313] reviewed evidence on QoL, wellbeing and mental health, while van Kempen et al (2018)[314] reviewed evidence on cardiovascular and metabolic effects. Both reviews concluded that the quality of evidence identified concerning wind turbine sound exposure was 'very low', noting inconsistent and non-significant results, and high risks of bias. No exposure-response relationships were reported.

Infrasound and low frequency sound

Several studies have investigated the claimed links between adverse health symptoms and infrasound emissions from wind turbines. Although some experimental studies have linked infrasonic signals with activation of physiological sensory processing[315,316], these have tended to be based on signals that are not representative of wind turbine infrasound. There remains no compelling evidence of adverse health effects associated with wind turbine infrasound exposure at sound frequencies and levels expected to be present at noise-sensitive receptor locations in the vicinity of wind farms[317]:

- While biologically plausible pathways for infrasound activation of the auditory or vestibular systems cannot yet be definitively ruled out, the infrasound emissions from wind turbines at ranges relevant to neighbouring dwellings are typically too low to expect any adverse effects, even for people with heightened sensitivity due to medical conditions[318]. Any observed sensory

---

311 Kuwano, S, Yano, T, Kageyama, T, Sueoka, S & Tachibana, H, 2014. Social survey on wind turbine noise in Japan. *Noise Control Engineering Journal*, 62 (6), 503-520. [URL]
312 Basner, m & McGuire, S, 2018. WHO Environmental Noise Guidelines for the European Region: a systematic review on environmental noise and effects on sleep. *International Journal of Environmental Research and Public Health*, 15 (3), 519 [URL]
313 Clark, C & Paunovic, K, 2018. WHO Environmental Noise Guidelines for the European Region: a systematic review on environmental noise and quality of life, wellbeing and mental health. *International Journal of Environmental Research and Public Health*, 15 (11), 2400 [URL]
314 van Kempen, E, Casas, M, Pershagen, G & Foraster, M, 2018. WHO Environmental Noise Guidelines for the European Region: a systematic review on environmental noise and cardiovascular and metabolic effects: a summary. *International Journal of Environmental Research and Public Health*, 15 (2), 379 [URL]
315 Salt, AN & Hullar, TE, 2010. Responses of the ear to low frequency sounds, infrasound and wind turbines. *Hearing Research*, 268 (1-2), 12-21. [URL]
316 Weichenberger, M, Bauer, M, Kühler, R, Hensel, J, Forlim, CG, Ihlenfeld, A, Ittermann, B, Gallinat, J, Koch, C & Kühn, S, 2017. Altered cortical and subcortical connectivity due to infrasound administered near the hearing threshold- Evidence from fMRI. *PLoS ONE*, 12, e0174420. [URL]
317 van Kamp, I, & van den Berg, F, 2021. Health effects related to wind turbine sound: An update. *International Journal of Environmental Research and Public Health*, 18 (17), 9133. [URL]
318 Harrison, RV, 2014. On the biological plausibility of Wind Turbine Syndrome. *International Journal of Environmental Health Research*, 25 (5), 463-468. [URL]

activation has not been reliably linked with any physiological or psychological effects on individuals, and has typically been observed during exposures higher than expected for wind turbine infrasound incident at dwellings. Moreover, similar levels of exposure as are typical for wind turbine infrasound at dwellings can be expected from other common environmental sources of infrasound[319], which tend not to be associated with the wide range of specific and non-specific symptoms that have been claimed to be attributable to wind turbine infrasound[320].

It has been demonstrated in controlled experiments[321,322,323,324], including the involvement of participants self-reporting to be sensitive to wind turbine infrasound, that exposure to infrasound at levels representative of wind turbine immissions at dwellings is not associated with physiological or psychological health effects, whereas the expectation of effects from being exposed to wind turbine infrasound, and positive or negative messages influencing that expectation, can affect health symptom reporting[325].

Overall, the findings from the existing evidence base indicate that infrasound from wind turbines at typical exposure levels has no direct adverse effects on physical or mental health, and reported symptoms of ill-health are more likely to be psychogenic in origin.

- It is expected that further evidence from ongoing studies into wind turbine infrasound effects will emerge soon, in particular from the NHMRC studies in Australia. However, based on the existing scientific evidence, it does appear probable that the above findings will not be contradicted by newer evidence.

Studies have highlighted that wind turbines emit a greater proportion of low frequency sound than is associated with some other common sources of environmental sound (such as road traffic[326]). However, it has also been noted that the typical spectrum of wind turbine sound does not have the expected features to indicate it would be associated with specific low frequency noise issues[327] (which is consistent with experiments undertaken as part of the Japan study[328]). Previous evidence reviews have concluded that there are unlikely to be specific adverse effects or health outcomes associated with wind turbine low frequency sound exposure beyond annoyance[317,319]. Furthermore, a comparison of noise annoyance exposure-response functions from various studies concluded that

[319] van Kamp, I & van den Berg, F, 2018. Health effects related to wind turbine sound, including low-frequency sound and infrasound. *Acoustics Australia*, 46, 31-57 [URL]
[320] Chapman, S & Simonetti, T, 2012. *Is there anything not caused by wind farms?* [URL]
[321] Tonin, R, Brett, J & Colagiuri, B, 2016. The effect of infrasound and negative expectations to adverse pathological symptoms from wind farms. *Journal of Low Frequency Noise, Vibration and Active Control*, 35 (1), 77-90. [URL]
[322] Nelson, P, Bryne, A, Waggenspack, M, Lueker, M, Feist, C, Herb, B & Marr, J, 2019. *Testing the human response to wind turbine emissions*. Wind Turbine Noise 2019, 12-14 June, Lisbon. INCE-Europe.
[323] Maijala, PP, Kurki, I, Vainio, L, Pakarinen, S, Kuuramo, C, Lukander, K, Virkkala, J, Tiippana, K, Stickler, EA & Sainio, M, 2021. Annoyance, perception, and physiological effects of wind turbine infrasound. *Journal of the Acoustical Society of America*, 149 (4), 2238-2248. [URL]
[324] Krahé, D, Alaimo Di Loro, A, Müller, U, Elmenhorst, E, De Gioannis, R, Schmitt, S, Belke, C, Benz, S, Großarth, S, Schreckenberg, D, Eulitz, C, Wiercinski, B & Möhler, U 2020. *Lärmwirkungen von Infraschallimmissionen* (Noise Effects from Infrasound Immissions, in German, with abstract in English). [URL]
[325] Crichton, F, Dodd, G, Schmid, G, Gamble, G & Petrie, KJ, 2014. Can expectations produce symptoms from infrasound associated with wind turbines? *Health Psychology*, 33 (4), 360-364. [URL]
[326] Alamir, MA, Hansen, KL & Catcheside, P, 2021. Penalties applied to wind farm noise: Current allowable limits, influencing factors, and their development. *Journal of Cleaner Production*, 295 (2021). [URL]
[327] Hessler, G, Leventhall, G, Schomer, P, & Walker, B, 2017. Health effects from wind turbine low frequency noise & infrasound: Do wind turbines make people sick? That is the issue. *Sound and Vibration*, 51 (1), 34-44. [URL]
[328] Yokoyama, S, Sakamoto, S & Tachibana, H, 2014. Perception of low frequency components in wind turbine noise. *Noise Control Engineering Journal*, 62 (5), 295-305. [URL]

low frequency sound is unlikely to be a primary factor in responses[329]. This conclusion was based on the observed fit of the modelled relationships (which were developed from an assumed loudness function that would not provide a good fit if low frequency components had a strong influence on the observed responses).

Prioritised theme 2: Amplitude modulation

Causal mechanisms, contributing factors and prediction

As outlined in section 2.4.3, two forms of AM in wind turbine sound are distinguished in the research literature, according to the factors believed to contribute to their occurrence[330,331,332,333]:

- 'Blade swish' AM, which is relatively well understood and is associated with the blade trailing edge directivity and the convective amplification intrinsic to a moving source relative to a stationary observation position (TEDCAR-AM); this is also commonly described as 'normal' AM, has a higher frequency character, and is known to have its largest modulation depth in the crosswind directions, but is less prominent in the up or downwind directions, except at relatively close ranges (1-2 rotor diameters)[334]. Since crosswind directivity of wind turbines results in relatively low overall sound emissions parallel to the rotor plane, the combination of these factors means that TEDCAR-AM is not expected to be audible at long ranges – this form of AM corresponds with the guidance provided in ETSU-R-97 (discussed in section 6.3.1).
- AM that is not associated with the trailing edge directivity and convective amplification (non-TEDCAR-AM) and could be generated or influenced by a range of mechanisms or factors, as discussed below; this is also commonly described as 'other', or 'enhanced', or 'abnormal' AM, and can be prominent at longer ranges, with a lower frequency character, and over varying wind directions – this form of AM has been more widely reported as being associated with noise disturbances[335], and does not correspond with the guidance on AM provided in ETSU-R-97.

Causal mechanisms and contributing factors involved in non-TEDCAR-AM identified in the evidence include:

- transient blade stall: this mechanism has been identified as a plausible cause for AM with increased modulation depth and lower frequency spectral character in simulations[330] and has also been found to be consistent with measurements and theory:
    - Blade stall occurrence is primarily linked with the blade angle of attack, which may be affected by flow variation across the rotor span[336], and is linked with wind shear, wind veer, and 'low level jets' caused by atmospheric conditions[332], and with topography[331].

[329] Michaud, DS, Keith, SE, Feder, K, Voicescu, SA, Marro, L, Than, J, Guay, M, Bower, T, Denning, A, Lavigne, E, Whelan, C, Janssen, SA, Leroux, T & van den Berg, F, 2016. Personal and situational variables associated with wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1455-1466. [URL]
[330] Oerlemans, S, 2015. Effect of wind shear on amplitude modulation of wind turbine noise. *International Journal of Aeroacoustics*, 14 (5-6), 715-728. [URL]
[331] Sedaghatizadeh, N, Arjomandi, M, Cazzolato, B, & Kelso, R, 2017. Wind farm noises: Mechanisms and evidence for their dependency on wind direction. *Renewable Energy*, 109, 311-322. [URL]
[332] Makarewicz, R, & Golebiewski, R, 2019. The Influence of a low level jet on the thumps generated by a wind turbine. *Renewable and Sustainable Energy Reviews*, 104, 337-342. [URL]
[333] Conrady, K, Bolin, K, Sjoblom, A, & Rutgersson, A, 2020. Amplitude modulation of wind turbine sound in cold climates. *Applied Acoustics*, 158, 107024. [URL]
[334] Oerlemans, S, 2009. Prediction of wind turbine noise and validation against experiment. *International Journal of Aeroacoustics*, 8 (6), 555-584. [URL]
[335] van den Berg, F & Bowdler, D, 2011. Amplitude modulation. In: Bowdler, D & Leventhall, G (eds), *Wind turbine noise* (chapter 5). Multi-Science Publishing.
[336] Makarewicz, R, & Golebiewski, R, 2015. Influence of blade pitch on amplitude modulation of wind turbine noise. *Noise control engineering journal*, 63(2), 195-201. [URL]

- inflow turbulence variation: analysis of inflow turbulence (and blade stall) directivity patterns has indicated that reported disturbances attributed to AM are consistent with this possible contributing mechanism[331]
- complex turbine wake effects being exaggerated in stable atmospheric conditions, which have been identified in simulations incorporating turbulent airflow fields with coupled source and propagation models[337,338]. These studies have focussed on single turbine wake effects, which are considered to comprise small-scale turbulence and refractive effects that contribute to greater AM fluctuations. While stable atmospheric effects are normally associated with reduced inflow turbulence, enhanced wake effects during stable conditions could possibly also contribute to greater inflow turbulence in wind farms, when turbines are exposed to the enhanced wake region from another turbine.
- partial rotor 'shading' associated with the 'shadow zones'[339] created due to refraction of sound propagation in the atmosphere, which has been investigated in simulations and found to be consistent with measurements[340,341]

Some of these factors will be influenced to some degree by the size of the turbine rotor, which suggests that larger turbines may be expected to be at greater risk of non-TEDCAR-AM. However, no studies have been identified that systematically investigated this aspect.

One of the research groups engaged on the NHMRC-funded studies in Australia has also highlighted a further distinct type of non-TEDCAR-AM, which manifests as a modulated low frequency tone (which they report residents describing as a 'rumbling' or 'thumping' sound[342]), mechanisms for which have yet to be determined[343]. This low frequency tonal form of AM is not prominent in the research from other countries (although another researcher in Australia has also presented evidence of tonal AM at low frequencies[344]), and may have particular associations with situations more relevant in Australia, including relatively long propagation distances and very quiet residual sound environments. Some authors from this research group have suggested that blade-tower interaction sound may play some part in very low frequency AM extending upwards in the spectrum from the infrasonic region[345], however at present this evidence is at an early stage, and it is not known whether this mechanism could contribute energy from real turbines at levels of any significance for hearing; blade-tower interaction sound is conventionally thought of as a source contributing to infrasound emissions, and may not be found to play any role in AM within the normal auditory frequency range.

It appears from the evidence that any of the above factors could play a role in the AM character at receptor locations. Variations over time are also expected to play a part, as discussed further below.

---

337 Barlas, E, Zhu, WJ, Shen, WZ, Dag, KO, & Moriarty, P, 2017. Consistent modelling of wind turbine noise propagation from source to receiver. *Journal of the Acoustical Society of America*, 142 (5), 3297-3310. [URL]
338 Barlas, E, Zhu, WJ, Shen, WZ, Kelly, m & Andersen, SJ, 2017. Effects of wind turbine wake on atmospheric sound propagation. Applied Acoustics, 122, 51-61. [URL]
339 Zones of reduced sound pressure level (compared with 'illuminated' zones of higher sound pressure levels)
340 Cotté, B, 2018. Coupling of an aeroacoustic model and a parabolic equation code for long range wind turbine noise propagation. Journal of Sound and Vibration, 422, 343-357. [URL]
341 Bolin, K, Conrady, K, Karasalo, I, & Sjöblom, A, 2020. An investigation of the influence of the refractive shadow zone on wind turbine noise. *Journal of the Acoustical Society of America*, 148 (2), EL166-EL171. [URL]
342 Hansen, K, Nguyen, P, Zajamsek, B, Catcheside, P, & Hansen, C, 2019. Prevalence of wind farm amplitude modulation at long-range residential locations. *Journal of Sound and Vibration*, 455, 136-149. [URL]
343 Nguyen, D-P, Hansen, K & Zajamsek, B, 2018. *Characterizing tonal amplitude modulation of wind farm noise*. Acoustics 2018, 6-9 November, Adelaide. Australian Acoustical Society. [URL]
344 Cooper, S, 2021. Wind farm noise – modulation of the amplitude. *Acoustics*, 3 (2), 364-390. [URL]
345 Yauwenas, Y, Zajamsek, B, Reizes, J, Timchenko, V, & Doolan, C, 2021. Directivity of blade-tower interaction noise. *JASA Express Letters*, 1 (6), 063601. [URL]

While detailed numerical models have provided insights into the contributing causal factors, these types of models are computationally intensive, require highly detailed information on a wide range of parametric variables, and are likely to be very sensitive to the input assumptions. Simpler analytical models have been proposed, but also require detailed inputs, and are limited to modelling only specific aspects of the complex processes involved. At present, it seems evident that reliable predictions of AM in the context of development planning and noise assessment guidance are unlikely to be practically feasible in the near future, although it may be possible to identify broad risk factors that indicate sites at which AM might be more likely to occur (eg[346]).

Detection, measurement, prevalence, and distribution

Detection and measurement

The IOA undertook a review of AM detection and measurement methods in 2015[347], from which it subsequently developed a proposed metric, including an open-source software implementation[348]. Since then, the IOA 'Reference Method' has been adopted by researchers in simulation[349], experimental[350] and field measurement[351] studies. In some cases, proposals have been made for modifications to extend its applicability or for refinement purposes[351,352,353] (eg to balance its sensitivity and specificity[354], or to ensure AM depths are accurately quantified during rapid or severe modulation[353]).

It has also been noted that the IOA did not publish a systematic validation exercise of the metric using field data[355]. Nonetheless, its application to field measurement research, including comparisons against other methods[352,356] has demonstrated that it is a robust and practical approach to quantifying AM within large datasets.

Alternative approaches to detecting and quantifying AM in wind turbine sound have been documented in both the black and grey literature since the IOA published the conclusions to its review and recommendations[357,358]:

---

346 Birchby, A, Tough, F & Bass, J, 2017. *Pre-construction site prediction tool for wind farm AM – do we now know enough?* Wind Turbine Noise 2017, 2-5 May, Rotterdam.

347 IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group, 2015. *Discussion document: Methods for rating amplitude modulation in wind turbine noise*. Institute of Acoustics. [URL]

348 https://sourceforge.net/projects/ioa-am-code

349 Barlas, E, Zhu, W, Shen, W, Dag, K, & Moriarty, P, 2017. Consistent modelling of wind turbine noise propagation from source to receiver. *Journal of the Acoustical Society of America*, 142 (5), 3297-3310. [URL]

350 Nguyen, D, Hansen, K, Zajamsek, B, & Catcheside, P, 2020. Evaluation of wind farm noise amplitude modulation synthesis quality. *Applied Acoustics*, 166, 107349. [URL]

351 Hansen, K, Nguyen, P, Zajamsek, B, Catcheside, P, & Hansen, C, 2019. Prevalence of wind farm amplitude modulation at long-range residential locations. *Journal of Sound and Vibration*, 455, 136-149. [URL]

352 Jennings, S, & Kennedy, J, 2019. Detection and evaluation of amplitude modulation from a wind energy development, Ireland. *Acta Acustica united with Acustica*, 105 (6), 1042-1052. [URL]

353 Lotinga, M, & Lewis, T, 2021. *Subjective responses to wind turbine noise amplitude modulation: Pooled analysis of laboratory listening studies and synthesis of an AM character rating penalty*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe. [URL]

354 Sensitivity: how good the method is at avoiding 'false negatives'; specificity: how good it is at avoiding 'false positives'

355 Hansen, C & Hansen, K, 2020. Recent advances in wind turbine noise research. *Acoustics*, 2, 172-207. [URL]

356 Nguyen, P, Hansen, K, Lechat, B, Catcheside, P, Zajamsek, B, & Hansen, C, 2021. Benchmark characterisation and automated detection of wind farm noise amplitude modulation. *Applied Acoustics*, 183, 108286. [URL]

357 IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group, 2016. *Final report: Methods for rating amplitude modulation in wind turbine noise*. Institute of Acoustics. [URL

358 During the preparation of this report, the results of a study funded by the German Environment Agency (Umweltbundesamt) were published, which included the development of a metric to measure AM depth and frequency. The metric is based on evaluation of the $L_{Aeq,100ms}$, and is quite similar in technical approach to the IOA Reference Method. Details are found in: Schmitter, S, Alaimo Di Loro, A, Hemmer, D, Schreckenberg, D, Großarth, S, Pörschmann, C & Kühner, T, 2022. *Noise effects of the use of land-based wind energy*. Project Number 3717 43 110 0 Report No. FB000656/ENG (Final report). Umweltbundesamt. [URL]

- An application of the cross-correlation function to the sound level time-series signal (containing wind turbine sound) and an assumed form of modulation signal. Comparisons with other techniques suggest this has reasonable accuracy, and its main advantage is robustness at low signal-noise-ratios[359].
- A modulation frequency domain-based approach that includes a phase-comparison procedure to determine whether third-octave sound level time-series have phases that are within defined coherency limits – this process is used to reject periods that are considered to have 'incoherent' spectral AM (and therefore unlikely to be wind turbine AM)[360].
- One author proposed using a simple statistical level subtraction L_1-L_{90} in third-octave bands[361]; this has the singular advantage of relative simplicity, but since it involves no detection discrimination between wind turbine AM and any other modulation, and uses a high (99th) percentile, it would be highly susceptible to contamination from other sounds. Therefore, it is unlikely to be useful other than for manual analysis of short periods with uncontaminated wind turbine AM signals, which would have to be confirmed by other means.
- An AI-based detection tool comprising a machine learning algorithm trained using large datasets of wind turbine sound and residual sound recordings[362]. The advantage of the tool is that its confirmed detection rate is higher than other methods, including the IOA metric. However, there are also several disadvantages:
  - It requires audio signals as input, which remain data-intensive for storage and handling over long continuous survey durations, which are often necessary for wind turbine assessments.
  - The algorithm can only be as applicable as the training dataset allows it to be – for example, all of the data used to train this particular algorithm was acquired in South Australia, so, to an extent, will be specific to the soundscapes and wind turbines in that region (this could be overcome by incorporating other location-specific training datasets, however this would require substantial data acquisition).
  - The algorithm is useful for reliable detection of AM, but relies on standard signal processing routines to calculate AM parameters such as modulation depth and modulation frequency.
- An application of the wavelet transform to extract a 'reconstructed' modulation signal from the sound level time-series, in a manner analogous with the IOA approach (but using alternative means). Advantages and disadvantages with this method are not clearly identified in the paper, and the details are referenced to German-language publications[363]. It is noted that 'interfering' residual sounds should be manually removed, which suggests the process may not be useful for large datasets.

A simulation study[364] examined the potential influence of wind turbulence at the microphone on the ability of two proposed AM metrics to accurately measure AM. This study identified that, for 100 mm wind screens (which are smaller and less effective than the wind screen types advised for use in the

[359] Lenchine, V, 2016. Assessment of amplitude modulation in environmental noise measurements. *Applied Acoustics*, 104, 152-157. [URL]
[360] Thorsson, P, Persson Waye, K, Ogren, M, Smith, M, Pedersen, E, & Forssen, J, 2019. Creating sound immission mimicking real-life characteristics from a single wind turbine. *Applied Acoustics*, 143, 66-73. [URL]
[361] Cooper, S, 2021. Wind farm noise – modulation of the amplitude. *Acoustics*, 3 (2), 364-390. [URL]
[362] Nguyen, P, Hansen, K, Lechat, B, Catcheside, P, Zajamsek, B, & Hansen, C, 2021. Benchmark characterisation and automated detection of wind farm noise amplitude modulation. *Applied Acoustics*, 183, 108286. [URL]
[363] Pies, K, & Martinez, S, 2021. *Assessment and rating of Wind turbine noise immission at dwellings – the influence of amplitude modulation, aerodynamic noise sources and the Doppler effect*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe.
[364] Kendrick, P, von Hünerbein, S, & Cox, T, 2016. The effect of microphone wind noise on the amplitude modulation of wind turbine noise and its mitigation. *Journal of the Acoustical Society of America,* 140 (1), EL79-EL83. [URL]

IOA GPG), the influence of wind could impede the ability of measurement methods to quantify AM, even at relatively low wind speeds (above 2 ms^{-1}).

Prevalence and distribution

In the 2016 BEIS-published review of human response to AM[365], it was highlighted that some evidence indicated AM is more prevalent (ie, more commonly occurring) during the night, early morning and evening periods than during the daytime. This evidence is now stronger, with long-term surveys in varying geographic areas observing this phenomenon[366,367,368], and detailed simulation studies identifying behaviour consistent with measurements[369]. These observations are also consistent with UK measurements reported in the grey literature[370].

The evidence strongly indicates that wind turbine AM is more prevalent during the night, early morning, and evening periods. This is believed to be due to the atmospheric and situational conditions that prevail at these times, contributing to increased AM occurrence, and potentially enhanced sound propagation, including higher wind shear, temperature inversion, low level jets and extended turbine wake regions, as well as quieter residual sound environments.

Some studies[367,368] have also examined the seasonal variation in AM, which is less consistent than the diurnal analysis and is probably more dependent on local climatic environments. However, the colder seasons coincide with longer nights, and the evidence suggests that it is the night-time atmospheric conditions that enhance AM, suggesting that greater AM prevalence can be expected during the colder months of the year.

Evidence on AM prevalence with wind direction variation is inconsistent, with studies observing differing behaviours; this suggests that the influence of wind direction on AM prevalence is highly site-dependent.

Studies in Australia have investigated the relationship between wind speed and AM depth and prevalence[366,368], with inconsistent observations (which may be due to the different types of non-TEDCAR-AM investigated in each study). Measurements reported from one site in the UK have also found wind speed to be of low importance in AM occurrences[371].

Differences between AM measured indoors and outdoors have been investigated in some studies, which indicate that AM could in some cases have a greater modulation depth indoors than outdoors, but could also be less prevalent (ie less commonly occurring) indoors[366,368]. However, evidence from outdoor versus indoor observations will depend on the character of the AM, as well as the specifics

[365] WSP | Parsons Brinckerhoff, 2016. *Wind turbine AM review: Phase 2 report.* 3514482A Issue 3. Department for Business, Energy & Industrial Strategy. [URL]
[366] Hansen, K, Nguyen, P, Zajamsek, B, Catcheside, P, & Hansen, C, 2019. Prevalence of wind farm amplitude modulation at long-range residential locations. *Journal of Sound and Vibration,* 455, 136-149. [URL]
[367] Conrady, K, Bolin, K, Sjoblom, A, & Rutgersson, A, 2020. Amplitude modulation of wind turbine sound in cold climates. *Applied Acoustics, 158*, 107024. [URL]
[368] Nguyen, P, Hansen, K, Catcheside, P, Hansen, C, & Zajamsek, B, 2021. Long-term quantification and characterisation of wind farm noise amplitude modulation. *Measurement,* 182, 109678. [URL]
[369] Barlas, E, Wu, K, Zhu, W, Porté-Agel, F, & Shen, W, 2018. Variability of wind turbine noise over a diurnal cycle. *Renewable Energy*, 126, 791-800. [URL]
[370] Lowe, K & Broneske, S, 2017. *Putting the IOA preferred AM assessment method and the proposed penalty scheme into practice – an outlook for future developments of wind farms in the UK*. Wind Turbine Noise 2017, 2-5 May, Rotterdam. INCE-Europe.
[371] Birchby, A, Tough, F & Bass, J, 2017. *Pre-construction site prediction tool for wind farm AM – do we now know enough?* Wind Turbine Noise 2017, 2-5 May, Rotterdam.

of the receptor environment, including the building envelope design, room dimensions, and internal sound sources.

One study examined the AM depth distributions detected at 3 locations over one year (estimated using L_{AF5}-L_{AF95}[372]) in 10-second samples, which indicated a low-skewed distribution, with median values of around 2-3 dB, as shown in Figure 3-21. Larger AM depth values were identified in lower frequency spectral bands, which demonstrates that the AM depth calculated in the overall A-weighted levels tends to be dominated by mid-high frequency bands.

[372] Since this subtraction uses the broadband A-weighted and 'Fast' time-weighted signal to estimate AM depth, it would be expected to produce estimates that are systematically smaller than those obtained using the IOA Reference Method, which is based on the bandpass-filtered L_{Aeq} time series – see section 2.1.2.

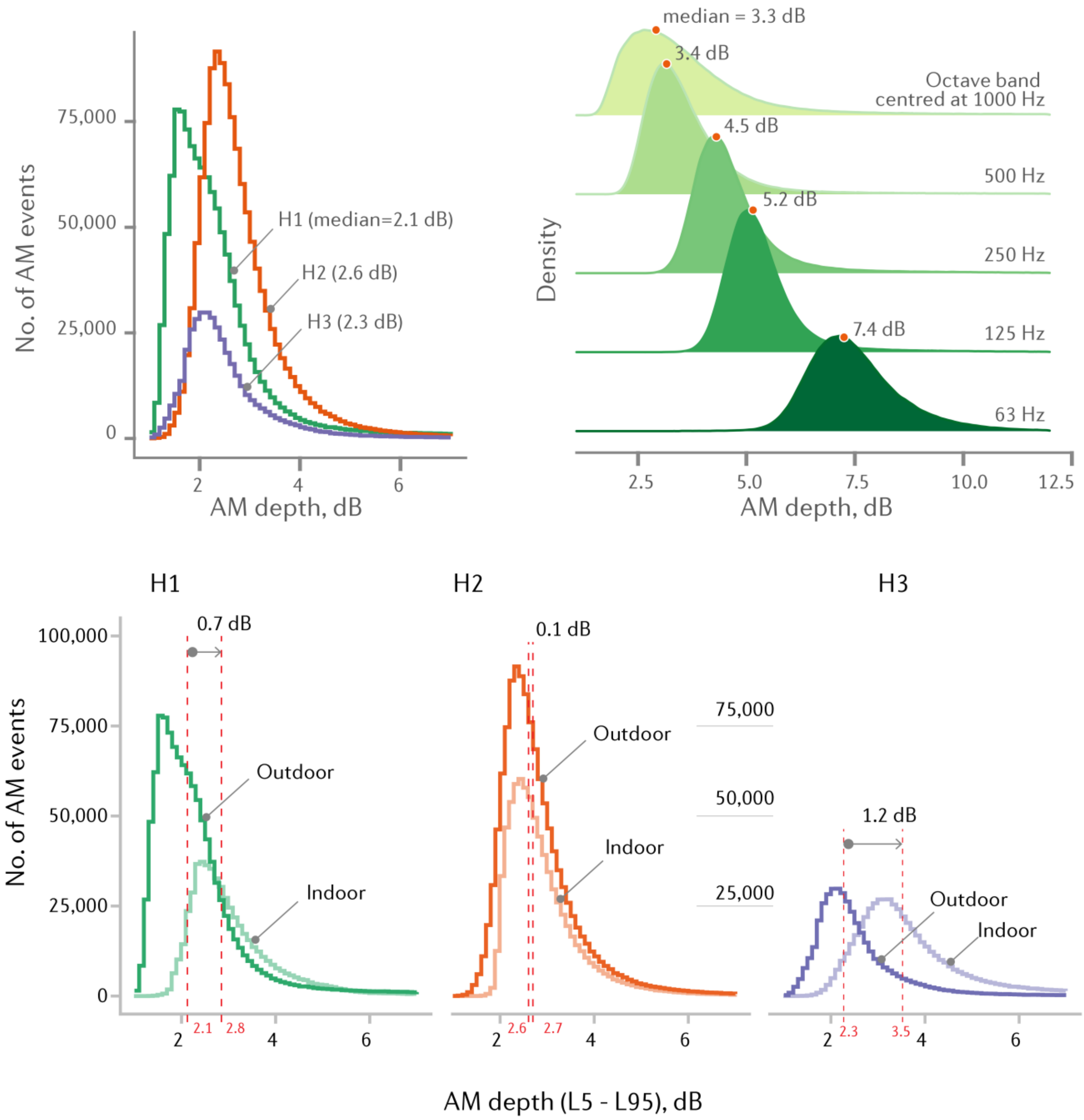


Figure 3-21: Measured AM depth distributions at three locations over one year in Australia (data from Nguyen et al, 2021[368]; images © 2021 Elsevier Ltd)

Effects, controls, and mitigation

Effects

Key conclusions from the 2016 review of human response to AM in wind turbine sound[373] (covering publications 2000-2015/16) included:

[373] WSP | Parsons Brinckerhoff, 2016. *Wind turbine AM review: Phase 2 report.* 3514482A Issue 3. Department for Business, Energy & Industrial Strategy. [URL]

- The presence of AM increased noise annoyance in both laboratory and field settings (although it was noted that there was very little exposure-response evidence from observational field studies available).
- Noise annoyance associated with AM seemed to be greater during late evening, night-time or early morning periods when people tend to be resting, which was thought likely due to increased sensitivity or increased AM prevalence (or both) during these hours.
- The relationship of increasing degree of modulation (in terms of AM depth) with adverse response was not very marked, and less prominent than the relationship between increasing energy time-averaged level and adverse responses.

These conclusions continue to be supported by the reviewed research evidence published 2015-21 (see Appendix B, section 9.2.2).

There remains relatively little evidence available from observational studies in the field; one study reported in the black literature and one in the grey literature have been identified:

- A long-term study over one year in Australia comprised sound measurements alongside noise event and sleep disturbance diaries completed by two participants[374]. The authors acknowledged that the very small number of participants limits the study generalisability, and carries high risks of bias in the results (evidence of bias in the results was observed, ie, the participants tended to only record noise events at higher annoyance ratings). Nonetheless the results indicated that outdoor AM prevalence (as well as sound levels) were associated with reported noise annoyance. It was also observed that reported noise annoyance tended to be more frequent in winter than in the summer, as well as in late evenings, night or early mornings. Furthermore, the sound measurements showed that AM was also more prevalent in the evening, night and early morning; these findings are consistent with the notion that AM contributes to greater noise impact occurring during the darker hours of the day.
- Preliminary results reported by Pörschmann et al (2021) from a field study at 3 sites in Germany included 353 participants living within 2.5 km of wind turbines[375,376]. The response survey included questions about noise annoyance and specific characteristics of sound influencing annoyance. The results indicated that the sound characteristics most associated with annoyance were 'swooshing' and 'swinging', followed by 'droning' and 'whistling'; this suggests that AM was the most annoying sound characteristic identified, followed by tonality.

Evidence from experimental studies has shown that annoyance associated with AM in wind turbine sound is influenced by the modulation frequency as well as the modulation depth[377] , and these two parameters interact in affecting responses[378]. This is an expected result, however the evidence available during the 2016 review[373] did not identify a robust basis for confirming this finding. This suggests that any control for AM should address both modulation frequency and modulation depth.

[374] Hansen, K, Nguyen, P, Micic, G, Lechat, B, Catcheside, P, & Zajamšek, B, 2021. Amplitude modulated wind farm noise relationship with annoyance: A year-long field study. *Journal of the Acoustical Society of America*, 150 (2), 1198-1208. [URL]
[375] Pörschmann, C, Großarth, S, Arend, J, Schmitter, S, Schreckenberg, D, & Wunder, K, 2021. *Amplitude modulations increase annoyance due to wind turbine noise immission*. Inter-noise 2021, 1-5 August. Washington: I-INCE. [URL]
[376] During the preparation of this report, the final report from this study (funded by the German Environment Agency) was published, the findings of which support the preliminary published results. Details are found in: Schmitter, S, Alaimo Di Loro, A, Hemmer, D, Schreckenberg, D, Großarth, S, Pörschmann, C & Kühner, T, 2022. *Noise effects of the use of land-based wind energy*. Project Number 3717 43 110 0 Report No. FB000656/ENG (Final report). Umweltbundesamt. [URL]
[377] Alamir, MA, Hansen, KL & Catcheside, P, 2021. Penalties applied to wind farm noise: Current allowable limits, influencing factors, and their development. *Journal of Cleaner Production*, 295 (2021). [URL]
[378] Lotinga, M, & Lewis, T, 2021. *Subjective responses to wind turbine noise amplitude modulation: Pooled analysis of laboratory listening studies and synthesis of an AM character rating penalty*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe. [URL]

It has also been noted that some results exhibit an interaction effect between AM depth and the overall (energy time-averaged) sound level[378], which suggests that as the overall level increases, the AM depth becomes less important in the increased annoyance.

It has been suggested from an experimental study by Pörschmann et al (2021)[375,376] with 79 participants that noise annoyance response to AM increases from the point at which it is perceived in the sound, which is consistent with the observations in the 2016 evidence review[373]. A slight interaction effect between AM depth and overall sound level was also noted, consistent with the earlier results noted above.

The WiTNES[379] project in Sweden included an experimental study that systematically investigated the effects of wind turbine sound including AM on subjective and objective (PSG) sleep indicators for 50 participants. The results showed that, at indoor sound levels varying between 29 dB $L_{Aeq,2h}$ and 34 dB $L_{Aeq,2h}$ (averaging to 32 dB $L_{Aeq,8h}$), but including periods with relatively high AM[380], some effect on objectively measured sleep structure was observed, although this also depended on the sound spectrum, and was not consistent across the PSG-measured sleep quality indicators[381].

Further preliminary research addressing wind turbine sound effects on sleep has emerged from the National Health and Medical Research Council (NHMRC) studies in Australia. This indicates that there is a weak relationship between wind turbine AM sound and objective (PSG) measurements of sleep indicators[382].

Controls

As noted in section 3.3, there has been some debate in the UK over whether a suitable control for AM characteristics should take the form of restricting the frequency or duration of occurrences (independent of sound level), or a character penalty scheme (ie, a penalty added to the sound level). The evidence reviewed on the adverse effects of AM suggests that the latter is more appropriate, since the degree of modulation in the sound is not as strong a predictor of annoyance as the overall sound level, and there appears to be some interaction between sound level and AM depth that influences responses.

It was proposed in the 2016 review[373] that AM could be controlled using a penalty scheme consistent in concept with that already applied under the ETSU-R-97 guidance to tonality in wind turbine sound. This type of approach is supported in later black literature publications[383,384], although research is ongoing concerning the details and the most appropriate scheme. The AM penalty control proposed on the basis of subjective response data from experimental evidence available in the 2016 review[385] is shown in Figure 3-22. This was based on a single parameter, the AM depth.

[379] 'Wind turbine noise effects on sleep'
[380] Indoor levels of sound exposure of ~31 dB $L_{Aeq,8h}$, or 29-34 dB $L_{Aeq,2h}$, which corresponded with simulated outdoor levels of 45 dB $L_{Aeq,8h}$, or ~43-48 $L_{Aeq,2h}$; AM depths of ~8-9 dB $\Delta L'_{Aeq,100ms(100\text{-}400Hz)}$ (quantified from the original study samples using the IOA Reference Method https://snd.gu.se/en/catalogue/study/snd1118/1#dataset); modulation frequency of ~0.7 Hz
[381] Smith, MG, Ogren, M, Thorsson, P, Hussain-Alkhateeb, L, Pedersen, E, Forssen, J, Ageborg Morsing, J & Persson Waye, K, 2020. A laboratory study on the effects of wind turbine noise on sleep: Results of the polysomnographic WiTNES study. *Sleep*, 43 (9), zsaa046. [URL]
[382] Dunbar, C, Catcheside, P, Vakulin, A, Zajamsek, B, Hansen, K, Lack, L, Scott, H & Micic, G, 2021. P031 Associations between sound pressure levels and amplitude modulation from wind farm noise and ambulatory recorded objective macro-sleep parameters. *SLEEP Advances*, 2 (1), A31. [URL]
[383] Hansen, C & Hansen, K, 2020. Recent advances in wind turbine noise research. *Acoustics*, 2, 172-207. [URL]
[384] Davy, JL, Burgemeister, K, Hillman, D & Carlile, S, 2020. A review of the potential impacts of wind turbine noise in the Australian context. *Acoustics Australia*, 48, 181-197. [URL]
[385] WSP | Parsons Brinckerhoff, 2016. *Wind turbine AM review: Phase 2 report.* 3514482A Issue 3. Department for Business, Energy & Industrial Strategy. [URL]

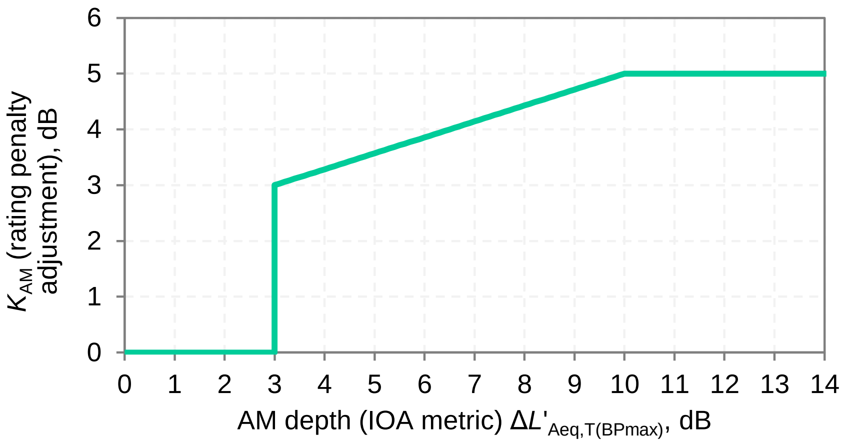


Figure 3-22: AM penalty control proposed in 2016 review[385]

Alamir et al (2021)[377] reviewed penalties for AM, noting the scheme proposed following the RenewableUK 2013 AM study[386] (which was equal in magnitude with the scheme shown in Figure 3-22, but employed a different AM measurement metric), and the fixed +5 dB applicable under the New Zealand standard NZS 6808:2010[387] – it is also notable that this standard stipulates a maximum combined penalty for multiple sound characteristics (ie alongside tonality or impulsivity) of +6 dB.

Alamir et al also highlighted experimental research by Turku University in Finland[388], which proposed a variable AM penalty of up to ~11 dB for wind turbine AM with modulation frequencies up to 2 Hz and modulation depths up to ~13 dB $\Delta L'_{Aeq,100ms(BPmax)}$ (re-analysed using the IOA metric[389]).

Emerging evidence further establishes how the AM parameters that influence annoyance responses could be incorporated into a penalty control scheme. A study in the grey literature used the IOA AM metric to reanalyse and pool the data from three laboratory listening tests, to form a relatively large combined sample of 107 participants[389]. The synthesis included data from the Turku study alongside the RenewableUK study[390] and an experiment conducted in Switzerland[391], and was shown to have an improved correlation with annoyance responses compared with the scheme recommended in the 2016 review. The penalty control scheme devised from the combined dataset is shown in Figure 3-23 alongside the 2016 review scheme[385]. In considering Figure 3-23, it should be noted that, for most commercial wind turbines, modulation frequencies tend to be in the range 0.5-1.0 Hz, and that larger turbines tend to have lower modulation frequencies within this range. The evidence on AM measurements in the field (discussed further in section 6.3.2) also indicate that AM depths of ≥6 dB are relatively unusual. This suggests that the penalty for AM as proposed by Lotinga et al (2021)[389] would typically be expected to take a value in the range ~0.5 to 5 dB, compared with a range of 3-

[386] RenewableUK, 2013. *The development of a penalty scheme for amplitude modulated wind farm noise*. [URL]
[387] Standards New Zealand, 2010. *NZS 6808:2010 Acoustics - Wind farm noise*. [URL]
[388] Virjonen, P, Hongisto, V & Radun, J, 2019. Annoyance penalty of periodically amplitude-modulated wide-band sound. *Journal of the Acoustical Society of America*, 146 (6), 4159-4170. [URL]
[389] Lotinga, M, & Lewis, T, 2021. *Subjective responses to wind turbine noise amplitude modulation: Pooled analysis of laboratory listening studies and synthesis of an AM character rating penalty*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe. [URL]
[390] von Hünerbein, S, King, A, Piper, B & Cand, M, 2013. Work package B2: Development of an AM dose-response relationship. *Wind turbine amplitude modulation: Research to improve understanding as to its cause and effect.* RenewableUK. [URL]
[391] Schäffer, B, Pieren, R, Schlittmeier, SJ & Brink, M, 2018. Effects of different spectral shapes and amplitude modulation of broadband noise on annoyance reactions in a controlled listening experiment. *International Journal of Environmental Health Research*, 15 (5), 1029. [URL]

4 dB based on the scheme proposed in the 2016 review[385] (which did not include modulation frequency as a variable). Measuring AM with relatively high modulation frequencies >1.6 Hz, such as might be expected with relatively small turbines, requires modifications to be made to the IOA AM metric, which is limited to modulation frequencies ≤1.6 Hz (and may underestimate AM depths at the upper end of this range[389]).

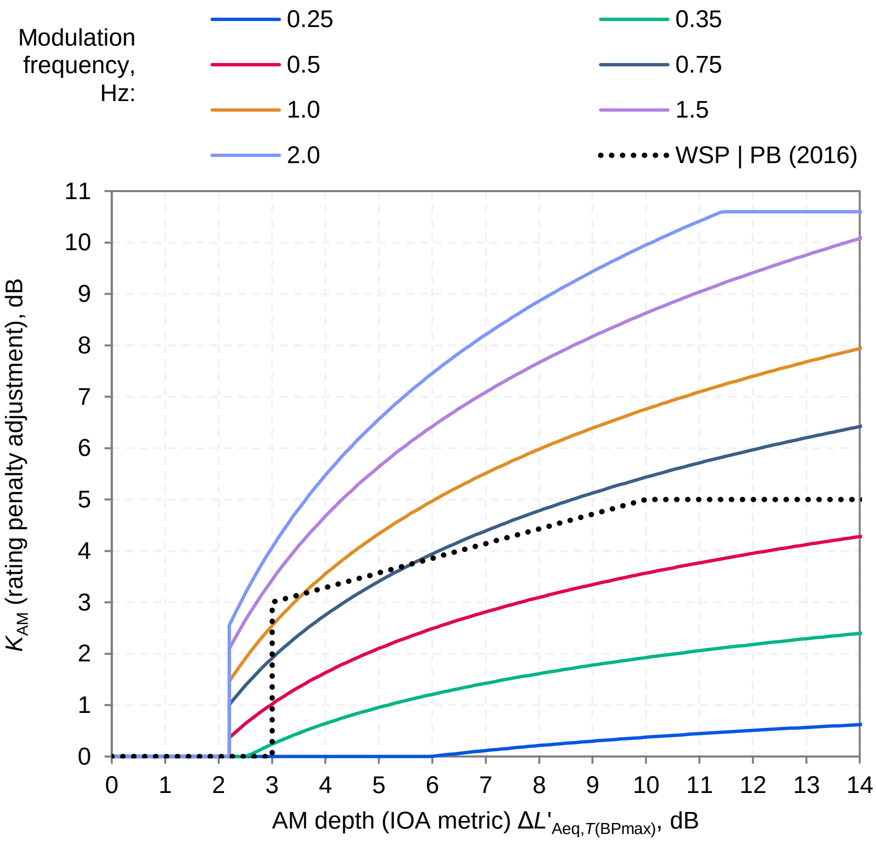


Figure 3-23: AM penalty control proposed by Lotinga et al (2021)[389], shown alongside the scheme from the 2016 AM review[385]

It has been noted that interaction effects observed in experimental studies between AM depth and overall sound level imply that a penalty for AM based on AM depth should decrease in magnitude as level increases. However, it has also been noted that further evidence is needed to understand this effect, and that it could be problematic to try and represent this in a penalty scheme[389], as it would imply that higher wind turbine sound immission levels lead to a lesser penalty at the same AM depth than lower wind turbine sound immission levels.

Mitigation

One potential method of mitigation for TEDCAR-AM was investigated in a simulation study[392]. The conceptual system devised comprised a responsive individual blade pitch angle control system, used to modify the blade pitch angles to minimise the modulation depths predicted by the simulation (by varying the angle of attack). The simulation results for idealised conditions indicated that the

[392] Mackowski, L & Carolus, TH, 2021. Wind turbine trailing edge noise: Mitigation of normal amplitude modulation by individual blade pitch control. *Journal of Sound and Vibration*, 510, 116279. [URL]

modulation depth at a single target location can be reduced to negligible magnitude. It was shown that the control system can be optimised for the specified location, however the optimisation for one location can result in increased TEDCAR-AM at other locations. It was noted that, for multiple locations, the outcome of the process could be different. It was also highlighted that increasing wind shear reduced the effectiveness of the AM control, because the pitch angle modification became less effective in controlling the angle of attack.

Summary of key findings

Noise limits and effects

It is clear from this review that the investigation and evidence on the effects of wind turbine sound has progressed substantially since ETSU-R-97 was published. It is less clear whether the ETSU-R-97 noise limits represent (or exceed) expected thresholds for adverse effects, due to the complexities of comparing results across the many studies:

- The ETSU-R-97 daytime minimum limits appear to be broadly consistent with the approaches taken in overseas national or regional guidelines, and are among the more stringent limits imposed.
- It has been highlighted that the ETSU-R-97 night-time minimum limit is higher (less stringent) than for many other territories, and, with the exception of the Ireland guidance (which is based on ETSU-R-97), it does appear to be unique in advising a higher night-time limit than for daytime, among the other national and regional regulations examined. Nonetheless, it remains unclear from the research evidence whether sleep disturbance would be expected to occur at the level permitted by the night-time minimum limit. However, several studies have found that self-reported sleep disturbance is more strongly associated with noise annoyance than with the actual levels of sound exposure. Evidence on the direct effects of wind turbine sound exposure on sleep disturbance is inconsistent, which suggests that any effect that may be present is relatively weak – this indicates that typical exposure levels are too low to directly disturb sleep. Controlled laboratory studies of wind turbine sound indicate that some physiological indicators of effects on sleep can be detected at levels of 32-33 dB L_{Aeq} indoors, but the implications of these indicators for individual and long-term sleep quality are not fully understood.
- The ETSU-R-97 relative limit is among the less stringent of the overseas regulations that use a 'margin above background sound level' approach – Australia and Japan impose relative limits that are 2 dB more stringent. The evidence on effects of relative impacts does not appear to be substantial, and no clear margin above background for relative impacts associated with annoyance has been identified in this review. However, there is some evidence to suggest this factor could have some influence on noise annoyance responses.
- It has also been noted that the imposition of noise limits used as pass/fail criteria precludes the assessment of impact in terms of adverse effects and the mitigation approach that is required under the wider policy frameworks in place in England and Northern Ireland.

Annoyance is the most widely investigated and consistently identified effect of wind turbine sound exposure:

- Studies have shown that noise annoyance due to wind turbine sound can occur at relatively low sound levels, lower than for other common sound sources, and there is now a substantial body of evidence available concerning wind turbine noise annoyance responses in terms of absolute levels of sound exposure.

- For exposure to estimated 'worst-case'[393] sound levels ≤35 dB L_{Aeq} (~33 dB L_{AF90}), proportions of study participants reporting feeling high annoyance tend to be relatively low (≤2%). For exposure to worst-case levels >35 dB L_{Aeq}, annoyance rates rise, but inter-study variation in responses also increases considerably.
- Noise annoyance responses can be strongly influenced by a range of personal and contextual factors, which can result in a wide variation in the observed responses within individual studies.

The evidence on noise annoyance and on sleep disturbance should undergo further systematic review, including critical appraisal of quality and risks of bias, as well as meta-analysis, with the aim of identifying relevant effects thresholds and exposure-response relationships.

Overall, the evidence for other adverse health effects of wind turbine sound exposure is inconsistent, although emerging evidence from the Danish nationwide studies indicates that further research is warranted. The weight of evidence on the effects of infrasound and low frequency sound at present supports the conclusions that (a) wind turbine infrasound at exposure levels typical for dwellings has no adverse effects on health and reported symptoms are more likely to be psychogenic in origin, and (b) that controls on A-weighted wind turbine sound levels are expected to be sufficient to control the effects of low frequency noise.

Amplitude modulation

It is evident that amplitude modulation in wind turbine sound as investigated in the field and studied theoretically varies considerably from the form of TEDCAR-AM ('blade swish') described within ETSU-R-97. The generation mechanisms of TEDCAR-AM are relatively well understood, and due to its features, it is only expected to be audible at relatively close range to turbines, and has a higher frequency characteristic. Non-TEDCAR-AM is less well understood, and contributing factors are subject to ongoing research. The evidence indicates that these could include transient blade stall (influenced by wind shear, wind veer, atmospheric and topographic conditions), inflow turbulence variation, wake effects, and partial refractive rotor shading. It is also apparent that this non-TEDCAR-AM, when present in the sound, can be expected to impart greater adverse impact than was assumed when devising the ETSU-R-97 noise controls:

- It is noted that there is strong evidence demonstrating that non-TEDCAR-AM is more prevalent at night, due to the contributing factors influenced by atmospheric conditions.
- The AM depths for non-TEDCAR-AM can be greater than TEDCAR-AM.
- Non-TEDCAR-AM is associated with modulation in the lower frequency region of the spectrum, which propagates further, and is more effective at transmitting through structures.
- Some evidence suggests that AM is associated with greater annoyance than tonality in wind turbine sound.

The IOA Reference Method appears to be a robust and practical general-purpose approach to quantifying AM within large datasets, which has been applied and tested in research studies.

The increased annoyance associated with non-TEDCAR-AM is influenced by AM depth and modulation frequency, which also interact in determining responses; these observations indicate that both these parameters should be included in an AM control. The evidence also suggests that the AM depth is not as strongly associated with changes in annoyance as the overall averaged sound level, and there may be a slight interaction effect between AM depth and sound level; these

[393] Downwind at 8 ms^{-1} wind speed at 10 m height

observations support the suggestion that AM should be controlled using a character penalty approach.

A character penalty scheme was proposed in the 2016 review, which was based on the AM depth, as clear, robust evidence concerning modulation frequency was not available. More recently, a pooled reanalysis of experimental data using the IOA Reference Method has led to a proposed penalty scheme that incorporates AM depth and modulation frequency, and is based on a larger combined participant sample than other studies; the more recent scheme shows an improved correlation with annoyance responses compared with the earlier scheme recommended in the 2016 review.

Conclusions

> Considered against the aims and objectives of current government policies and regulatory frameworks (outlined in section 1.1.1), the evidence indicates that the guidance would benefit from further review and updating, to ensure that the wind turbine noise controlling values reflect the state of understanding of the effects of wind turbine noise and control of AM, and are consistent with the overall policy approach to noise management.

In addition, there are several other areas identified that would also benefit from review and potential updating, which it has only been possible to briefly touch upon in the course of this review:

- the assessment of cumulative impacts from multiple developments
- the complexities of assessing compliance (including cumulative impact situations), and the potential benefits of employing proxy measurement locations close to wind turbines to address the issue of low sound levels
- the approach to addressing the effects of wind shear on assessments
- further specification of appropriate measurement instrumentation
- the approach to measurement data aggregation and treatment of uncertainty

3.5.2 SECONDARY RESEARCH QUESTION 2A

- *What further evidence or information may need to be obtained to robustly support updates to the current guidance (if it does require updating)?*

A systematic review and meta-analysis of the evidence on wind turbine noise annoyance and sleep disturbance effects would be valuable in providing a robust basis for determining appropriate noise control values. According to the policy frameworks in England and Northern Ireland, such a review should aim as a minimum to identify a LOAEL for community noise annoyance, and could consider what might constitute a SOAEL. It must be recognised, however, that personal and contextual factors, which may be influenced by local circumstances, have a strong influence on individual annoyance responses. Therefore, the evidence gained from overseas studies may be useful in determining an 'interim' position, until further UK-based evidence becomes available. It is important that any meta-analysis of existing exposure-response relationships takes careful account of differences in study methods, and, where necessary, applies normalisation to differing exposure-response scales to ensure compatibility and avoid misleading results – this is discussed further in section 6.2.1.

At present, there are no epidemiological studies reported in the peer-reviewed literature to draw on for understanding of expected noise annoyance responses or sleep disturbance effects within the rural areas of the UK in which the majority of onshore wind energy generating capacity is likely to be sited. An observational study of the effects of wind turbine sound exposure including rural communities in the UK would therefore be valuable.

It has also been noted[394] that no sleep studies (observational or experimental) are known to have been undertaken to investigate the effects of wind-induced sound (eg, wind interaction with vegetation or structures) on sleep quality, which could be highly relevant when investigating the potential effects of wind turbine sound on sleep.

There appears to be very little scientific evidence on the influence of residual sound to understand the relative impact of wind turbine noise. If relative impact assessment is to continue to form a part of wind turbine noise controls, further investigation of this aspect, which could comprise experimental or observational study, would be important.

There is also very little evidence on the impact of AM from observational studies; current findings on AM are mainly informed by experimental studies. Similarly, there is very little scientific evidence addressing how the intermittency and prolongation of wind turbine sound influences responses or outcomes. Study of these aspects would therefore be valuable.

No studies have been identified that systematically investigate associations between turbine size and prevalence of AM, but some evidence indicates that some potentially contributing factors, such as wind shear, partial refractive rotor shading and wake effects, would be partly dependent on the turbine dimensions. This suggests further study of this aspect could be helpful in understanding the risk of AM occurrences.

A study addressing the most effective approach to controlling AM should be undertaken. Based on the present review, it is recommended that the application of a character penalty scheme similar to that already in place for tonality should be confirmed. The study should aim to determine all the relevant details, including practical application and worked examples for inclusion in new guidance.

3.5.3 SECONDARY RESEARCH QUESTION 2B

- *What evidence is there on the influence of turbine age and design on the sound emission characteristics?*

A small amount of evidence has been identified addressing the influence of turbine design on sound emissions.

It has been suggested that the increased size of turbines may result in a shift towards lower frequency sound immissions due to increased separation distances (a discussion on the scientific debate around the potential for lower frequency sound *em*issions associated with larger turbines can be found in section 6.5.2).

It has also been noted that the control flexibility afforded to operators by modern variable speed, pitch regulated systems may enable power generation and sound emissions to be maximised while complying with noise limits, which could potentially lead to more sustained impact than may have been typical in the past.

[394] Michaud, DS, Feder, K, Keith, SE, Voicescu, SA, Marro, L, Than, J, Guay, M, Denning, A, Murray, BJ, Weiss, SK, Villeneuve, PJ, van den Berg, F & Bower, T, 2016. Effects of wind turbine noise on self-reported and objective measures of sleep. *Sleep*, 39 (1), 97-109. [URL]

Accurate control of the blade pitch angle can also be used to reduce AM, by modifying the blade angle of attack (which reduces the occurrence of local blade stall).

4

STAKEHOLDER ENGAGEMENT

4 STAKEHOLDER ENGAGEMENT

4.1 METHODOLOGY

This section outlines the approach to the stakeholder engagement exercise, the methodology for which has been based on relevant Government Communication Service guidance[395].

4.1.1 ENGAGEMENT OBJECTIVES

The objectives of the engagement were to:

- gather perspectives on the adequacy of current wind turbine noise guidance
- enable identification of gaps in current knowledge and understanding of wind turbine noise impact
- build relationships for possible further engagement on guidance development or wind turbine study
- lay foundations for stakeholder acceptance of the findings of this project and possible future guidance

4.1.2 ENGAGEMENT STRATEGY

The engagement comprised two parts:

1. Online / email survey questionnaire
    - All stakeholders included in the engagement were provided with a survey questionnaire. An email invitation was sent to each stakeholder with a web link to an online browser-based survey, and, as an alternative, a questionnaire response template electronic document for those who preferred to complete the survey offline.
2. Telephone interview
    - Key stakeholders agreed with the project steering group were also invited to engage in a telephone interview to discuss their responses further.
    - The questionnaire offered the opportunity for other stakeholders to indicate if they would like to participate in a telephone interview, alongside an advisory note stating that telephone interviews could not be guaranteed for all requests.
    - This tiered approach was intended to encourage responses and maximise the quality of information, while managing stakeholder expectations and the deliverability of the engagement process.

All stakeholders participating in the engagement survey were made aware that their responses would be anonymised in any published material, and that a summarised analysis of anonymised responses is likely to form part of the published output from the project.

The offline version of the questionnaire used in the survey is included in Appendix C1. The questionnaire is separated into three main response sections:

1. questions gathering views and opinions about the current guidance and the need for any updates

[395] Government Communication Service, 2021. *Ensuring effective stakeholder engagement*. [URL]

2. requests for information about wind turbine technology, wind farm design, and how these may influence sound or noise, including any changes occurring since ETSU-R-97
3. requests for ancillary information including:
   - suggestions for managing guidance development and ongoing maintenance
   - any relevant published evidence stakeholders had not identified elsewhere in their response

4.1.3 STAKEHOLDER IDENTIFICATION

Identification of stakeholders was initially carried out by discussion with the project steering group. During the engagement, additional stakeholders were identified and incorporated into the exercise. The stakeholders invited to participate in the exercise are listed in full in Appendix C2, and the respondents are listed in Table 4-1. It is important to note that several respondents to the survey stressed that their responses represented their individual views, or the collated views of a department within their organisation, and did not necessarily represent the whole organisation; these are noted in Appendix C2.

Local planning authority (LPA) stakeholders were identified from the *Renewable Energy Planning Database: quarterly extract* (March 2021, published 28 April 2021[396]) as any authority that had recorded an onshore wind energy planning application. After rationalising the list of authorities identified in the record against the most recent authority formations (ie, replacing any superseded council bodies with their successors, which in some cases combined authorities), this resulted in 204 invitee LPAs. During the initial contact phase, the environmental health and development planning departments of LPA stakeholders were specifically targeted with the aim of ensuring that the most appropriate council officers were made aware of the exercise.

Table 4-1: Summary of respondent stakeholders

Type	Organisation
UK government	Defra
	Planning Inspectorate
	UK Heath Security Agency
Welsh Government	Planning and Environment Decisions Wales
	Public Health Wales
Scottish Government	Energy Consents Unit
Local planning authority (England)	Great Yarmouth Borough Council

[396] https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract#history

Type	Organisation
Local planning authority (England)	Medway Council
	Hambleton District Council
	North Kesteven District Council
	King's Lynn and West Norfolk Borough Council
	North Somerset Council
	South Cambridgeshire District Council
	Redcar and Cleveland Borough Council
Local planning authority (Northern Ireland)	Antrim and Newtownabbey Borough Council
	Fermanagh and Omagh District Council
	Causeway Coast and Glens Borough Council
	Armagh, Banbridge and Craigavon
	Mid Ulster District Council
	Derry City and Strabane District Council
Local planning authority (Scotland)	Aberdeenshire Council
	East Ayrshire Council
	South Lanarkshire Council
	Shetland Islands Council
	Highland Council
Industry professional association	RenewableUK
	Institute of Acoustics
	Association of Noise Consultants
	Scottish Renewables
	BSi PEL/88 Committee
Civic organisation	Independent Noise Working Group

4.2 ENGAGEMENT RESPONSE ANALYSIS SUMMARY

This section provides a summary of the engagement response analysis – further analysis of the responses is included in Appendix C3.

4.2.1 SURVEY ANALYSIS APPROACH

The questionnaire included closed and open questions. Responses to closed questions have been analysed quantitatively, with both overall numbers of responses and in some cases stratified responses (eg, by respondent type, or by devolved administration). Responses to open questions have been analysed qualitatively and quantitatively using a thematic analysis approach[397]: responses were reviewed, with underlying themes apparent in each response extracted and grouped. The grouping enabled a quantitative analysis of the qualitative data to identify and highlight

[397] Kiger, ME & Varpio, L, 2020. Thematic analysis of qualitative data: AMEE Guide No. 131. *Medical Teacher*, 42 (8), 846-854. [URL]

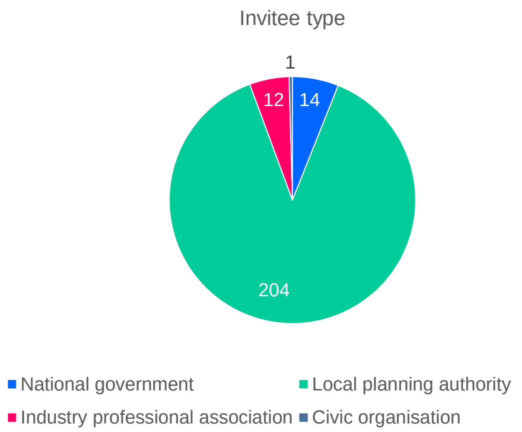
the most common themes. Key quotes taken from the responses were also extracted to provide supporting illustrations of the common themes, using respondents' own words. Where dissenting views were specifically identified on common themes, each view has been presented to provide context.

The analysis also highlights which themes have been raised in responses from interviewee stakeholders, and which have been raised by non-interviewees only – this is to provide further context and to address the fact that a larger number of responses were received from LPAs than from the interviewee organisations. Much of the additional information gained from interview discussions has been incorporated into the interviewees' original survey responses, as clarifications or elaborations of the answers given in the questionnaire. Interview responses that have not been incorporated in this way are outlined in section 4.3.

4.2.2 SURVEY METADATA ANALYSIS

231 organisations were invited to participate in the stakeholder engagement exercise. The numbers of engagement invitees according to organisation type is shown in Figure 4-1a, which illustrates that LPAs formed the majority (88%) of invitees.

32 organisations submitted responses to the exercise; Figure 4-1b shows the numbers of respondents by organisation type, which indicates that the response rate among LPAs was lower than other organisation types.



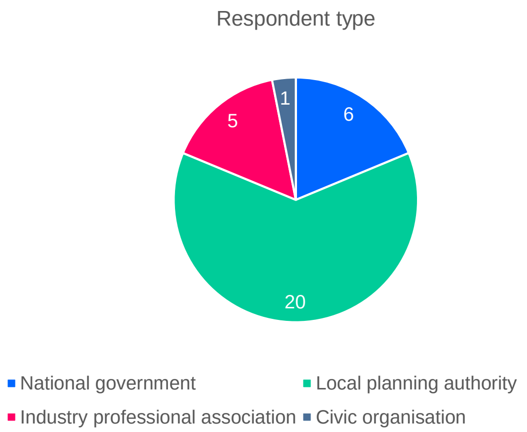


Figure 4-1: Stakeholder engagement organisation numbers, by type (a, left: invitees; b, right: respondents)

The difference in response rates by organisation types is further illustrated in Figure 4-2, which shows that the overall response rate was 14%, which is mainly influenced by the LPA response rate of 10%, while the response rate among non-LPA organisations was 44%.

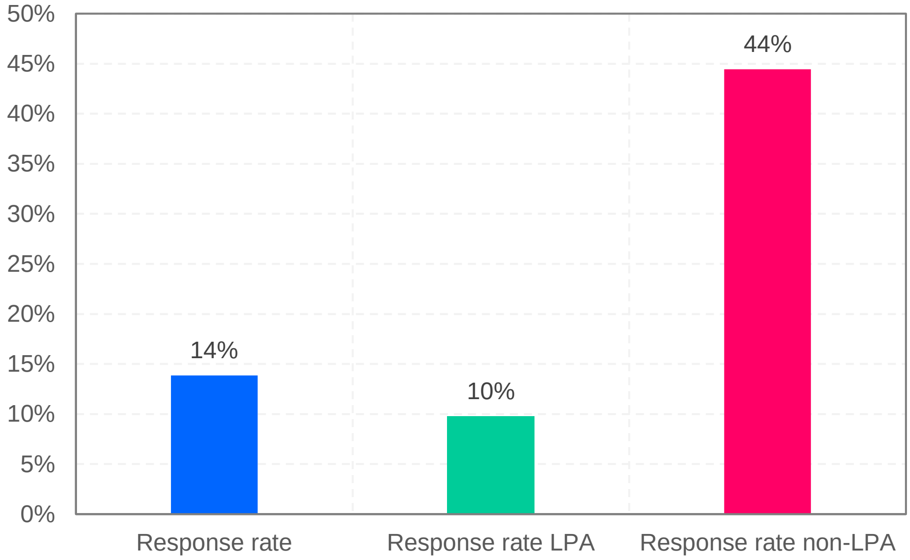


Figure 4-2: Stakeholder engagement response rates

A relatively low response rate among LPAs could be expected, due to the much larger number of invited LPAs, and the fact that many LPAs would have been included from the planning database on the basis of one or a small number of applications, and may not have had substantial experience with wind turbine developments that could otherwise motivate engagement with this kind of survey. This consideration is also supported by the geographic data on onshore wind energy developments recorded in the *Renewable Energy Planning Database: quarterly extract*[398]. As shown in Figure 4-3, this indicates that, for Northern Ireland and Scotland, the respondent LPAs tended to correspond with geographic areas containing greater densities of onshore wind energy developments, suggesting that the LPAs for those areas would have greater experience of onshore wind turbine noise (either in terms of development planning, or responding to reports of noise disturbance) than those of other areas. The situation in England is less clear, as onshore wind installations tend to be more sparsely distributed.

[398] https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract

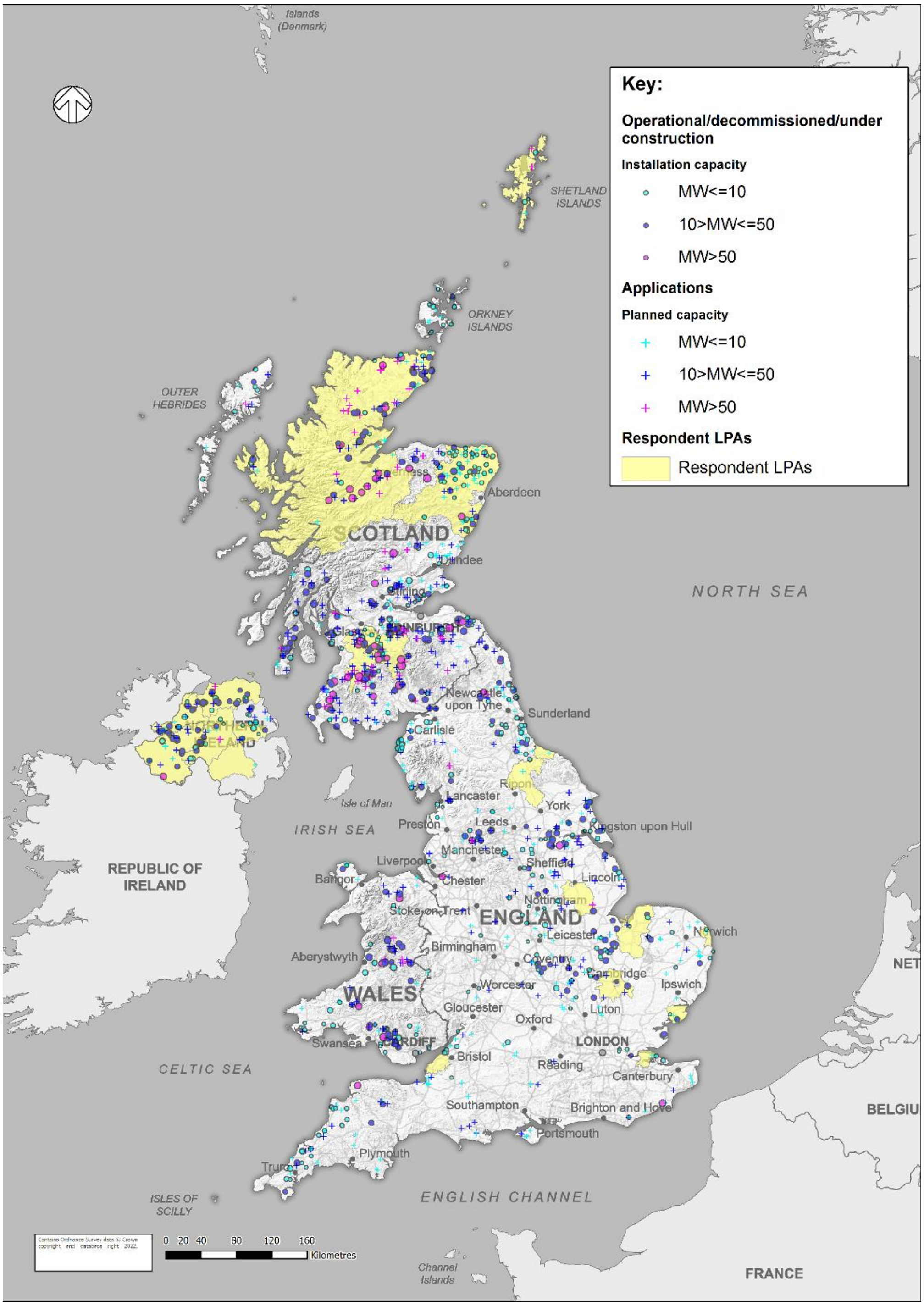


Figure 4-3: Map of onshore wind energy developments[399] and LPAs responding to the engagement survey

As shown in the break down by devolved administration in Appendix C3, while the majority of LPAs invited to respond were in England, the proportional response rates were greatest for Northern Ireland, and lowest for Wales (for which none of the 20 invited LPAs responded to the engagement). Reasons for the lack of response from LPAs in Wales are unclear, as onshore wind generation

[399] Development symbol sizing is scaled to the logarithm of turbine quantity, as an indicator of turbine density.

capacity in Wales is larger than in Northern Ireland, and growing at a faster rate than in England or Northern Ireland (generation capacity in Wales grew by 39% in 2020, compared with 10% in England, 5% in Northern Ireland, and 47% in Scotland[400]). Further efforts to engage with LPAs in Wales could be valuable, but is beyond the scope of the present study.

The following respondents either formally entered joint responses, or entered responses that were virtually word-for-word identical, such that it was clear a single response had been circulated for consideration and (almost invariably) adopted:

- Planning Inspectorate (for England) and Planning and Environment Decisions Wales (formal joint response)[401]
- RenewableUK and Scottish Renewables (formal joint response)
- Northern Ireland local planning authorities (duplicated responses / informal joint response):
  - Fermanagh and Omagh District Council
  - Armagh, Banbridge and Craigavon
  - Mid Ulster District Council
  - Derry City and Strabane District Council
  - Causeway Coast and Glens Borough Council (NB: some parts of the Causeway Coast and Glens Borough Council responses varied from those for the other Northern Ireland councils listed above, while other parts were word-for-word identical, indicating a partially adopted joint response)

4.2.3 SURVEY SECTION 1: VIEWS ON CURRENT GUIDANCE

Q1.1: Which description most closely describes your level of familiarity with the current UK wind turbine noise assessment guidance?

The responses to Q1.1 are illustrated in Figure 4-4, which shows that:

- (a) roughly equal proportions of respondents judging themselves to have at least some familiarity with the guidance assigned themselves to each category for level of familiarity
- (b) all of the industry professional respondent organisations assigned themselves to the most familiar category ('A'), while the LPA respondents had a roughly even spread among the other familiarity categories 'A-C' (NB: respondents placing themselves in category 'D' – unfamiliar / no understanding – were asked if they could nominate an alternative representative in their organisation with greater familiarity, and were directed not to enter responses to the other questions within the survey section concerning the current guidance).

[400] BEIS, 2021. *Energy trends: September 2021, special feature article – Renewable electricity in Scotland, Wales, Northern Ireland and the regions of England in 2020*. Department for Business, Energy & Industrial Strategy. [URL]
[401] When the survey invitations were issued, the Planning Inspectorate for England and Wales was for official purposes one UK government unit, however, during the engagement, the Welsh part of the Planning Inspectorate became Planning and Environment Decisions Wales, a Welsh Government body

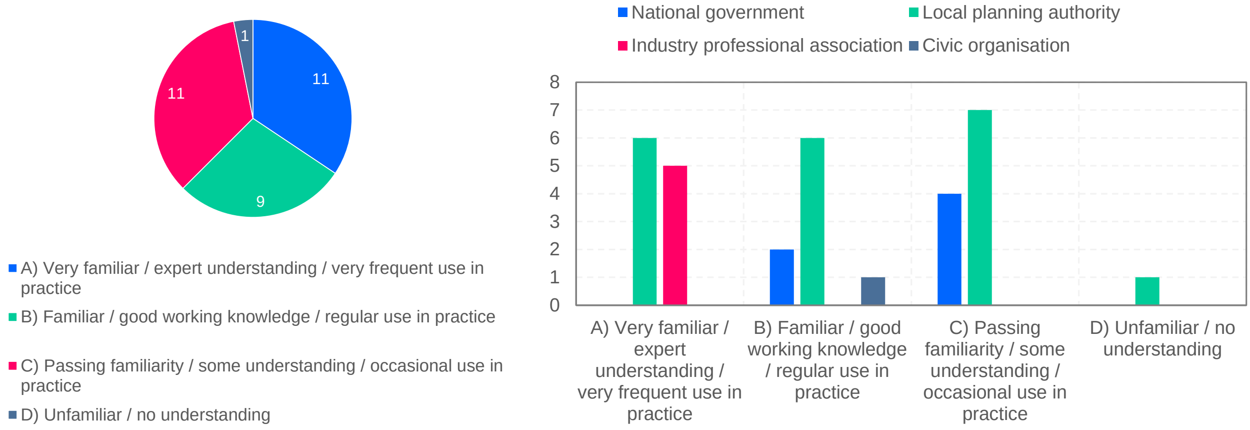


Figure 4-4: Stakeholder familiarity with current guidance (a, left: overall; b, right: by organisation type)

Q1.2: Which description most closely matches your view on the adequacy of the current UK wind turbine noise guidance in ensuring wind turbine noise is managed effectively and consistently in line with Government policies on noise and Net Zero?

The responses to Q1.2 are illustrated in Figure 4-5, which shows that there was an almost even split between respondents whose views were most closely represented by the 'mostly adequate' or 'inadequate' categories. Only one respondent clearly gave their view that the guidance is 'adequate, no updates necessary', while two were unsure.

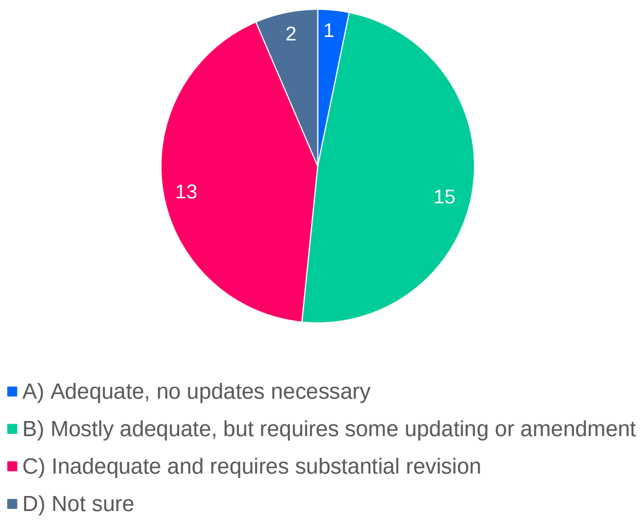


Figure 4-5: Stakeholder views on need for updates to current guidance (overall)

During the survey responses and the interviews, three stakeholders, all comprising industry professional associations with multiple members, advised that some members had differing views on the appropriate response to this question. Specifically:

- one association that gave an overall consensus response of 'B) mostly adequate', stated that there was a minority among their members who would have preferred to answer 'C) inadequate'

- the other two associations answered 'B) mostly adequate', but clarified that their members tended towards the view that the guidance is adequate (answer 'A'), while recognising that, if the government is minded to take new guidance development forwards, there are some areas that could benefit from minor updating (described as 'tweaks')

It can be seen from Figure 4-5 that, even if these stakeholders had decided to enter a different answer, the overall picture would not be greatly altered.

> The majority of stakeholders agree that the current guidance requires updating, with a roughly even split between those who think it is mostly adequate, with some updating required, and those whose view is that it is inadequate and requires substantial revision.

Further analysis of the responses to Q1.1 shown in Appendix C3 indicates that:

- Stratifying responses by devolved administration shows:
  - the majority of respondents representing organisations (of any type) in England responded 'B) mostly adequate'
  - all of the respondent Northern Ireland organisations answered 'C) inadequate' (discussed further below)
  - organisations in Scotland tended to be roughly evenly split between 'B) mostly adequate' and 'C) inadequate'
- All of the industry professional associations, and the majority of the national government body respondents answered 'B) mostly adequate'.
- The majority of LPA respondents answered 'C) inadequate':
  - The majority of LPA respondents answering 'C) inadequate' comprised Northern Ireland LPAs.
  - The majority of LPA respondents in England answered 'A) adequate' (1 council), or 'B) mostly adequate'.
  - LPA respondents in Scotland were roughly evenly split between 'B) mostly adequate' and 'C) inadequate'.

This analysis suggests that views on the need for and scope of any updates to the current guidance vary somewhat depending on both sector and devolved administration. In particular, it is notable that respondent LPAs in Northern Ireland unanimously supported the view that the guidance is inadequate and requires substantial revision, while respondent LPAs in England tended towards the view that it is mostly adequate, but requires some updating or amendment.

Q1.3: Which (if any) of the following topics relevant to the current UK wind turbine noise assessment guidance do you consider need to be updated?

The responses to Q1.3 are illustrated in Figure 4-6.

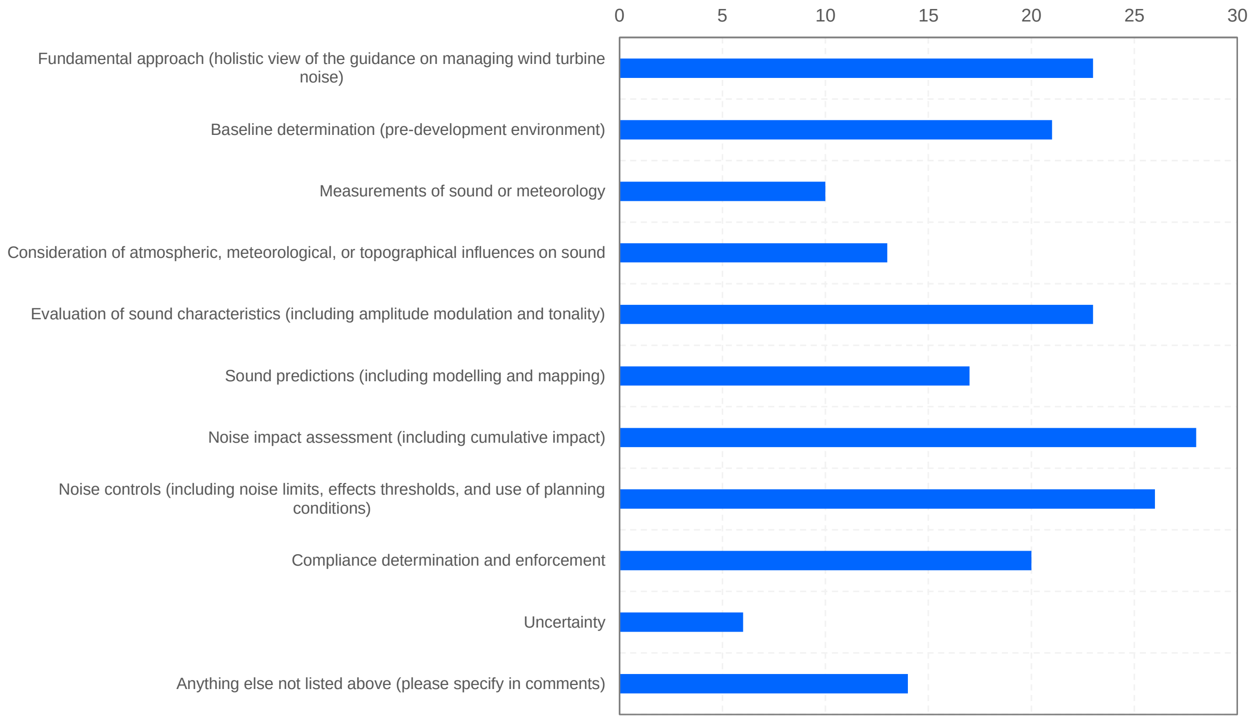


Figure 4-6: Stakeholder views on topics within guidance that require updating

Figure 4-6 shows that the topics most frequently identified as requiring updating included:

- 'noise impact assessment (including cumulative impact)'
- 'noise controls (including noise limits, effects thresholds, and use of planning conditions)'
- 'evaluation of sound characteristics (including amplitude modulation and tonality)'
- 'fundamental approach (holistic view of the guidance on managing wind turbine noise)'

Further analysis shown in Appendix C3 indicates that this was largely consistent among different respondent types, however the 'baseline determination (pre-development environment)' topic was among the most frequently identified by industry professional associations, more so than by other types of respondent organisations.

> The frequent identification of 'noise controls (including noise limits, effects thresholds, and use of planning conditions)' and 'evaluation of sound characteristics (including amplitude modulation and tonality)' as topics requiring updates is consistent with the evidence identified in the scoping review in section 3.3.

Analysis of the responses to Q1.3, separated by the response given to Q1.2, is shown in Figure 4-7 (NB: Figure 4-7 shows the data as a proportion of the total number giving each response; the absolute response numbers corresponding with Figure 4-7 are shown in Appendix C3).

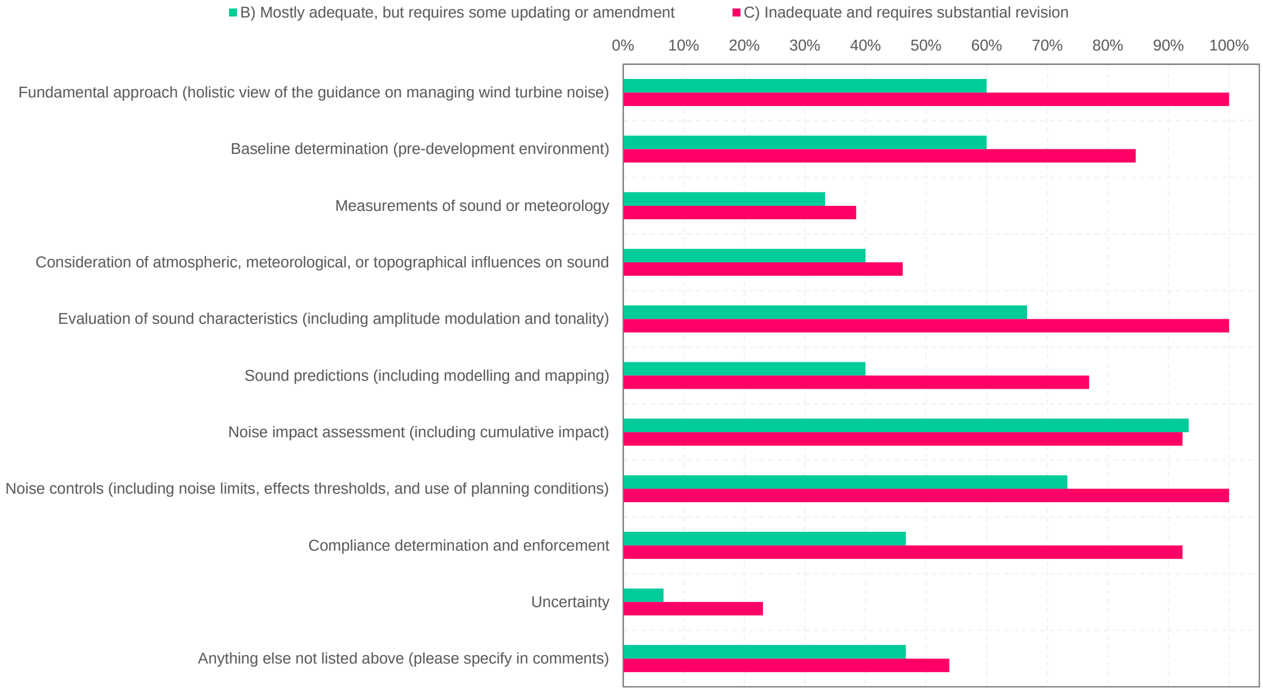


Figure 4-7: Stakeholder views on topics within guidance that require updating, separated by views on the need for updates to current guidance

The analysis in Figure 4-7 indicates both differences and consistencies in the responses of stakeholders providing differing views on the extent of updates required to the current guidance:

- The group responding 'C) inadequate and requires substantial revision' to Q1.2 highlighted (i) 'fundamental approach (holistic view of the guidance on managing wind turbine noise)', (ii) 'evaluation of sound characteristics (including AM and tonality)', and (iii) 'noise controls (including noise limits, effects thresholds, and use of planning conditions)', as the three most-frequently identified topics.
- The group responding 'B) mostly adequate, but requires some updating or amendment' to Q1.2 highlighted (i) 'noise impact assessment (including cumulative impact)', (ii) 'noise controls (including noise limits, effects thresholds, and use of planning conditions)' and (iii) 'evaluation of sound characteristics (including AM and tonality)', as the three most-frequently identified topics.

Q1.4: Please could you briefly outline the updates you believe need to be made to the current UK wind turbine noise assessment guidance, and identify any publicly accessible evidence you are aware of that would support or inform the updates indicated?

Q1.4 asked respondents to submit suggested updates associated with each of the specific topic areas listed in Q1.3 (including 'anything else not listed'). This section details analysis of the four most frequently identified topics; further analysis of other topics is shown in Appendix C3 and summarised below.

Noise impact assessment (including cumulative impact)

The thematic analysis of the responses identified under this topic is shown in Figure 4-8.

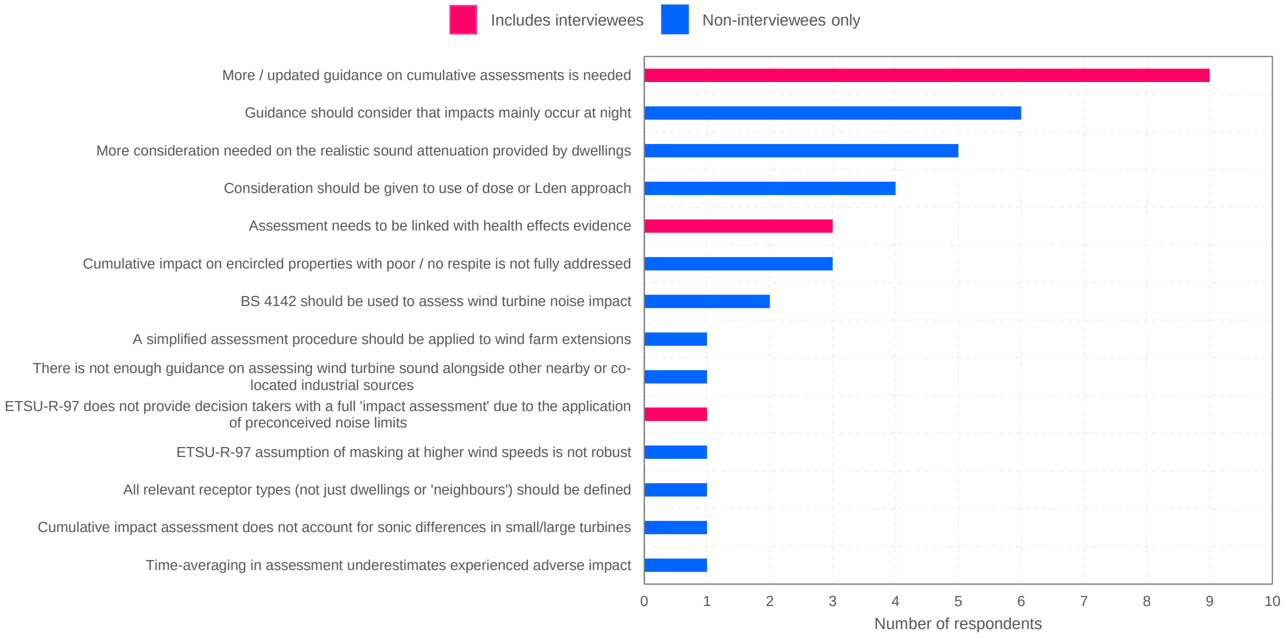


Figure 4-8: Thematic analysis of stakeholder responses concerning 'noise impact assessment'

Key quotations illustrating the most commonly raised themes are shown in Table 4-2.

Table 4-2: Key quotations from stakeholder responses concerning 'noise impact assessment'

Theme	Key quote
More / updated guidance on cumulative assessments is needed	*ETSU-R-97 defines a general principle of the limit applying to total noise from all turbines. The consequences of this for cumulative wind farm development are complex and sometimes strongly restrictive to further wind farm development. This should ideally be considered from a strategic perspective. Good practice guidance has evolved to advise how to manage this and set individual limits for different wind farms. It would be useful to reflect the progress made on this topic within any revised form of ETSU-R-97.*
Guidance should consider that impacts mainly occur at night	*In* [our] *experience, significant noise impacts occur within dwellings during night-time hours when sleep is disturbed or is proving difficult due to wind turbine noise.*
More consideration needed on the realistic sound attenuation provided by dwellings	*The assumption (implied within ETSU-R-97) that the building structure will protect residents at night does not appear to be valid with modern turbine types and sizes and with the separation distances involved to receptor properties. Modern large turbines produce different dominant frequencies than 1990s turbines.*

Theme	Key quote
Consideration should be given to use of 'dose' or L_{den} approach	*The impact assessment approach should consider whether new survey data regarding wind farm annoyance is available to inform assessment thresholds. This should include consideration of new advice provided by the WHO regarding windfarm noise average noise exposure levels and the use of the L_{den} and L_{night} indicators.*

Noise controls (including noise limits, effects thresholds, and use of planning conditions)

The thematic analysis of the responses identified under this topic is shown in Figure 4-9.

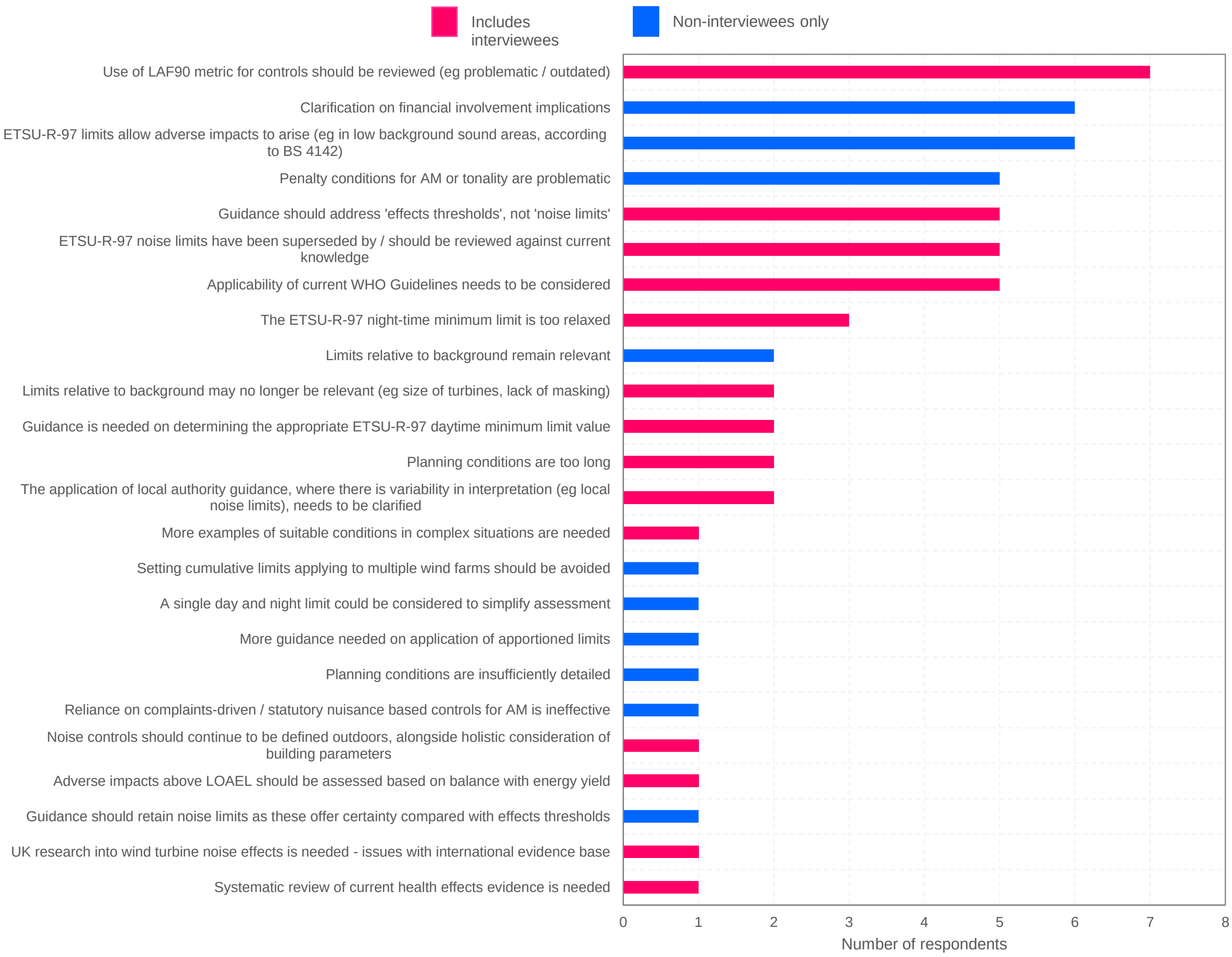


Figure 4-9: Thematic analysis of stakeholder responses concerning 'noise controls'

Key quotations illustrating the most commonly raised themes are shown in Table 4-3.

Table 4-3: Key quotations from stakeholder responses concerning 'noise controls'

Theme	Key quote
Use of L_{AF90} metric for controls should be reviewed (eg, problematic / outdated)	*Is use of L_{A90} appropriate in the context of a health pathway approach? - no evidence linked to effects is expressed in terms of L_{A90} exposure*
Clarification on financial involvement implications	*We believe that given the significance of financial involvement to the level of noise deemed acceptable/ derived limits (and the anticipated lengthy duration of such agreements) that the extent and nature of financial involvement should be laid out and specified within noise assessment guidance.*
ETSU-R-97 limits allow adverse impacts to arise (eg, in low background sound areas, according to BS 4142)	*ETSU-R-97 suggests a night-time lower limit of 43 dB which could be 20 dB higher than background noise in some areas and is clearly excessive.*
Penalty conditions for AM or tonality are problematic	[We] *would have concerns about the use of penalty planning conditions to address tonality and amplitude modulation impacts that may occur on a site-specific basis. This provides no certainty that adverse noise impacts will not occur and places huge uncertainty on the ability of the operator to comply. This is particularly the case for single turbine schemes with machines that may be less capable of adjustment.*
Guidance should address 'effects thresholds', not 'noise limits'	*Given current policy, the terminology must evolve to reflect that. Elsewhere, Government (in the context of aviation) has defined the impact which equates to the Lowest Observed Adverse Effect Level, but has not defined a value for Significant Observed Adverse Effect Level. The word 'limit' is not used.*
ETSU-R-97 noise limits have been superseded by / should be reviewed against current knowledge	*Since ETSU-R-97 was written, turbine technology has evolved such that it is possible to operate turbines with different operational modes at different times, meaning noise levels could potentially be higher at night in line with the increased limit, which is arguably against the original intention of ETSU-R-97. Furthermore, there has been considerable research on sleep disturbance effects of wind turbine noise, specifically, which has been published since ETSU-R-97 was written, and this should be taken into account.*

One dissenting view was noted concerning the theme *Guidance should address 'effects thresholds', not 'noise limits'*:

Table 4-4: Dissenting views from stakeholder responses concerning 'noise controls'

Theme	Dissenting theme	Key quote
Guidance should address 'effects thresholds', not 'noise limits'	*Guidance should retain 'noise limits', as these offer certainty compared with 'effects thresholds'*	*In relation to thresholds and limits, much of the UK's noise guidance issued in recent years has moved away from specific noise level limits (e.g. X dBA or Y dBA above the background noise) towards guidance which considers impacts as considered using LOAEL and SOAEL. Consideration of specific noise level limits enables wind farm developments to be designed, consented and operated with a relatively high degree of certainty, which helps developers understand project risk. Use of specific noise limits should also make it easier for consenting authorities to quickly consider applications and should therefore speed up the achievement of net zero.*

Evaluation of sound characteristics (including amplitude modulation and tonality)

The thematic analysis of the responses identified under this topic is shown in Figure 4-10.

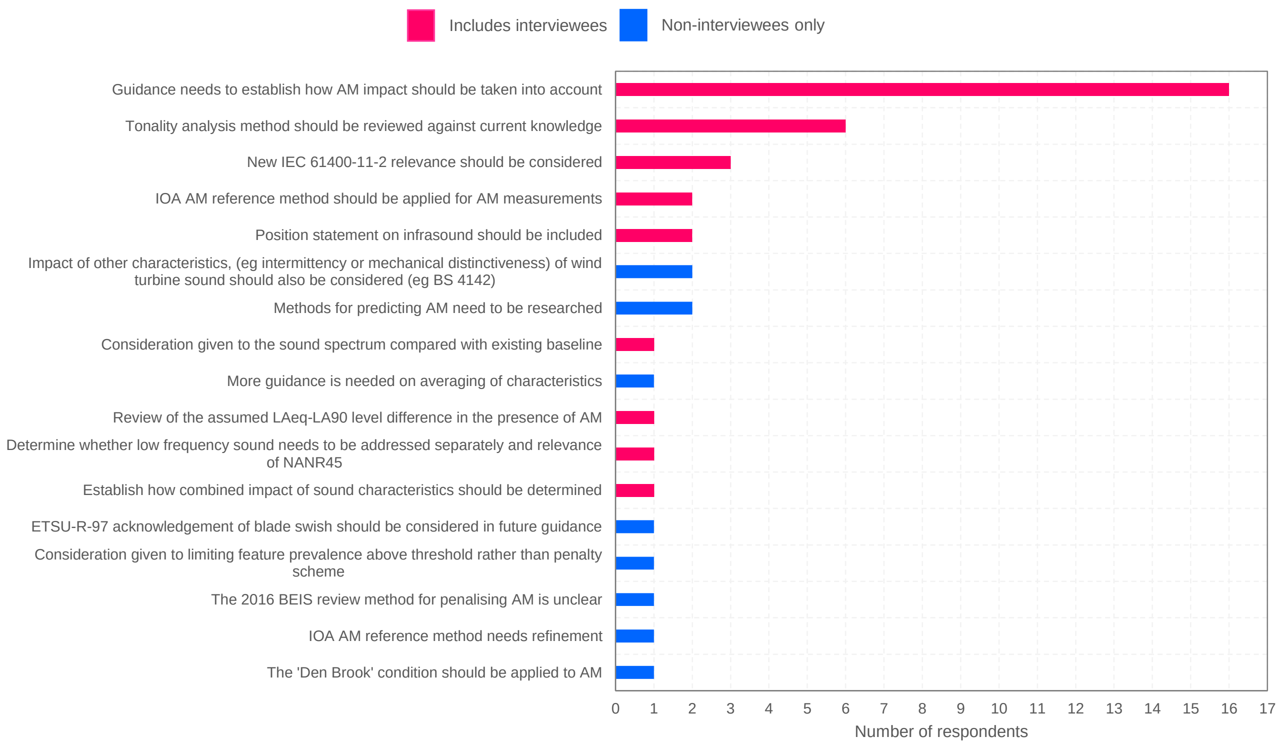


Figure 4-10: Thematic analysis of stakeholder responses concerning 'evaluation of sound characteristics'

Key quotations illustrating the most commonly raised themes are shown in Table 4-5.

Table 4-5: Key quotations from stakeholder responses concerning 'evaluation of sound characteristics'

Theme	Key quote
Guidance needs to establish how AM impact should be taken into account	*The existing guidance does not consider so called 'other amplitude modulation' or 'excess amplitude modulation' in detail. Whilst the IOA method enables the quantification of AM there is no (Government endorsed) guidance that can be used to determine whether that level of AM is acceptable and, if it is not, what level of penalty should be considered. This is an area where further guidance would be useful, either to reaffirm the approach set out in the existing guidance (which notes that "At the time of writing, current practice is not to assign a planning condition to deal with AM.") or build on previous research to confirm an approach to controlling AM.*
Tonality analysis method should be reviewed against current knowledge	*It is recommended that more research and clarity is needed: Should the tonal noise assessment methodology in ETSU-R-97 be brought into line with current best practice? This would include a review of all methods such as ISO/PAS 20065 and/or a variation on that in the most current version of IEC61400-11, and should the penalty scheme be updated?*
New IEC 61400-11-2 relevance should be considered	*The proposed IEC Technical Specification "IEC 61400-11-2 Measurements at receptor position"*[402] *may be relevant when published.*

[402] At the time of preparing this report, the IEC 61400-11-2 standard is at drafting stages, and the standards development procedures mean it is unlikely to be published sooner than late-2022 or early-2023 [URL]

Fundamental approach (holistic view of the guidance on managing wind turbine noise)

The thematic analysis of the responses identified under this topic is shown in Figure 4-11.

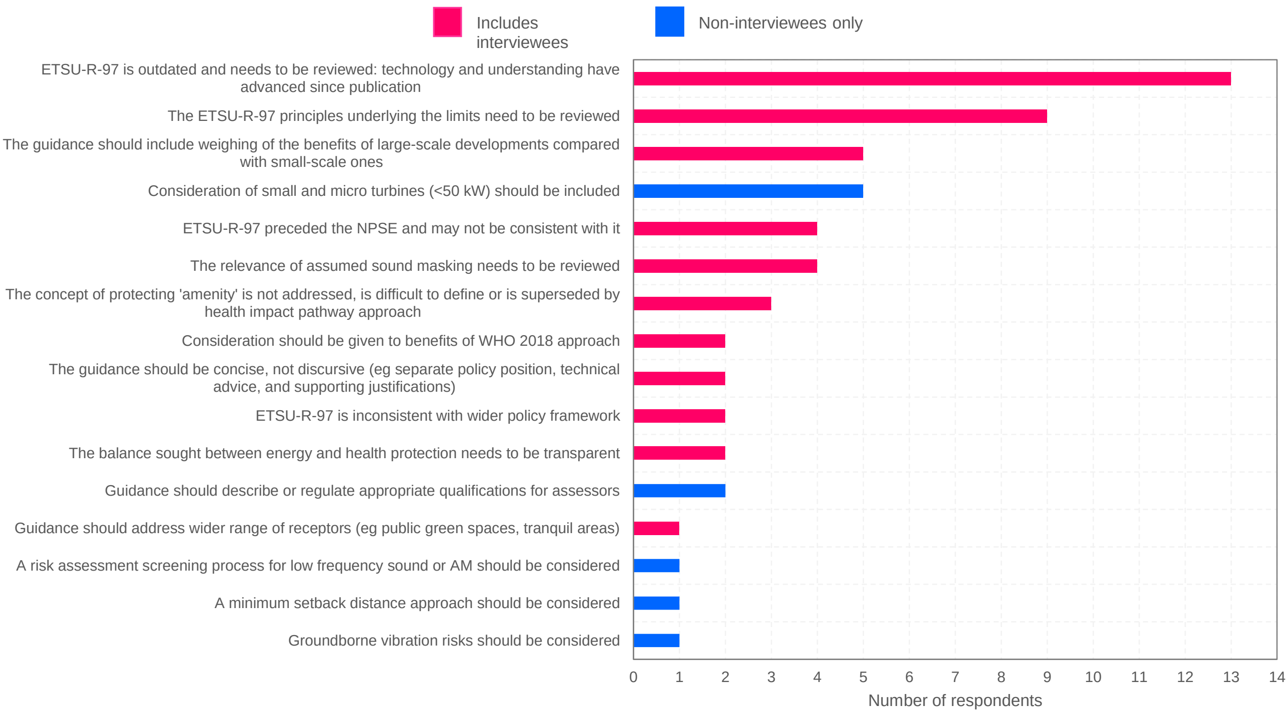


Figure 4-11: Thematic analysis of stakeholder responses concerning 'fundamental approach'

Key quotations illustrating the most commonly raised themes are shown in Table 4-6.

Table 4-6: Key quotations from stakeholder responses concerning 'fundamental approach'

Theme	Key quote
ETSU-R-97 is outdated and needs to be reviewed: technology and understanding have advanced since publication	*What is needed is an update to ETSU-R-97 which was produced in 1996. Turbine design has advanced significantly, and our experience is that we are seeing proposals for much taller turbines than we used to.*
The ETSU-R-97 principles underlying the limits need to be reviewed	*The underlying principle of ETSU-R-97 is that 'acceptable' noise limits can be achieved by limiting the turbine noise to no more than 5 dB above background, or, where the background is low, a lower fixed limit can be applied. However, the fundamental question of whether the assessment methodology remains fit for purpose, given changes in turbine size and their locations relative to properties is highly pertinent and requires exploration. Furthermore, given that 'unacceptable' now has a specific meaning within noise planning policy, it is important to avoid using the word 'acceptable' to describe the relevant noise thresholds and targets.*

Theme	Key quote
The guidance should include weighing of the benefits of large-scale developments compared with small-scale ones	*We believe that the development of the on-shore wind sector should take a maximum benefit view to the dis-benefits of the noise generated as a result – so that small-scale single turbines near to dwellings are less favoured over larger schemes set further away (both of which will result in the same or similar noise impact).*
Consideration of small and micro turbines (<50 kW) should be included	*The experience in Northern Ireland relates to a very large proportion of single-turbine schemes which utilise older turbines, de-rated hybrid turbines or types of wind turbine that do not fall directly within the scope of ETSU-R-97, nor the IOA GPG, nor the AM guidance directly. We believe that for the successful development of on-shore wind energy that retains public confidence – that all types of development should be considered within the noise assessment guidance.*

It is notable from Table 4-6 that smaller turbines are a particular concern in Northern Ireland, which has only been raised as an issue by one other UK stakeholder (a Scotland LPA). This is discussed further in section 6.4.9.

Compiled topics

An analysis of all the topics compiled (including those addressed in Appendix C3) has been undertaken to provide further context and because different numbers of respondents addressed each topic. A truncated set of the results is shown in Figure 4-12 (the full analysis is included in Appendix C3).

> The theme most commonly raised by stakeholders is the need for guidance to define the approach to addressing AM impact.

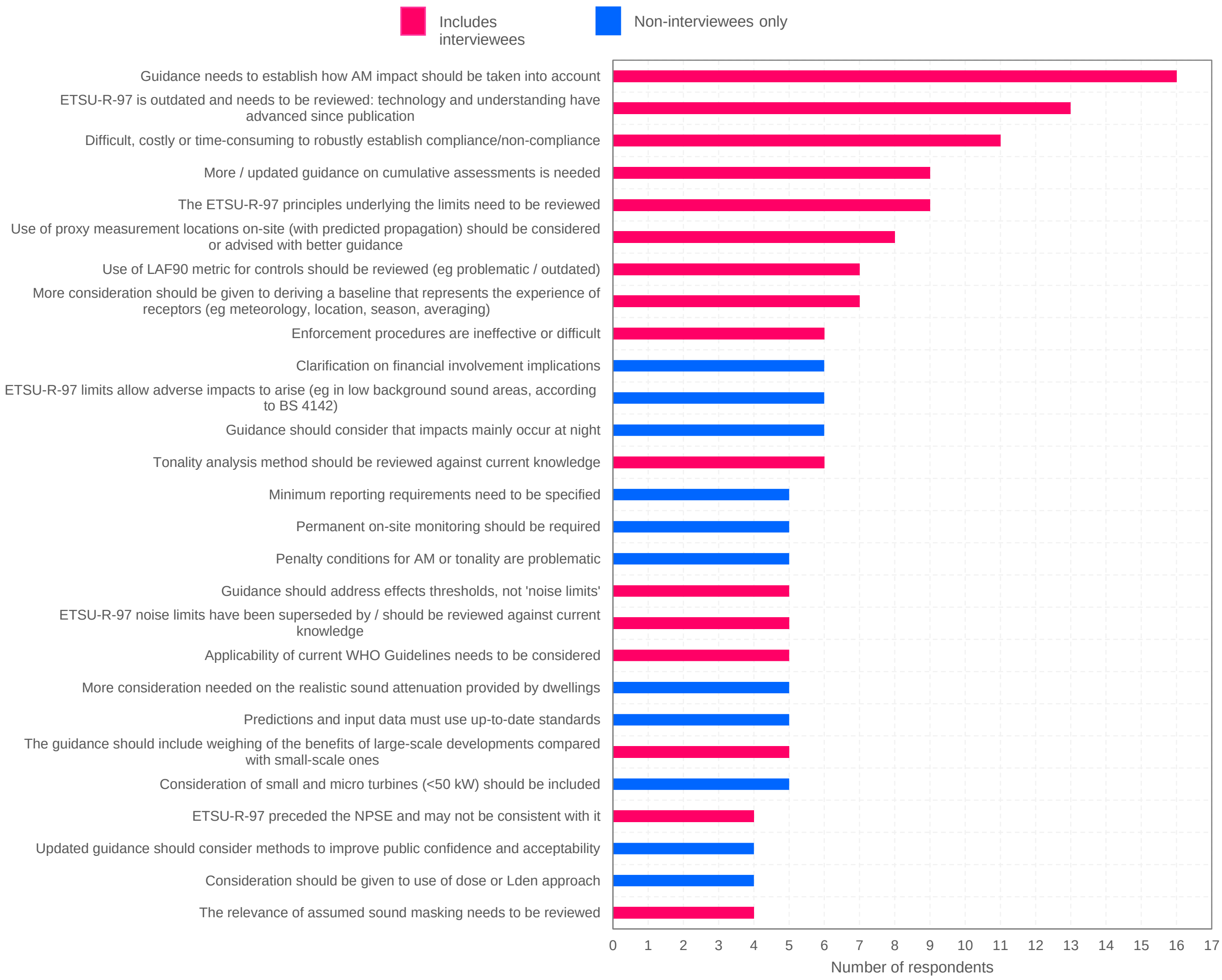


Figure 4-12: Thematic analysis of stakeholder responses for all topics (truncated: ≥4 respondents only – see Appendix C3 for full analysis)

Other themes

Analysis of the other individual topics is shown in Appendix C3. The following list provides a summary of the first two most commonly raised themes for each of the other topics:

- Compliance determination and enforcement:
  - It is difficult, costly or time-consuming to robustly establish compliance/non-compliance.
  - The use of proxy measurement locations on-site (with predicted propagation) should be considered or advised with better guidance.
- Baseline determination:
  - More consideration should be given to deriving a baseline that represents the experience of receptors (eg, meteorology, location, season, averaging).
  - Further guidance is needed on determining baseline in presence of cumulative developments.

- Measurements of sound or meteorology:
  - More guidance could be given on meteorological instrumentation and measurement.
  - More guidance on wind screens is needed.
- Consideration of atmospheric, meteorological or topographical influences on sound:
  - More guidance on attenuation by local features (including wooded areas or solid obstacles) is needed.
  - The approach to concave ground profiles needs to be reviewed[403].
- Sound predictions:
  - Predictions and input data must use up-to-date standards.
  - Validation of prediction model accuracy would be helpful.
- Uncertainty:
  - More specific uncertainty guidance is needed.
  - Consideration of wake effects influencing the accuracy of wind speed measurements during compliance testing is needed.
- Anything else (not listed under other topics):
  - Updated guidance should consider methods to improve public confidence and acceptability.
  - A centralised database of approved turbine sound data should be established, with any turbines not approved precluded from developments.

4.2.4 SURVEY SECTION 2: WIND TURBINE AND WIND FARM DESIGN INFLUENCE

Q2.1: Do you have any specific experience or research knowledge of the potential influence of wind farm or wind turbine design or age on sound emissions?

The responses to Q2.1 are illustrated in Figure 4-13, which shows that the majority of stakeholders did not consider they had experience or knowledge on this subject. Only respondents answering 'yes' to Q2.1 were asked to complete the other questions in this section.

[403] This refers to the treatment of valley-like topography, which can result in enhanced sound propagation due to ground reflections

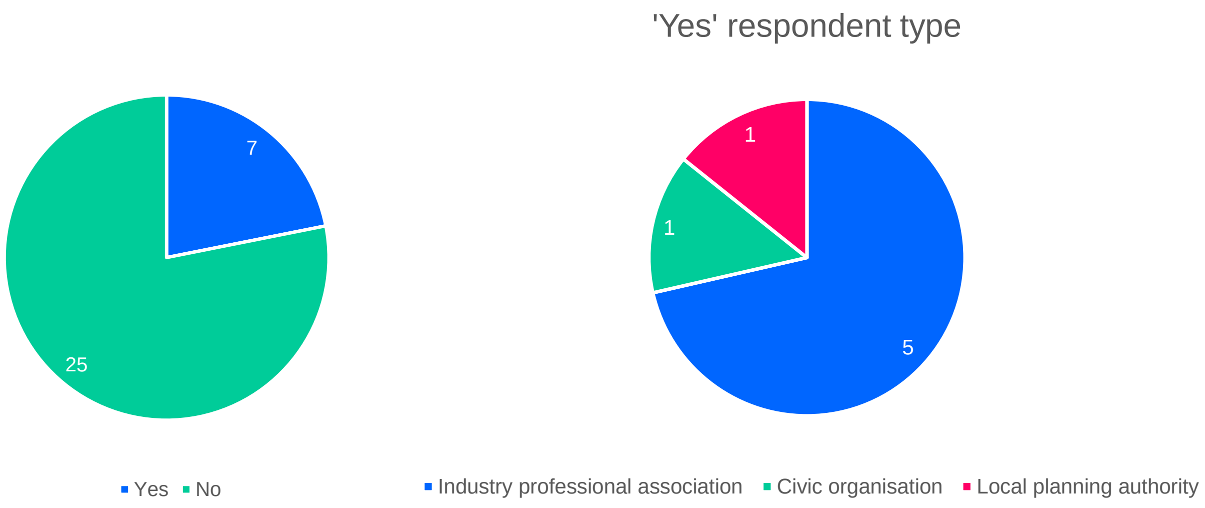


Figure 4-13: Stakeholder experience or knowledge of wind farm or wind turbine design/age influence on sound emissions

Since the number of respondents answering the remaining questions in survey section 2 was small, the combined qualitative-quantitative thematic analysis approach was not adopted, and instead the responses were considered qualitatively only.

Q2.2: Please could you briefly outline how the design of more modern wind turbines has influenced the sound emissions (including sound characteristics), compared with wind turbine designs prevalent around the time of the preparation of ETSU-R-97?

The following influencing factors were identified in the responses to Q2.2 as having changed since ETSU-R-97:

- Turbine sizes have increased (hub height and rotor diameter).
- Turbine design and operational control systems have developed:
  - Standard operation has advanced from fixed/dual speed, stall regulated control to variable speed, pitch regulated control.
  - Reduced sound emission modes are now available as standard.
  - Further noise mitigation measures are also available as standard, such as blade attachments, stall strips and vortex generators.
  - Operational control flexibility and accuracy has improved.

The responses received on these factors are outlined below.

Increase in turbine size

Table 4-7: Summary of stakeholder responses concerning the influence of changes in turbine size on sound emissions since ETSU-R-97

Summary of information provided
Turbine size has increased, but improved design means that sound emissions have not increased significantly. The increased size also means reduced turbine density, so overall immission levels remain similar for greater power capacity.

Summary of information provided
Increased rotor diameter leads to greater potential for variation in flow across the rotor span, increasing the risk of transient blade stall, which can cause increased AM.
Increased rotor diameter means a lower rotation frequency, resulting in lower frequency sound emissions.
Increased hub heights mean turbines 'cut-in' (commence operation) and reach rated power at lesser 10 m height-referenced wind speeds (ie, wind speeds relevant to receptors), so wind-induced sound may be lower at receptors for a given hub height wind speed, and so the relative impact on receptors may be greater (when compared with a smaller turbine with the same total sound emission).
Larger turbine size generally means separation distances to neighbours are increased, leading to increased atmospheric attenuation of higher frequencies, resulting in sound immissions with lower frequency character.
Research undertaken for the government of Denmark[404] indicates that increasing turbine size is not systematically associated with lower frequency sound emissions. However, it was also noted that when tones are present in the sound emissions, for larger turbines they tend to occur at lower frequencies.

Developments in turbine design and operational control systems

Table 4-8: Summary of stakeholder responses concerning the influence of changes in turbine design and operational control systems on sound emissions since ETSU-R-97

Summary of information provided
Fixed/dual speed, stall regulated turbines have given way to variable speed, pitch regulated models. The variable speed means sound emissions are lower at lesser wind speeds, and the pitch regulation means sound emissions are lower at greater wind speeds; the combination of these developments means that turbines start ('cut-in') more quietly and achieve rated power more quickly with increasing wind speed, beyond which sound emissions remain at a constant level with increasing wind speed.
More precise operational control enables reduced sound emission modes. Further noise mitigation measures are also available, including blade attachments, stall strips and vortex generators, which reduce sound emissions.
More precise control and reduced sound modes also enable operators to optimise power output while also maximising the sound emissions within the noise limit envelope, meaning that sound levels may be closer to the limits, under all conditions of operation and at different times, than would previously have been possible.
Pitch regulation can be used to mitigate the risk of blade stall, to reduce the potential for AM occurrence.

One stakeholder also noted that these issues are complex, and difficult to address in a survey questionnaire.

[404] Madsen, KD & Pedersen, TH, 2010. *EFP-06 project: Low frequency noise from large wind turbines*. Final report. AV 1272/10. Danish Energy Authority.

Q2.3: Please could you briefly outline any knowledge or evidence for how the age or wear and tear of wind turbines could influence the sound emission characteristics, including AM?

Table 4-9: Summary of stakeholder responses concerning evidence on the influence of turbine age and condition on sound emissions

Summary of information provided
There is evidence of increased noise as turbines age, which can be seen in the Bald Hills case in Australia[405].
Provided turbine blades are cleaned and turbines maintained, no increase in sound emissions is expected; commercial operators are incentivised to maintain turbines properly, to ensure efficiency of operation and power generation.
Mechanical, electrical or auxiliary component failures can result increased sound emission and changes in sound character. However, commercial operators are incentivised to maintain turbines properly to ensure efficiency of operation and power generation.
Based on re-certification measurements of turbine sound power levels after a period of time, the current view is that no allowance for age or wear and tear is required in the assessment process.
It is plausible that dirty turbine blades or rainfall could affect the airflow over blades that may influence AM, but evidence of this occurring is not known.
Blade attachments added post installation can become detached causing noise issues; attachments should be made in the factory or otherwise increased maintenance is required. Blade chips have the potential to result in increased tonal noise emissions. Experience suggests that regular maintenance should ensure that such tonal issues can be avoided or rectified. Evidence from two sites indicates that delamination of blades on older turbines (over a period of 10 years) can contribute to increased AM; repairs to resolve the issue are relatively straightforward.

Q2.4: Please could you briefly outline any suggestions you have for how the prevalence of AM from various turbine models and ages could be investigated?

Table 4-10: Summary of stakeholder responses concerning suggestions for how to investigate AM prevalence from UK wind turbines

Summary of information provided
The IOA AM measurement method should be used.
LPAs could be consulted to gain information, for example on reported disturbances (eg, a repeat of the 2007 investigation[406])

[405] Bald Hills Wind Farm was involved in a case heard at the State Supreme Court in Victoria, Australia. The full court judgement, issued in 2022, indicates that a tonality issue arising from a gearbox defect had been identified as contributing to noise disturbance reported by neighbours. The wind farm was commissioned in 2015, and noise complaints were first lodged in the same year. In 2016, an investigation confirmed that tonality had been detected in the sound emissions, and in 2017, further investigation identified gearbox defects as the cause. There is no suggestion in the judgement that the age or wear and tear condition of turbines (rather than a defective component) was associated with the noise issues. https://www.austlii.edu.au/cgi-bin/viewdoc/au/cases/vic/VSC/2022/145.html

[406] Moorhouse, A, Hayes, M, von Hünerbein, S, Piper, B & Adams, M, 2007. *Research into aerodynamic modulation of wind turbine noise: final report*. [URL]

Summary of information provided
This would require extensive and detailed large-scale research to investigate. The approach taken would need to be carefully considered: there are many potential pitfalls to avoid, and generalisability would be difficult to achieve - pilot studies could be valuable. The challenges involved in such a study include the number and variety of turbine models, varying site topography, variation in wind conditions and operational regimes, the need for operator cooperation and access to sites, turbine operational data, and the amount of surveying equipment required to monitor sound and weather, with no guarantees of obtaining useful measurements.
AM and methods of control are now well understood, so further extensive research is unnecessary. Manufacturers are aware of the risks of maximising power using pitch angle control, and that pitch control must be used to control AM for applications in the UK market.
IOA members with wind energy industry connections have offered to collaborate on such an investigation.
Wind farm operators and wind turbine manufacturers may already have archived data that could be valuable and could be consulted.

Q2.5: Please could you briefly outline any knowledge or evidence for how the design of wind farm layouts could influence cumulative noise impacts?

Table 4-11: Summary of stakeholder responses concerning the influence of wind farm layouts on cumulative noise impact

Summary of information provided
Wind farm layouts place turbines too close together, which contributes to unsettling synchronisation and desynchronisation effects.
Increasing density of wind farm developments leads to receptor encirclement and lack of respite from wind turbine sound.
The existing ETSU-R-97 guidance provides some consideration for duration of exposure in setting the daytime minimum limit, which may be used to address lack of respite in cumulative impact situations.
Noise limit 'headroom budgets' need to be carefully planned, which requires cooperation between developers.
Small-scale developments situated near to receptors may impact viability of larger-scale developments due to use of the 'headroom' in the ETSU-R-97 noise limits.
Guidance concerning cumulative impacts is available in the IOA GPG and a subsequent Acoustics Bulletin article[407].
Wind farm layouts can influence AM.

[407] Bowdler, D, Branney, E, Cand, M, Carmichael, B, Carter, R, Farmer, L, Irvine, G, Jiggins, M, Leventhall, G, McKenzie, A, Richard Perkins, R, Reid, M & Travis, P, 2016. Wind farms cumulative impact assessment. *Acoustics Bulletin*, 41 (1), 44-48. [URL]

4.2.5 SURVEY SECTION 3: DEVELOPMENT AND MAINTENANCE OF GUIDANCE

(Q3.1 asked respondents to identify evidence not already discussed in their response, which was reviewed against the systematic map; this resulted in three publications being added to the database)

Q3.2: Please could you briefly outline any suggestions you have for how any future UK wind turbine noise assessment guidance could be developed and maintained to provide a stable platform for development planning and assessment, while ensuring that it is kept up to date with robust scientific evidence?

Table 4-12: Summary of stakeholder responses concerning any future development and maintenance of guidance

Summary of information provided
Set up a guidance review programme (suggestions for periodic review timescales were in the range 2-5 years)
Set up a working group of experts from a range of sectors to oversee guidance development and updates
Ensure that any future guidance development is open-minded and not constrained by existing development situation
Make any future guidance web-based rather than document-based
The technical guidance could be kept separate from the overarching policy position (on the balance between noise impact and renewable energy) to ensure future updates can be made more easily and quickly
Provide training to public bodies on guidance
Careful preparation and communication of any future review and development of guidance is required to ensure that in the interim period the current guidance continues to be applied
A collaborative approach to updating guidance (eg, the IOA GPG and the AMWG methodology development) results in faster progress (eg, reliance on a single author to be supplemented by consultation is understood to have been the approach taken in Ireland, which has been developing new guidance since 2013)
Ensure that a decision on the policy balance between renewable energy and allowable noise impact is clear
Undertake a research review on subjective responses to wind turbine sound characteristics
Undertake a review of international guidance
Develop a national sound prediction model for public use (eg, like Defra maps for transportation)
Set up a research framework with guidance reviews linked to research milestones
The IOA would be willing to lead the development of new technical guidance, or otherwise the British Standards Institute may be a candidate organisation, however the BSi route may take longer than with the IOA

Summary of information provided

Several areas of wind turbine sound would benefit from further research, which may require government and industry funding to deliver

4.3 INTERVIEWEE FOCUS

A further analysis of the compiled topics thematic analysis is shown in Figure 4-14, which is filtered to include only themes identified by at least one interviewee stakeholder (the full analysis is shown in Appendix C3). This serves to emphasise some of the issues identified by interviewee stakeholders.

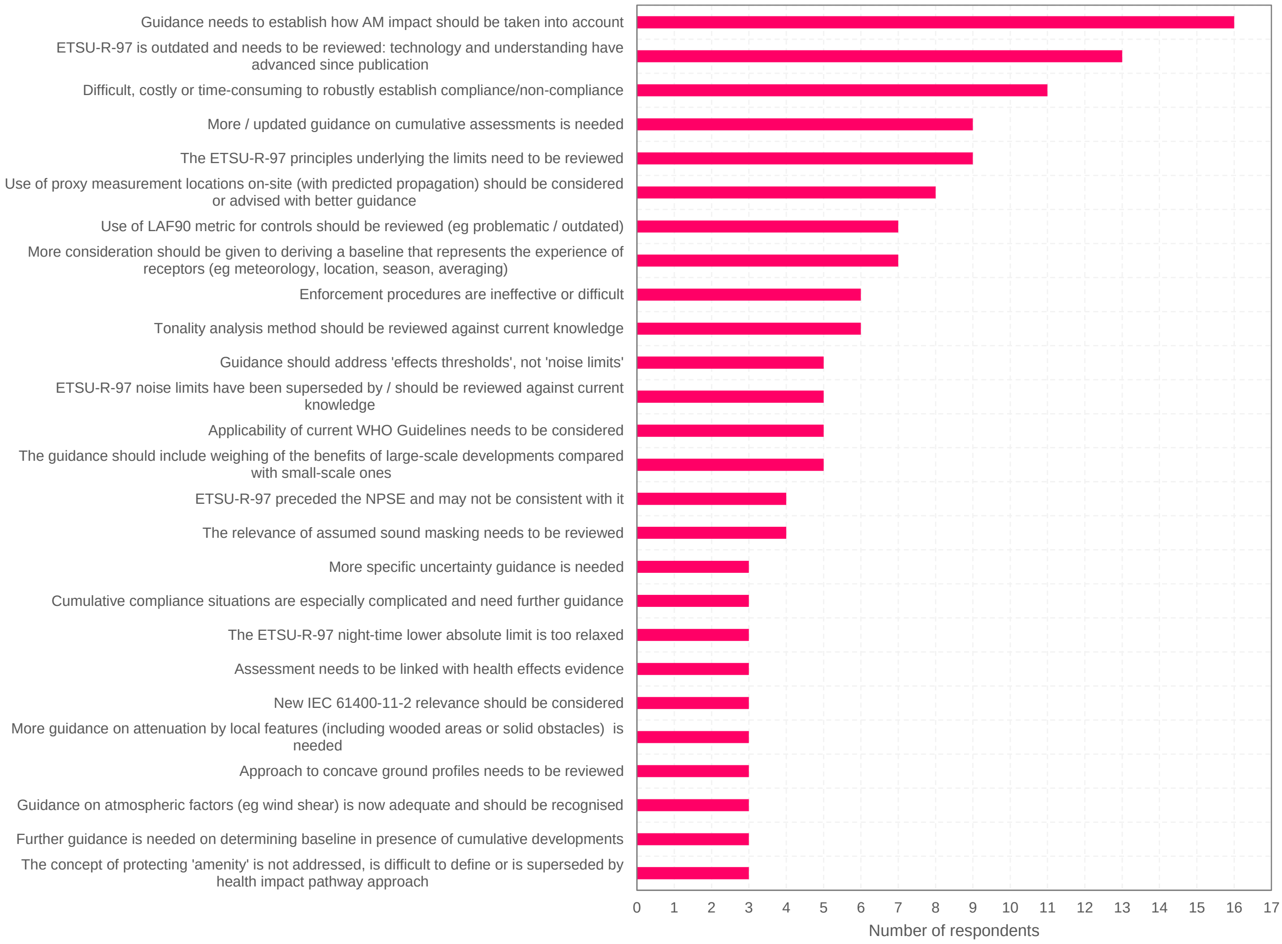


Figure 4-14: Thematic analysis of stakeholder responses for all topics (filtered for interviewee-identified themes and truncated: ≥3 respondents only – see Appendix C3)

As noted above, most of the interview discussion content has been incorporated into the survey response information in the form of clarifications or expansions to the responses initially entered. However, specific discussions and questions stemming from the interviews are summarised in Table 4-13. It should be noted that the responses presented have been paraphrased from the discussions, but interviewees were asked to review and confirm that the summaries taken down adequately represented the points made.

Table 4-13: Summary of stakeholder interview responses

Question	Stakeholder responses (paraphrased)
Do you consider the current guidance is compatible with the wider policy framework? (eg, NPSE, NPS-EN1, NPS-EN3 in England)	There is weak or no compatibility – in ETSU-R-97 there is no reference to health or quality of life, which suggests it is not compatible. The guidance should be linked to valuation methodologies using a health impact pathway approach – this is used for transportation, so, subject to evidence, why shouldn't it be applied to wind turbines? Identifying a LOAEL is essential – without a LOAEL it is inconsistent with the NPSE Some of our members feel that ETSU-R-97 can be interpreted as making a planning judgement about what the acceptable balance is in terms of wider policy; others feel that by pre-judging it, ETSU-R-97 is not compatible with the NPSE, and the guidance should have its own LOAELs and SOAELs defined. One member from Scotland also provided views based on Scottish policy, but the general view from members is that it is inconsistent with wider policies. We're not aware of any glaring incompatibilities, but it is important to maintain policy alignments going forward.
What do you think are the main issues with applying international research evidence on health?	The evidence shows that subjective responses can be heavily influenced by personal and contextual factors, which may be affected by particular local circumstances, for example: norms of cultural acceptance or preferences for different renewable energy technologies; the local regulatory frameworks could be linked with perceived fairness, eg compensation mechanisms and the participatory role of communities in planning decisions. For physiological sleep disturbance, this is more sensitive to sound events than long-term averages, so the characteristics of the sound (which could be locally influenced), such as AM, could be important in understanding the response.
Are there other gaps in the international evidence base beyond just the (non-UK) geographic locations of studies?	In the past, the UK has been a world leader in noise research, but so far there's never been a UK epidemiological study for wind turbine noise[408]. Looking at other countries with large-scale wind energy adoption (eg, Canada or Denmark), they have underpinned their approaches with large-scale epidemiological studies. Moving beyond just noise annoyance and sleep disturbance, eg, the Danish nationwide studies, it would be valuable to have equivalent UK studies to compare or confirm these observations – otherwise, we continue saying that there is limited evidence and we can go no further. For example, we could be studying the sound level indices: is L_{AF90} a more suitable predictor of health effects from wind turbine sound than L_{Aeq}? And what about the influence of personal and contextual factors – what is driving annoyance beyond the sound itself?

[408] Since this interview was held, the first peer-reviewed publication documenting an epidemiological UK-based observational study on the effects of wind turbine sound exposure was published in August 2021. This study is summarily reviewed in section 3.5.1 and Appendix B, section 9.2.1.

Question	Stakeholder responses (paraphrased)
Do you perceive value in applying a noise effects monetisation appraisal procedure to wind farm developments, such as the method developed by the IGCB(N) that underlies the TAG (maintained by the Department for Transport)?	It is a useful way of bringing focus to considering health impacts of noise, and consistent with the overall approach to other sound sources. Research is currently being undertaken in the area of cost-benefit analysis that includes wind turbine noise.
How do you view emerging Welsh Government policy on soundscape in the context of wind turbine developments, and do you foresee any potential compatibility issue with the Future Wales 2040 National Plan, given that this appears to have been prepared primarily from a noise impact control perspective, and wind turbines are typically location-constrained to rural areas?	It's an acknowledgement that soundscape is important – eg, that there are positive aspects of sound. How will a wind turbine development affect the soundscape of a National Park? If we are going to see more wind turbines to meet carbon reduction policies, will that change the soundscapes of these types of areas? We need to be conscious of soundscape. There is the potential for people to view it as incompatible with the Future Wales 2040 National Plan. Expectations are important. Future generations may see wind turbines as part of the soundscape in some areas.
One recommendation from the ClimateXChange study report[409] for Scottish Government was that qualitative assessments of the impact from wind turbine sound should be included in assessment reports, including the likely 'audibility' of the sound – do you support this recommendation?	At present, this recommendation does not form part of the Onshore Wind Policy Statement[410] or any other policy. If this is something that is being recommended in the outputs from this scoping review study, then we would support it.
Other points raised	Our members believe the fundamental approach of the current guidance remains valid and works well, and any updates should take the form of minor tweaks. Historically, any problems have mainly arisen in England, where turbines may have come closer to people than ideal. These issues arose due to the Renewables Obligation, which encouraged developments to be proposed in lowland areas (rather than highland areas). Currently developers have to seek out the best sites, which tend to be in highland areas. We're aware of very few complaints in Scotland. We see no problem with the ETSU-R-97 noise limit values - the night-time minimum limit of 43 dB is seldom required, and could be brought down to 40 dB without having a major impact on operation; in our experience, complaints tend to arise in quiet daytime periods, so night-time doesn't seem to be a problem. The daytime minimum noise limit range of 35-40 with three flexibility factors to consider seems unwieldy, but we find it works tolerably well.

[409] SLR & Hoare Lea, 2015. *Wind Farm Impacts Study: Review of the visual, shadow flicker and noise impacts of onshore wind farms.* Final report: 405.04528.00001. ClimateXChange. [URL]
[410] Scottish Government, 2017. *Onshore wind policy statement*. [URL]

Two industry professional associations provided additional written information concerning the potential for any future development of guidance:

> *Overall, the available guidance adequately addresses most of the aspects of wind turbine noise that require consideration. Current guidance has been developed from a progression of best practice, and presents a well-formed and robust methodology to adequately protect noise-sensitive receptors. It would, however, be preferable to have a single clear, practical, prescriptive document clearly setting out the procedures and methodologies that should be followed, including any supporting explanations or rationale provided as supplementary documentation.*
>
> *ETSU-R-97 must be read with the Good Practice Guidance (and associated Supplementary Guidance Notes) issued by the Institute of Acoustics in 2013. The 2013 documents addressed topics not covered by ETSU-R-97 (such as noise prediction models and the detail of wind shear). It updated ETSU-R-97 on other matters.*
>
> *The objective should be to produce updated guidance that demonstrably works, in the sense that it enables the coherent and reasonably reliable rating and assessment of wind turbine noise. This is important as the inevitable diversity of technical opinions on any given topic can endure without a firm conclusion for a considerable period to no great practical advantage. In a Net Zero context, a speedy process is required with a clear and reliable outcome. It should be noted that additional penalties on wind turbine noise, will reduce the potential installed wind capacity and affect the UK's ability to meet Net Zero.*
>
> *ETSU-R-97 and the GPG have both been successfully used in the industry across the UK, and internationally, for many years. The incidence of complaints about operational noise from windfarms has been very low. Compliance testing carried out at existing wind farms has shown that noise predictions based on the ISO 9613-2 model, coupled with the use of background noise material, works well enough, as currently written. Indeed, were the future of onshore wind across the UK likely to reflect the pattern of the last 20 years we would say that the current suite of advice works well enough that there would be little practical advantage in reviewing it.*
>
> *Any potential revision to the guidance should take account of the increased importance of the production of renewable energy since the ETSU-R-97 was written, in the light of the current climate crisis and the need to achieve Net Zero.*
>
> *Having all of this in mind, if a review is considered, it should with the objective of bringing together a single document demonstrably fit for purpose guidance for the 2020s and beyond.*
>
> *Our members would be very concerned if a review of ETSU-R-97 and the GPG were to be announced without careful thought and preparation. The fact that onshore wind development in the UK has attracted little adverse attention from those worried about noise does not mean that such an announcement would not stir up considerable interest from objector groups with no factual or scientific basis for their assertions. It is vital that the advice in national planning policy and guidance that ETSU-R-97 and the GPG be used to rate and assess operational noise should be maintained during any review process. If such clear advice is not given, those objector groups waiting to renew challenges to ETSU-R-97 and the GPG (which have*

been fought and universally lost over the years) will raise baseless assertions at public inquiries, causing considerable cost in time and expense.

Therefore, our suggestion is that a working group drawn from relevant professionals, developers, local authorities, and others with a truly constructive interest in advancing onshore wind should be brought into being including BEIS, the Scottish Government, the Welsh Government, and the Northern Ireland Government. That group should be tasked with reporting on the whether a review is required and, if so, the appropriate scope and timescales of that review. [We] *would have a key role to play in bringing together all relevant experience of working with ETSU-R-97 and the GPG over the last 25 years.*

While we do not feel there is a need for new UK wind turbine noise assessment guidance, any further modifications should include a panel of expert acousticians, wind farm, developers, government representatives and the IOA.

4.4 ENGAGEMENT FINDINGS SUMMARY

The main findings from the engagement exercise are summarised as follows:

- Almost all respondent stakeholders agreed that the guidance would benefit from updating, to ensure that wind turbine noise is managed effectively and consistently in line with Government policies.
  - There was a roughly even split between those who feel the guidance is 'mostly adequate but requires some updating or amendment', and those who feel the guidance is 'inadequate and in need of substantial revision'.
- The most commonly identified topics and themes suggested by stakeholders as requiring addressing in updated guidance include:
  - Evaluation of sound characteristics:
    - Responses indicated that any updated guidance needs to establish how AM impact should be taken into account (this was the single most commonly identified theme in the engagement exercise):
      - Several stakeholders identified the IOA AM metric as a suitably robust measurement method that should be applied in future guidance.
      - It was also highlighted that an approach to evaluating the impact of AM on people should be defined in future government-endorsed guidance.
    - It was suggested that the existing ETSU-R-97 method for evaluating tonality should be reviewed against current knowledge:
      - Several stakeholders identified that standardised tonality rating methods have been produced and updated since the publication of ETSU-R-97, including BS 4142[411] (which uses the Joint Nordic Method version 2) and ISO/PAS 20065[412], as well as forthcoming guidance expected in the (currently draft) IEC 61400-11-2[413].

411 BSi, 2019. *BS 4142:2014+A1:2019 Methods for rating and assessing industrial and commercial sound*. British Standards Institution. [URL]
412 ISO, 2016. *ISO/PAS 20065:2016 Acoustics – Objective method for assessing the audibility of tones in noise – Engineering method*. International Organization for Standardization. [URL]
413 At the time of preparing this report, the IEC 61400-11-2 standard is at drafting stages, and the standards development procedures mean it is unlikely to be published sooner than late-2022 or early-2023 [URL]

- One stakeholder also highlighted that the common approach of using a straight-line linear regression of tonal audibility values over wind speed does not generally reflect wind turbine tonality characteristics, and that another approach, such as straightforward averaging (within integer wind speed 'bins') would be better. (However, we note that both ETSU-R-97 and the IOA GPG SGN 5 already recognise that such use of a regression model may not lead to representative results, and binned arithmetic averaging is the recommended alternative.)

– Two stakeholders noted that intermittency or irregularity are features of wind turbine sound not currently taken into account in the existing guidance for wind turbine sound, but are highlighted in BS 4142 as potentially increasing the adverse impact of industrial or commercial noise.

– Two stakeholders suggested that a clear position statement on the relevance of infrasound to assessments should be included in future guidance, based on available robust evidence.

- Fundamental approach:

  – Several stakeholders felt that ETSU-R-97 is outdated by current wind energy technology and understanding of wind turbine sound and its effects on people.
  – A frequently raised issue was that the underlying rationale for the ETSU-R-97 noise limits needs to be reviewed against current evidence.
  – Some stakeholders highlighted that future guidance needs to be designed to ensure that developments with greater energy generation capacity are prioritised (in terms of noise impact) over smaller-scale developments.
  – Some stakeholders also suggested that guidance should state clearly the intended policy balance between enabling renewable energy and protection from noise impact.
  – Some stakeholders suggested that future guidance needs to address management of sound from small turbines not covered by the current guidance.
  – Some stakeholders highlighted that the ETSU-R-97 guidance may not be consistent with the policies in the NPSE.
  – It was also noted by some stakeholders that the approach in ETSU-R-97 is based on the assumption that wind-induced sound provides masking for wind turbine sound, which should be reviewed against current knowledge.

- Noise impact assessment:

  – Several stakeholders highlighted that more guidance is needed on approaches to cumulative impact assessments.
  – Some stakeholders suggested that guidance needs to consider that adverse impacts typically occur at night, as well as the sound attenuation performance of building envelopes against wind turbine sound.
  – Some stakeholders suggested that the potential merits of a sound exposure 'dose' approach (eg, use of an annual average index such as L_{den}) should be considered in future guidance.

- Noise controls:

  – The use of the 10th percentile (90% exceeded) sound level index L_{AF90} in the ETSU-R-97 noise limits was highlighted as an issue by stakeholders. The specific concerns raised

highlighted that this index is not connected with evidence on health effects, and that its use may underestimate noise impact (this is discussed further in section 6.2.1).
  - Some stakeholders suggested that guidance needs to advise further on the definition and implications of 'financial involvement' of receptors in determining noise controls.
  - Some stakeholders highlighted the concern that the ETSU-R-97 noise limits may allow adverse impacts to arise, for example in areas with relatively low residual sound levels.
  - Some stakeholders suggested that the use of sound character penalties in planning conditions does not provide 'certainty' that adverse impacts will not occur, and it may be difficult for operators to ensure compliance with such conditions.
  - It was noted by stakeholders that 'noise limits' are not necessarily relevant to some current government policies (such as the NPSE and NPPF in England), which instead refer to 'effects thresholds' defined by observed behavioural responses and health outcomes.
  - Some stakeholders highlighted the need to consider the applicability of the WHO 2018 ENGER to wind turbine noise controls in developing any future guidance.
  - Two stakeholders (the IOA and the ANC) noted that relative limits may not be as relevant to controlling noise from larger turbines as absolute noise controls, due to modern turbine operation (discussed further below) and uncertainty about wind-induced sound masking.
- Other topics and themes:
  - Compliance determination and enforcement:
    - Several stakeholders highlighted that determining compliance of developments (including cumulative impact situations) with noise limits and planning conditions is difficult, time-consuming and costly.
    - It was also noted that enforcement procedures are ineffective or difficult to implement.
    - Some stakeholders felt that alternative compliance assessment procedures should be considered, including use of measurements at proxy locations combined with modelling of sound propagation to receptor locations.
    - Some LPA stakeholders suggested that permanent on-site sound monitoring should be required for wind energy developments.
  - Some stakeholders suggested future guidance should consider how public acceptance and confidence in wind turbine noise management could be improved.

- Stakeholders advised that the following developments in wind turbine technology since the publication of ETSU-R-97 are relevant to consideration of the current guidance, and any future development of guidance:
  - Wind turbines are larger, which has particular implications for how their operation is affected by wind speeds at hub height compared with wind speeds at the typical heights of receptors:
    - Hub or rotor height wind speeds are greater for larger turbines under typical wind conditions (ie, with a positive wind shear gradient).
    - Since, under these conditions, receptor-height wind speeds will typically be lower for a given hub height wind speed with a larger turbine (compared with a smaller turbine), this could mean that wind-induced residual sound at receptors will be lower at a specified 'standardised 10 m height wind speed'.
    - Furthermore, (as noted in footnote 217 in the evidence review section 3.4.2), larger turbines may also reach rated power (and maximum sound emission) at a lower standardised wind speed than smaller turbines.

- Such a case is illustrated in the example shown in Figure 4-15; the standardisation procedure can result in a shift of the background sound level curve (and any associated relative noise limits) to the right along the axis scaled to standardised 10 m height wind speed. Additionally, the sound immission curve may shift to the left; either or both of these shifts would result in the margin between sound immissions and background sound becoming greater for a larger turbine. Since the ETSU-R-97 noise limit regime has minimum limits that tend to control the lower end of the wind speed range, this could mean a greater relative impact being imparted within the limits due to the increase in turbine size.

- Larger wind turbines also means that turbine density within sites is lower, which means that, even if sound power levels are higher, the total sound immissions at receptors may be similar to a larger number of smaller turbines.
- The increased size of turbines may be associated with lower frequency sound immissions:
  - One stakeholder highlighted that research evidence indicates larger turbines are not systematically associated with lower frequency sound emissions (ie, the sound power spectrum emitted by turbines), but if tones are present in the sound from larger turbines, these may occur at lower frequencies than for smaller turbines.
  - One stakeholder noted that as separation distances between (larger) turbines and receptors increases, atmospheric effects on sound propagation may lead to lower frequency character in sound immissions (ie, the sound pressure spectrum at receptors).

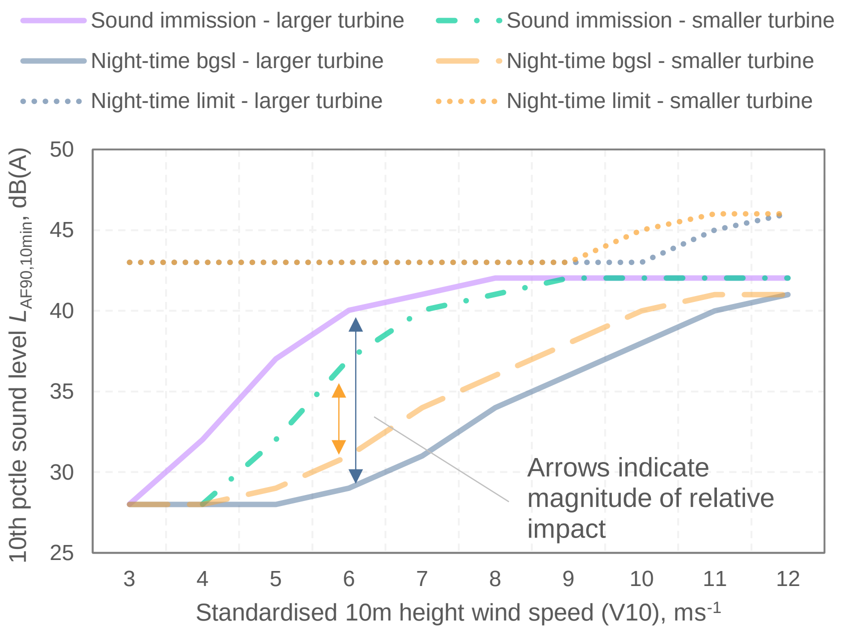


Figure 4-15: Illustrative example of the effect of turbine size on potential relative impact related to wind speed standardisation procedure (bgsl: background sound level)

- Wind turbine operational control systems have largely shifted from fixed/dual-speed, stall-regulated control to variable-speed, pitch-regulated control, which has several implications:
  - Turbines sound emissions no longer tend to rise steadily with increasing wind speed: now they tend to start (‘cut-in’) more quietly, rise relatively rapidly with wind speed, and then

reach a ‘plateau’ around the rated power for the turbine that does not increase further with wind speed. This means that in comparison with the ETSU-R-97 noise limit regime, there is typically a ‘pinch point’ where immissions are close to the limits, but otherwise (lower or higher wind speeds) may be quite far beneath the limits; an example of this situation is shown in Figure 4-16, which compares typical sound immission curves with some illustrative noise limits according to ETSU-R-97.

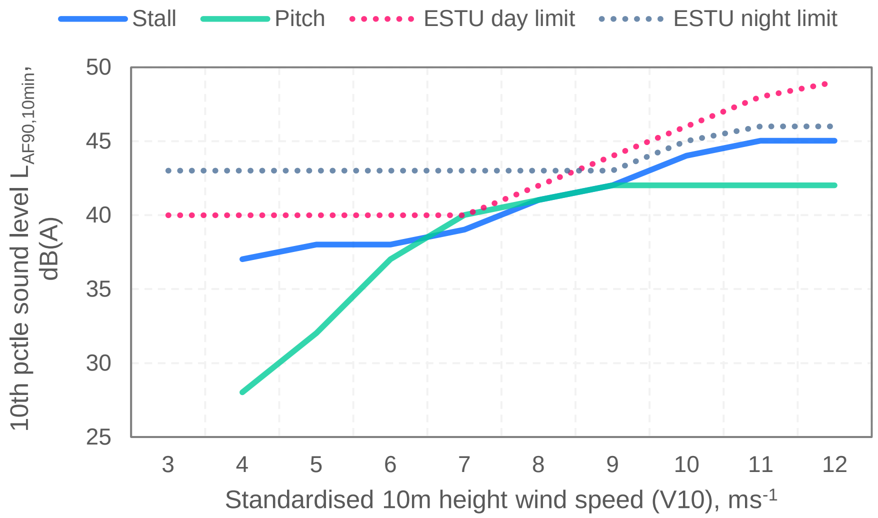


Figure 4-16: Illustrative example of typical stall-regulated and pitch-regulate turbine sound levels, alongside indicative ETSU-R-97 noise limits

- Operators have more accurate and more flexible control over the turbine operation, which enables:
  - sound-reduced operational modes
  - the use of pitch control to reduce AM (by adjusting the blade angle of attack)
  - maximisation of power generation while maintaining sound immissions below ETSU-R-97 noise limits – one stakeholder noted that this could have the potential to result in more sustained noise impact (albeit below the noise limits) than may have been previously experienced from turbines with less precise operational control

- Wind turbines now come with several potential options for noise mitigation as standard, including sound-reduced operational modes, so-called ‘blade furniture’ (blade attachments, which can include trailing edge serrations, leading edge ‘owl wing’ serrations, stall strips or vortex generators).
- There are several issues that can arise due to turbine aging or defects that could affect sound emissions, however these are all considered to be relatively straightforward to address and normally avoided by the routine maintenance completed by operators, which is generally incentivised by the potential impact on turbine power generation. These include:
  - failure or malfunction of mechanical or electrical components
  - detachment of blade attachments
  - blade delamination (roughening of blade surfaces, which one stakeholder highlighted can contribute to AM)

- Wind energy development spatial density is greater, which may lead to 'encirclement' of noise-sensitive properties, and a reduction in periods of potential respite from wind turbine sound than may previously have been experienced due to changes in wind direction:
  - One stakeholder noted that this situation may be partially addressed by the flexibility in the ETSU-R-97 daytime minimum noise limit range, which addresses 'duration of exposure' (although we note that such flexibility is not afforded in the ETSU-R-97 night-time minimum limit).
  - Another stakeholder highlighted the 'Gorsedd Bran judgement'. This effectively confirmed that, while the applicant's assessment had indicated the ETSU-R-97 noise limits would be met, the cumulative impact for 'encircled' dwellings could lawfully be considered (by the original planning inspector) to be unacceptable, due to the prolongation of sound exposure from the surrounding developments[414].

- Stakeholders highlighted that an investigation of AM prevalence from operational wind turbines is likely to require a substantial commitment in terms of time and resources, and the technical risks should not be underestimated. Suggestions made included:
  - enquiring with wind farm operators and manufacturers on available existing data
  - consulting local authorities, possibly including a repeat of a previous government-funded study
  - collaborative effort from members of the IOA
  - use the IOA AM method to quantify AM
- Stakeholders also offered suggestions for how any future guidance could be developed and maintained to take account of emerging evidence, while maintaining a stable platform for wind energy development planning:
  - Several stakeholders suggested a guidance review programme, with one suggesting that this should be linked with milestones from a defined research framework – suggestions for periodic review timescales were in the range 2-5 years.
  - Set up an expert working group involving representatives of multiple sectors to oversee guidance development and maintenance.
  - One stakeholder also highlighted that taking a collaborative approach to guidance development could have benefits in terms of speeding up the process, and noted the cautionary example of wind turbine noise guidance development in Ireland, which they understood to have taken a less collaborative 'single author plus consultation' approach, and noted that the process has been ongoing since 2013.
  - Some stakeholders highlighted that communication of any planned changes needs to be managed cautiously, with clear statements made about the adequacy of existing guidance during any interim period of new guidance development.
  - Some stakeholders suggested that guidance should be an online tool rather than document-based.
  - Some stakeholders suggested that technical guidance should be separated from the 'policy position' on the balance between noise impact and ensuring renewable energy viability.
- Other notable points from the interviewee focus include:

[414] Tegni Cymru Cyf v the Welsh Ministers & Anor, 2010. Court of Appeal (Civil Division) Case no C1/2010/1426/QBENF [URL]

- There were mixed views from interviewees on the compatibility of ETSU-R-97 with the wider policy frameworks; some stakeholders felt that compatibility with the NPSE was questionable, given that ETSU-R-97 specifies noise limits, which are not directly linked with any LOAELs or SOAELs.
- Two industry professional associations highlighted that most of their members feel the current guidance works reasonably well, and have concerns about the potential disruption to wind energy development planning that could arise if any future guidance development is not carefully communicated and managed.

4.5 ENGAGEMENT REVIEW

The Government Communication Service guidance[415] advises that stakeholder engagement activity is evaluated at the end of the project. This section summarises any feedback received, and outlines the lessons learned, to inform future engagement activity.

4.5.1 REVIEW OF OBJECTIVES

The engagement objectives have been achieved: views on the current guidance and identification of gaps in the knowledge have been gained, and some stakeholders have made offers to collaborate on or contribute to future efforts concerning guidance development. Stakeholder acceptance cannot currently be evaluated, but the involvement of a range of different organisation types and locations should contribute to the achievement of this objective.

4.5.2 ENGAGEMENT FORMAT

The engagement survey was delivered with the option of responding using an online web-based platform or an equivalent offline electronic document. The metadata analysis in Appendix C3 section 12.1 shows that the received number of responses using each format were roughly equal. Further analysis in Appendix C3 section 12.1 shows that the organisations providing a collated response from multiple respondents within their organisation tended to use the offline format (presumably because this could be easily circulated by email), whereas those providing individual responses tended to use the online version.

This indicates that the dual-format approach was helpful for respondents, which would be expected to contribute to improved response rates.

4.5.3 SURVEY DESIGN

The design of the survey was developed in response to the engagement objectives and the motivating research questions. Some of the survey questions focussed on ‘gap analysis’ in the current guidance, ie, asking stakeholders to make suggestions for what aspects require updating. A more nuanced approach could have included questions asking stakeholders to highlight aspects of the guidance they feel work well. This would have increased the length of the survey, which could then have impacted on response rates. However, this approach may have provided greater context and balance in the response analysis. Nonetheless, some stakeholders did highlight areas of the guidance that are considered helpful and should be retained (eg, responses to the Q1.4 topic ‘consideration of atmospheric, meteorological, or topographical influences on sound’ showed that

[415] Government Communication Service, 2021. *Ensuring effective stakeholder engagement*. [URL]

some stakeholders noted the GPG approach to addressing wind shear is effective – see Appendix C3).

4.5.4 FEEDBACK

The following feedback was received on the survey:

- Some stakeholder organisations representing multiple members did not understand that the exercise was intended to comprise a single organisational response rather than individual responses from any members of the organisation.
- One stakeholder highlighted that they would have preferred to see a separate topic 'health effects of noise' addressed in Q1.3 and Q1.4 (this sub-topic was instead addressed as 'effects thresholds' under 'noise controls').
- One stakeholder raised technical issues with the offline response form, which were believed to be connected with attempting to share it with other users over a third-party sharing platform (Google Docs).
- Some stakeholders stated that, due to the time of year of the survey (in the summertime), some staff were on annual leave who would have been the most relevant person to organise a response.
- Two stakeholders suggested that the exercise should have included questions specifically asking respondents to identify aspects of the current guidance that *are* considered to work well, in addition to identifying areas considered to require updates.

5

FIELD SURVEY MEASUREMENTS

5 FIELD SURVEY MEASUREMENTS

This section summarises a field measurement exercise undertaken at a sample of wind farm sites, the primary aim of which was to consider the AM characteristics of the measured sound, within the context of the current guidance.

5.1 OBJECTIVE

The objective of the exercise was to obtain a 'snapshot' of measurements of wind turbine sound under conditions thought most likely to result in clearly detectable AM, at distances representative of receptor locations around a sample of wind farm sites.

The ideal measurement conditions were presumed to be during the night-time hours, at downwind locations in simple terrain, with wind speeds marginally in excess of the cut in speed for the turbines, when residual sound is likely to be at a minimum at ground level (because sound from wind interacting with vegetation or obstacles would be minimal).

5.2 LIMITATIONS

It was noted at the project inception that the motivating ambition to understand more about the prevalence of AM, and to investigate associations of sound emissions and AM characteristics with turbine designs and age, must be viewed as a long-term goal that is beyond the constraints of the project. These are also unlikely to be issues that can be addressed by field measurements alone, and would require the support of results from experimental and theoretical analysis.

The measurement sample includes multiple sites, and a range of turbine models and ages. The survey has been limited in terms of duration, geographic coverage and land variability (topography), and the measurements cannot be considered to be generalisable. The approach taken provides a snapshot of AM for the sites during the surveys. It does not provide a dataset that could be used on its own to draw wider conclusions about prevalence of AM in general, or to provide definitive evidence on the association of AM with particular turbine designs or ages. These issues could only be robustly addressed with wider site sampling taken over a considerably longer period.

Longer-term monitoring and wider geographic coverage, site, and turbine diversity could be addressed in further work, if taken forwards in the future.

5.3 MEASUREMENT SITES

Measurements were made near to seven commercial wind farm sites with approximate years of first operation in the period 2006-2016, covering five different turbine models with power ratings in the range 1.8-2.1 MW. Measurement positions at each site were selected according to public accessibility, as well as the wind directions during site visits.

5.4 MEASUREMENT AND ANALYSIS APPROACH

Measurements were made at a height of 1.5 m above local ground level using a class 1 sound level meter, simultaneously logging sound levels in third-octave bands and recording audio files. Wind speed and direction were simultaneously measured at the sound level measurement position. The instrumentation used is detailed in Table 5-1. Sound level meter field calibration checks were made before and after measurements to ensure sound calibration had not drifted.

Table 5-1: Field measurement instrumentation

Instrument	Details
01dB Duo sound level meter	Meter serial no: 10330; Microphone serial no: 141182; DMK01 wind screen (UKAS calibrated 12 Feb 2021, certificate no: UCRT21/1222)
Brüel & Kjær 4231 sound calibrator	Calibrator serial no: 2524534 (UKAS calibrated 12 Feb 2021, certificate no: UCRT21/1211)
01dB Duo sound level meter	Meter serial no: 10618; Microphone serial no: 331635; DMK01 wind screen (UKAS calibrated 3 June 2021, certificate no: UCRT21/1705)
01dB CAL21 sound calibrator	Calibrator serial no: 34924047(2012) (UKAS calibrated 30 Nov 2020, certificate no: UCRT20/2177)
Davis Vantage Vue 6250UK meteorological station	Serial no MQ171109039

Each sound level meter microphone was fitted with a single-layer wind shield – the selection of this wind protection was considered adequate due to the relatively low wind speeds at the microphone during all measurements; wind speeds did not exceed 2 ms^{-1} at the microphone, which was in line with the measurement approach intended to capture conditions marginally above cut-in hub height wind speeds. As noted in section 3.5.1, simulation-based research indicates that AM algorithms similar to that used in this exercise are expected to remain accurate when using a single-layer 100 mm wind shield for wind speeds not exceeding 2 ms^{-1}.

Measurements were taken during the night, for durations of around 1-2 hours at each location.

Measurements were attended, and sound recordings were made and used to verify the AM detection.

5.5 RESULTS ANALYSIS

The measurements have been analysed to quantify AM using the Reference Method developed by the IOA[416]. The 10-minute ratings of the magnitude of AM derived for each location are summarised in Table 5-2 and Figure 5-1. The 10-minute period ratings are calculated from 10-second periods, where a 'validity' check is made in the Reference Method, which requires at least 50% of the 10-second periods to contain detectable AM. It can be seen that at two sites there were no 10-minute periods that passed the validity check during the site visits. Of the remaining five sites, three had short periods of AM, and two exhibited more prolonged periods of AM within the survey durations. Only one site (Site A) had detectable AM that was strongest in the lowest frequency range 50-200 Hz; detectable AM at the other sites was strongest in the 100-400 Hz range.

[416] IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group, 2016. *Final report: A method for rating amplitude modulation in wind turbine noise*. [URL]

Table 5-2: AM measurement results summary

Site	Approx. distance to turbine, m		Duration of measurement	Valid 10-min periods of AM measured	Measured AM (IOA Reference method)		
	Nearest receptor	Meas. loc.			Depth, dB $\Delta L'_{Aeq,100ms(BPmax)}$ median (range)	Frequency, Hz	Spectral band (max), Hz
A	400	310	1 hour	2	2.1 (2.0-2.1)	0.6	50-200
B	500	750	1 hour	3	2.1 (1.5-5.1)	0.5-0.6	100-400
C	640	940	1 hour	0	N/A	N/A	N/A
D	600	450	1 hour	0	N/A	N/A	N/A
E	570	640	2 hours	10	2.9 (2.1-4.1)	0.6	100-400
F	820	740	1 hour	2	3.5 (3.4-3.7)	0.5	100-400
G	600	660	1 hour	6	3.9 (2.7-5.0)	0.6	100-400

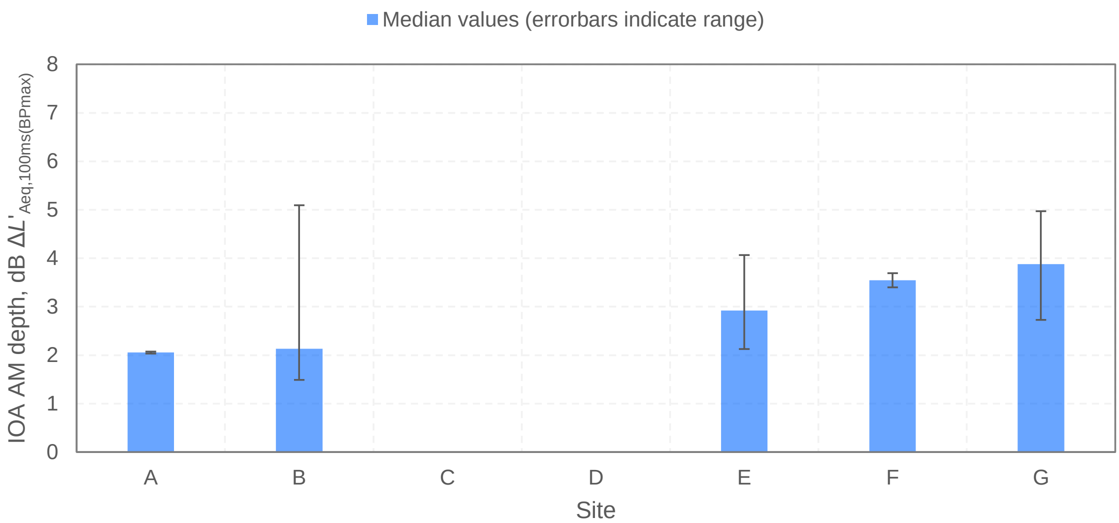


Figure 5-1: Summary of measured AM depths

A more detailed analysis of the AM measured at Site E, at which the most prolonged period of AM was recorded (though not the largest modulation depths) is shown in Figure 5-2 and Figure 5-3. Figure 5-2 shows the 10-second and 10-minute AM ratings together with the 10-second modulation frequencies detected using the method. Figure 5-3 shows the modulation spectrogram, which can be used to further confirm the presence of wind turbine AM – this is evident in the characteristic steady horizontal traces along the modulation frequency 0.6 Hz, and the fainter traces of the first two harmonics at 1.2 and 1.8 Hz.

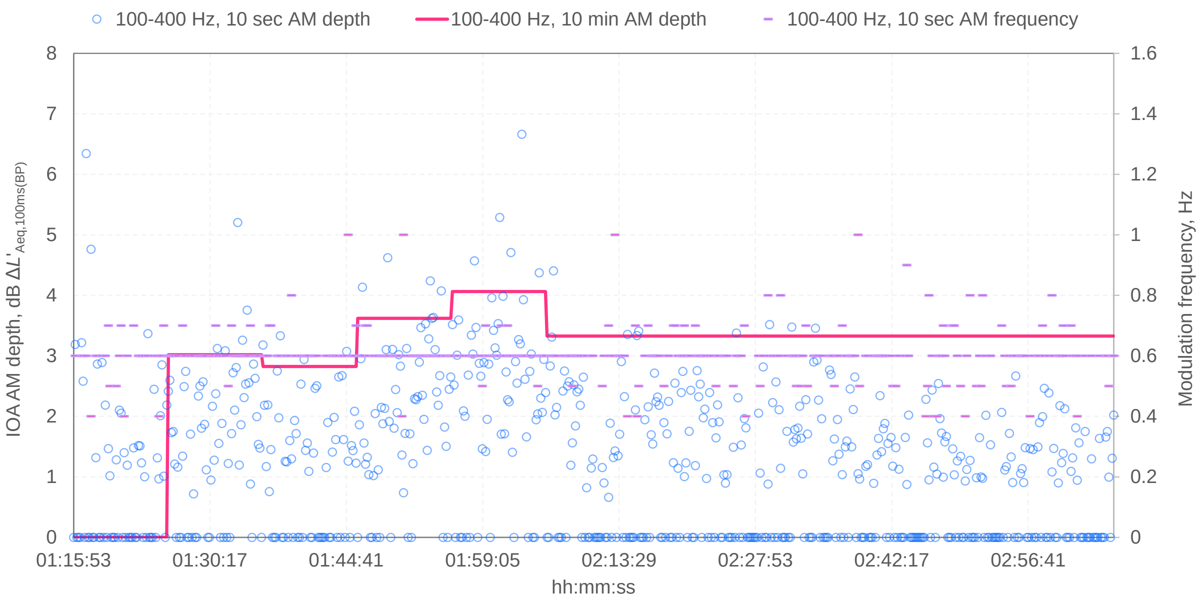


Figure 5-2: IOA Reference Method AM measurements at Site E[417]

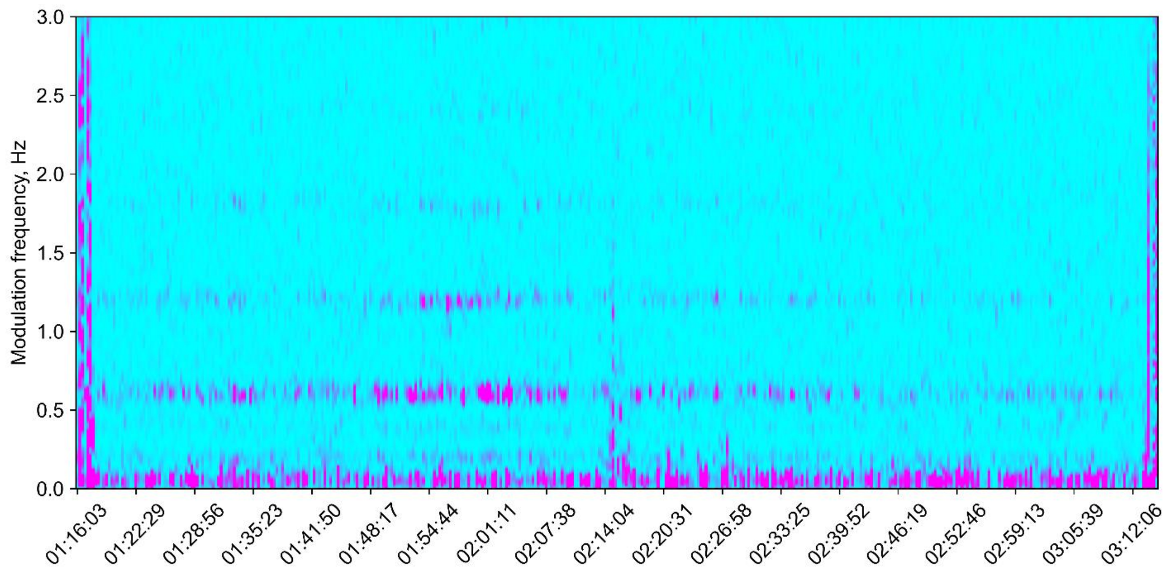


Figure 5-3: Modulation spectrogram for AM measurements at Site E

Equivalent plots are shown for the site with the highest median AM depth, Site G, in Figure 5-4 and Figure 5-5.

[417] Although the ordinate (y-axis) scale is shown from 0 dB AM depth, 0 dB depth represents AM that is 'not detectable', ie the IOA Reference Method returns no result

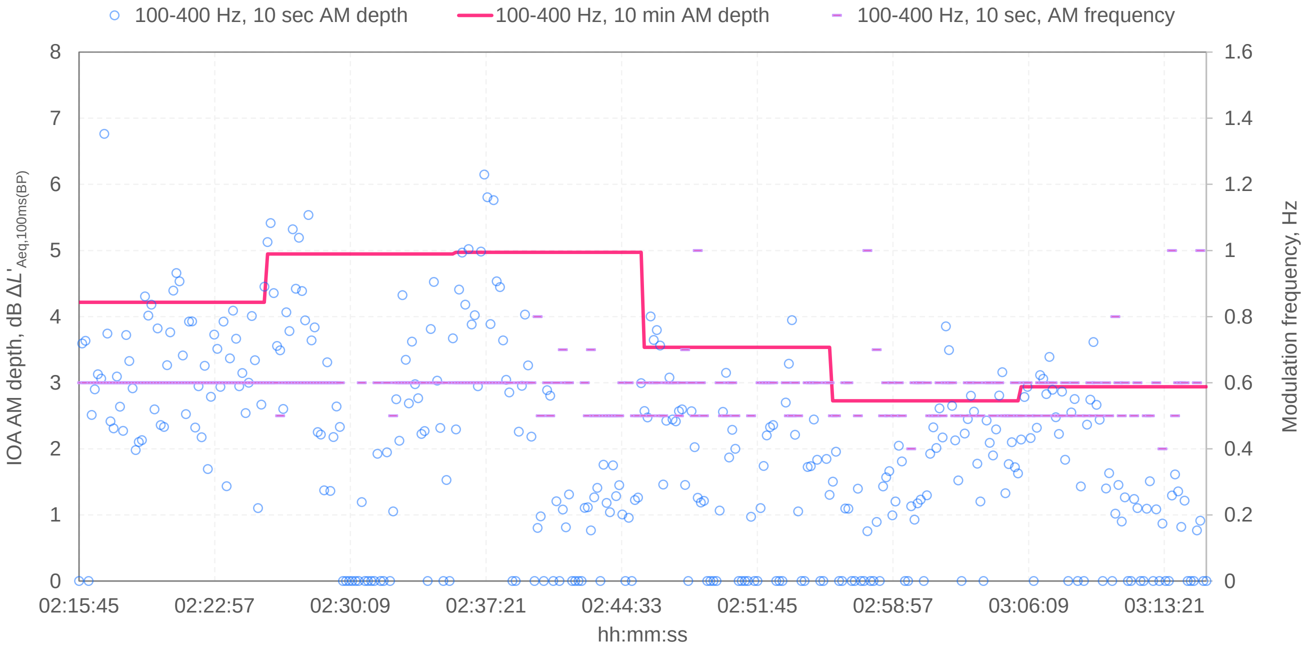


Figure 5-4: IOA Reference Method AM measurements at Site G[418]

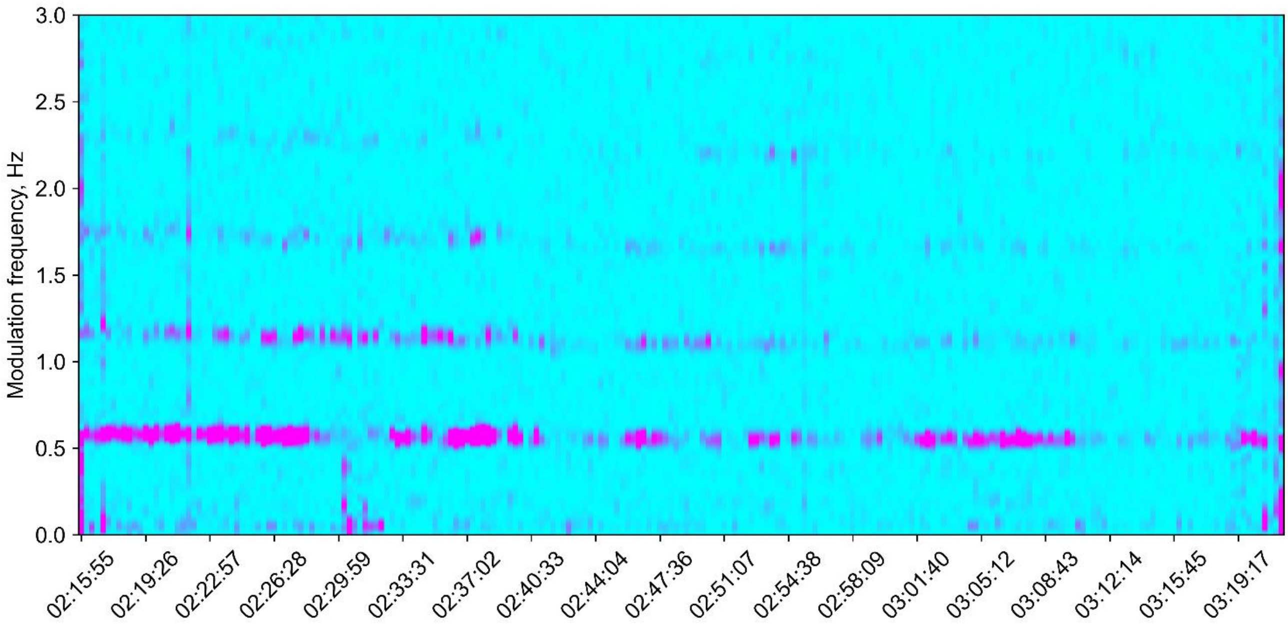


Figure 5-5: Modulation spectrogram for AM measurements at Site G

The distribution of AM depths across all the sites is shown in Figure 5-6. Although the dataset is too small to draw generalisations for these sites or for other sites, the distribution observed is consistent with the general shape of distributions measured over far longer periods, as discussed in section 3.5.1, and discussed further in section 6.3 – ie, a low-skewed distribution peaking around 2-4 dB AM depth. It is also consistent with our previous experience of AM field measurements. It can also be

[418] Although the ordinate (y-axis) scale is shown from 0 dB AM depth, 0 dB depth represents AM that is 'not detectable', ie the IOA Reference Method returns no result

seen from [Figure 5-6b](#) that as many periods were recorded *without* any detectable AM present as were periods *with* detectable AM.

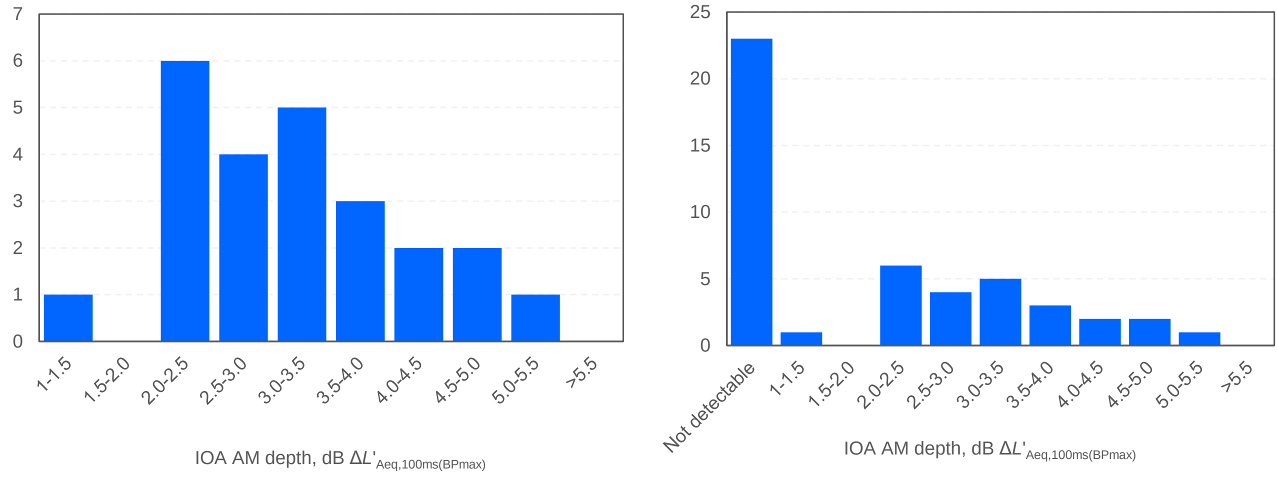


Figure 5-6: AM depth distribution over all the sites; (a, left) excluding periods without detectable AM; (b, right) including all periods

The measured data presented in Figure 5-6a also suggest (given the limited durations involved) that AM depths exceeding 3 dB may not be atypical, occurring equally as frequently as depths below 3 dB, when AM occurred. The measurements taken at Site G showed that AM was above 3 dB for almost all of the measured 10-minute periods. The 3 dB depth distinction is highlighted because it was selected as the lower 'cut-off' value in the penalty scheme recommended in the 2016 AM review[419] (see section 3.5.1) as signifying a modulation depth likely to contribute to increased annoyance. In a more recently proposed scheme, the 'cut-off' value has been lowered to 2.2 dB AM depth, according to a larger and more recent pool of experimental data on AM-related annoyance[420].

> The AM present in the analysed measurements is not consistent with the form of AM addressed in the ETSU-R-97 guidance, ie TEDCAR-AM (see section 2.4); the AM analysed in this exercise has been obtained at relatively long ranges, in downwind conditions, and is concentrated in a lower frequency range than is associated with TEDCAR-AM. It is surmised that these measurements therefore represent non-TEDCAR-AM.

During the evidence review in section 3.5.1 it was noted that a modification to the IOA Reference Method had been proposed to ensure accurate quantification of modulation, even during extreme AM[420]. The proposed modification, shortening the time-averaging interval to 50 ms, instead of the prescribed interval of 100 ms, has been applied to the measurement data to compare with the Reference Method. The results of this comparison are shown in Figure 5-7. It can be seen from Figure 5-7 that, in this case, a shorter averaging time had no significant effect on the measured AM depths, which can be explained by the low modulation frequencies and depths present during the

[419] WSP | Parsons Brinckerhoff, 2016. *Wind turbine AM review: Phase 2 report.* 3514482A Issue 3. Department for Business, Energy & Industrial Strategy. [URL]
[420] Lotinga, M, & Lewis, T, 2021. *Subjective responses to wind turbine noise amplitude modulation: Pooled analysis of laboratory listening studies and synthesis of an AM character rating penalty*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe. [URL]

measurements. However, this issue would benefit from further investigation using a dataset with a greater range of measured values.

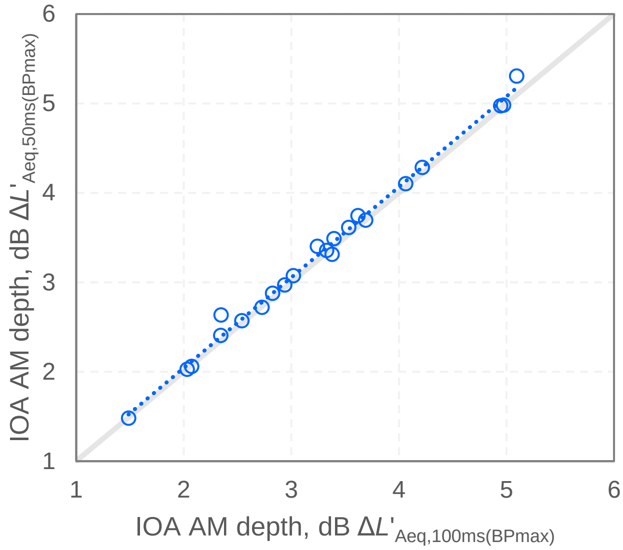


Figure 5-7: Comparison of alternative time-averaging interval (50 ms vs 100 ms)

5.6 SUMMARY

Field measurements have been undertaken to provide a snapshot of AM measured at multiple sites within a limited geographic area. The survey strategy was designed to target conditions that were thought likely to be worst-case for AM, which were expected to be at night-time, downwind of turbines, at wind speeds marginally above cut-in speeds, when residual sounds could be expected to be relatively low.

The results show that over all the sites surveyed, detectable AM was recorded for about half the total measurement duration. When detectable, AM depths tended to be within the 2-4 dB range as quantified using the IOA Reference Method, which has been found in this exercise to reliably identify the AM present during the measurements.

The features of the AM detected in the measurements indicate these are not consistent with the TEDCAR-AM described in the ETSU-R-97 guidance (discussed in section 6.3.1), but are more likely to be examples of non-TEDCAR-AM. Despite (and partly because of) the limited scope of the measurement exercise, this is an indication that non-TEDCAR-AM is an expected characteristic in wind turbine sound immissions, which is not currently addressed in the assessment approach under ETSU-R-97 and the IOA GPG.

6

DISCUSSION

6 DISCUSSION

This section provides discussion around the specific issues identified from each of the work streams, drawing the information together to consider the evidence and recommend future approaches.

6.1 FUNDAMENTAL APPROACH

In the stakeholder engagement, several respondents highlighted the fundamental approach in ETSU-R-97 as requiring reconsideration. The reasons given for this varied, which reflected the intentionally open nature of the question.

The most common response highlighted that technology and knowledge have advanced since ETSU-R-97 was developed, which itself implies there is a good reason to reconsider the approach – the evidence review largely supports this view insofar as the evidence base has expanded considerably, especially in the years from 2011 onwards. On the other hand, the two respondent organisations representing wind energy companies, RenewableUK and Scottish Renewables, highlighted that their members feel the fundamental approach of the current guidance remains appropriate.

The next most common response questioned the continuing adequacy of the justifying principles underlying the ETSU-R-97 noise limits, which is discussed further in section 6.2.

6.1.1 BALANCING CONTROL OF NOISE IMPACT WITH ACHIEVING NET ZERO

Another aspect of the fundamental approach raised in the stakeholder engagement was that the guidance needs to be clearer about the balance between policy objectives on controlling noise impact and those on achieving Net Zero by enabling renewable energy development. There is discussion in several parts of ETSU-R-97 around this issue (eg[421,422]), but the suggestions from respondents indicate that this should be made explicit in a position statement, which should be connected with the wider policies that underpin the government approach to noise management. The main benefit of this position statement would be management of expectations: it is made clear to all that some adverse impact from wind turbine noise may be expected, and would not be prevented by the planning system, if the balance of impacts and renewable energy meets with the relevant policies.

Such a statement could be supported by a ‘what if’ scenario study undertaken to consider the potential outcomes of selecting different approaches or controlling values for noise assessment. It is recognised that this type of study could be technically challenging in terms of making scenario projections on a large enough scale to provide useful information, and would also be subject to considerable uncertainties. However, with suitable assumptions, collaboration with relevant parties to obtain sufficient details, and sensitivity testing of an appropriate range of scenarios, this could provide a defensible basis for making a clear policy balance statement, and for taking decisions on the various aspects of the assessment approach.

[421] ETSU-R-97, section 2, pages 3-4 & page 9
[422] ETSU-R-97, section 6, pages 43, 54 & 60-65

6.1.2 LONG-TERM IMPACT ASSESSMENT AND NOISE CONTROL BASED ON 'DOSE'

The stakeholder engagement and evidence review also raised the suggestion that the merits of a long-term 'dose' approach should be considered.

The ETSU-R-97 method usually involves assessing the impact arising at each wind speed due to 'worst-case' estimations of wind turbine sound downwind in either day or night periods, based on evaluations of short term 10-minute intervals. The sound level predictions made during planning are intended to represent the short term reasonable worst-case value, by imposing assumptions that are considered to be conservative. Compliance assessments are similarly focussed towards the reasonable worst-case by filtering measurements for downwind conditions (although it is recognised that some authors identified in the evidence review have pointed out that the use of data aggregation in compliance measurements may not fully characterise worst-case estimates of immission levels). This approach means there is little consideration given to how often and for how long the impacts occur.

In the Netherlands and Norway, the controlling values for wind turbine sound levels are expressed in terms of the long-term (annual) average period-weighted day-evening-night sound level L_{den}. A long term 'dose' approach may have some benefits for assessing wind turbine sound, since it is inherently variable, so short-term exposure levels may not necessarily represent the overall experience of exposed people when considered in the longer term. On the other hand, the need to consider the many complex factors affecting sound propagation over a long term could present technical difficulties, as well as additional uncertainty that may be avoided by the 'worst-case' assessment approach, and compliance determination procedures would require careful definition.

The potential benefits and challenges of employing a form of long-term assessment approach could be considered in a further review.

6.2 NOISE CONTROLS, LIMITS, EFFECTS THRESHOLDS AND EXPOSURE RESPONSE RELATIONSHIPS

The evidence review and the stakeholder engagement have both identified the basis of the ETSU-R-97 noise limits as a priority area of concern with the current guidance. This section outlines the rationale for the limits as detailed in ETSU-R-97, and considers this within the context of the new information identified in this study.

6.2.1 ETSU-R-97 NOISE LIMITS

Sound level index

The relevance of the 10th percentile ('90% exceeded') $L_{\mathrm{AF90,10min}}$ used in ETSU-R-97 to set noise limits and assess compliance has been questioned in the evidence review and the stakeholder engagement.

Rationale in ETSU-R-97

The use of the $L_{\mathrm{AF90,10min}}$ index for all the limit values was rationalised on the basis that[423]:

- making reliable field measurements of wind turbine sound in terms of L_{Aeq} is often difficult, due to contamination from residual sounds

[423] ETSU-R-97, section 6, pages 54-58

- measurements made using L_{AF90} are more resistant to contamination by residual sounds
- wind turbine sound exhibits a relatively predictable and steady relationship between $L_{Aeq,10min}$ and $L_{AF90,10min}$, which implies that limits based on L_{Aeq} values could be straightforwardly transposed to L_{AF90} (by subtracting the 2 dB middle value from the expected range of differences ~1.5-2.5 dB)

Relevant information identified in this study

Differences between L_{Aeq} and L_{AF90}

The main issue raised in the literature with the use of the L_{AF90} index is the concern that during periods of AM, the assumption of a predictable ~2 dB difference compared with L_{Aeq} may no longer hold true. In such cases, measurements of L_{AF90} could underestimate the sound energy incident at receptor locations, and as such, underestimate the noise impact. Available field measurement evidence provides further information on this issue:

- Measurements made in Australia at 11 locations within 300-3000 m of 5 wind farms showed $L_{Aeq,10min}$-$L_{AF90,10min}$ differences in the range 1.1-1.7 dB (average value 1.4 dB, standard deviation 0.2 dB)[424]; no AM analysis was reported.
- Measurements made in Japan produced a dataset comprising 84 measurement points around 17 wind farms. After a process of manual elimination of contaminating sounds, the correlation between $L_{Aeq,3min}$ and $L_{AF90,3min}$ was shown to be close and consistent over a wide dynamic range of ~25-50 dB(A), and the average $L_{Aeq,3min}$-$L_{AF90,3min}$ difference was found to be 2.1 dB (standard deviation 0.7 dB)[425]. AM was also measured during the surveys showing a relatively wide range of AM depths, but the researchers noted that "*strictly speaking the difference between L_{Aeq} and L_{AF90}…depends on the level of the amplitude modulation, but its effect can practically be neglected when considering general* [wind turbine sound] *in immission areas around wind farms*"[426]. These studies have led to the introduction of wind turbine noise regulatory guidance in Japan that has guideline limiting values set in terms of $L_{Aeq,10min}$, but uses $L_{AF90,10min}$ (+2 dB) as a proxy measurement index[427].
- The RenewableUK AM study analysed measurements around three UK sites, noting that $L_{Aeq,10min}$-$L_{AF90,10min}$ differences were typically within the range assumed in ETSU-R-97, with some periods of elevated AM pushing the difference up to ~3 dB[428]. The study observed that "…*perhaps contrary to informed intuition,* [the difference between $L_{Aeq,10min}$ and $L_{AF90,10min}$ assumed in ETSU-R-97] *remains the case even for large modulation depths of up to 6dB(A) peak to trough*"[429].
- Measurement data presented in a conference paper, acquired at a single location at one wind farm (assumed to be in the UK), were used to directly plot the relationship between the $L_{Aeq,10min}$-$L_{AF90,10min}$ difference and AM depth (using the IOA metric)[430]. As illustrated in Figure 6-1, this

[424] Cooper, J, Evans, T & Najera, L, 2012. Comparison of compliance results obtained from the various wind farm standards used in Australia. *Acoustics Australia*, 40 (1), 37-44. [URL]
[425] Fukushima, A, Tachibana, H & Nameki, M, 2016. *Assessment of wind turbine noise and residual noise in immission areas around wind power plants*. Inter-noise 2016, 21-24 August, Hamburg. I-INCE. [URL]
[426] Tachibana, H, 2014. *Outcome of systematic research on wind turbine noise in Japan*. Inter-noise 2014, 16-19 November, Melbourne. I-INCE. [URL]
[427] Shimada, A & Nameki, M, 2017. *Evaluation of wind turbine noise in Japan*. ICBEN 2017, 18-22 June, Zurich. International Commission on Biological Effects of Noise. [URL]
[428] Cand, M, Bullmore, A & Wilson, B, 2013. Work package D: Measurement and analysis of new acoustic recordings. *Wind turbine amplitude modulation: research to improve understanding as to its cause & effect*. RenewableUK. [URL]
[429] Bullmore, A & Cand, M, 2013. Work package F: Collation of work package reports and final reporting. *Wind turbine amplitude modulation: research to improve understanding as to its cause & effect*. RenewableUK. [URL]
[430] Bowdler, D, Cand, M, Hayes, m & Irvine, G, 2018. *Wind turbine noise amplitude modulation penalty considerations*. Acoustics 2018, 23-24 April, Cardiff. Institute of Acoustics. [URL]

analysis showed that central tendency values for the acquired data (based on a 2nd order linear least squares regression model) indicated a difference of ~1.5-3.5 dB over a relatively wide AM depth range of ~1.5-10 dB $\Delta L'_{Aeq,100ms(BPmax)}$. The data also showed that the central tendency values stayed within the ETSU-R-97 assumed range for AM depths up to ~6 dB $\Delta L'_{Aeq,100ms(BPmax)}$.

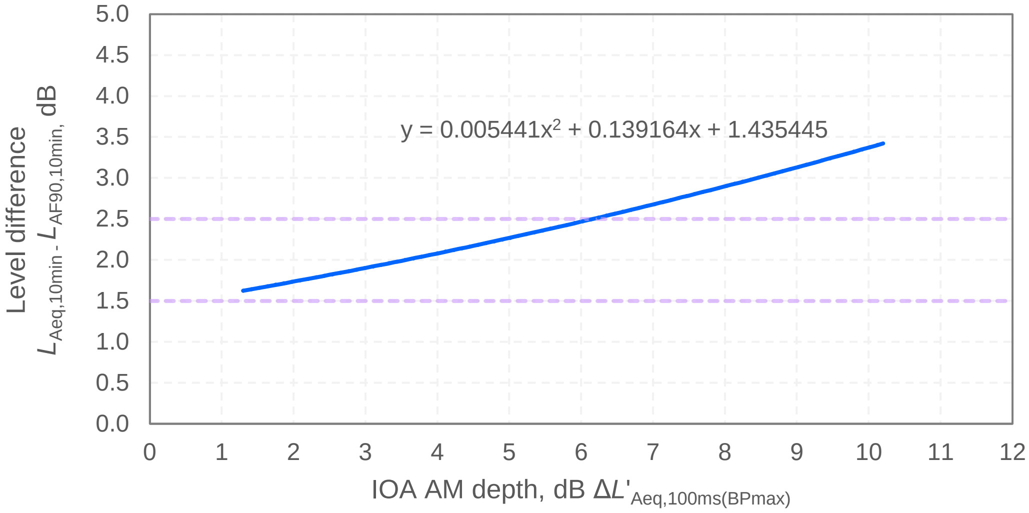


Figure 6-1: Relationship between sound level index difference $L_{Aeq,10min}$-$L_{AF90,10min}$ and AM depth (data from Bowdler et al, 2018[430]; solid line: polynomial regression model for central tendency within measured data at one location; dashed lines: indication of limits of ETSU-R-97 assumed typical difference)

- This evidence suggests that increasing AM depth does have some influence on the sound level index difference, but typically this only exceeds the ETSU-R-97 assumed value of 2 dB by up to 1.5 dB, and only for relatively large AM depths >4 dB $\Delta L'_{Aeq,100ms(BPmax)}$.
- Further measurement evidence would be valuable to understand whether this observation is found to be consistent for other measurement locations. However, as noted in the Japan study, extracting sufficiently 'clean' L_{Aeq} measurements (at distances relevant to receptors) to enable such analysis can be challenging[426].
- As noted by Bowdler et al[430], the 'excess' above the 2 dB assumed difference during periods of AM could be practically addressed by adding this on to an AM penalty value at a given AM depth, for application to measurements made using L_{AF90} – this is discussed further in section 6.3.

Sound level index conversions in exposure-response relationships

In addition to the issue of possible underestimation of impact, stakeholders also raised the concern that the L_{AF90} index is not investigated in epidemiological research or connected with established effects thresholds or exposure response relationships. The evidence review supports this observation: primary studies have almost exclusively focussed on the L_{Aeq} index. One publication however has presented a synthesis and a form of aggregated meta-analysis of exposure-response relationships from observational studies, converted into $L_{AF90,10min}$. This was undertaken primarily due to the continuing use of L_{AF90} in some Australasian countries and regions (which have historically based their regulations on ETSU-R-97)[431].

As outlined in section 3.5.1, the authors converted CTL curves (derived by Michaud et al[432] for several previous studies as well as the Health Canada study) from day-night sound level L_{dn} into $L_{AF90,10min}$ based on several assumptions, including the distribution of sound levels within different daytime periods. However, the assumptions adopted by Davy et al in the conversion may not reflect the actual site conditions that were relevant during the original studies:

- Davy et al assumed that L_{dn} would be equivalent to a 24h L_{Aeq} + 6.4 dB.
- They then argued that the 24h L_{Aeq} could be assumed to be approximately equal to $L_{Aeq,10min}$.
- However, the studies from which data were extracted challenge these assumptions:
  - In the Sweden and Netherlands studies, analysis of wind statistics from two sites in the Netherlands[433] were used to derive an approximate conversion factor of 4.7 dB for converting worst-case downwind L_{Aeq} into day-evening-night levels L_{den} (which have also been assumed by Michaud et al[432] and Davy et al[431] to be equal to L_{dn})
  - Similarly, the Health Canada study analysed wind data taken directly from the turbines included in the study, and arrived at a conversion factor of 1.9 dB[434].
  - The Japan study did not analyse the wind data but instead assumed that the turbines were operating continuously, to arrive at a L_{dn} conversion factor of 6 dB[435] (in fact, as pointed out by Davy et al[431], a 6.4 dB factor – assumed to have been rounded off to 6 dB in the Japan study – results from an assumption of equal distribution of operation during the day, evening and night periods, irrespective of continuity of operation). However, the estimation method used in the Japan study for levels of sound exposure was quite different from that used in the other studies (which modelled worst-case downwind levels):
    - Measurements were made just above ground level (0.2 m, in order to minimise wind incident at the microphone) and used to estimate sound levels at residential locations from a fitted distance attenuation curve.
    - There was no reported filtering of the measurements to account for different wind directions during the measurements, indicating that these included a mix of directions.

Old et al (2017)[436] presented a conference paper documenting an attempt to normalise various exposure-response functions to account for differences in the exposure estimation methods employed. This was done by use of a reference model that effectively employed very similar worst-case assumptions as those defined in the IOA GPG for sound predictions:

[431] Davy, JL, Burgemeister, K & Hillman, D, 2018. Wind turbine sound limits: current status and recommendations based on mitigating noise annoyance. *Applied Acoustics*, 140 (2018), 288-295. [URL]
[432] Michaud, DS, Keith, SE, Feder, K, Voicescu, SA, Marro, L, Than, J, Guay, M, Bower, T, Denning, A, Lavigne, E, Whelan, C, Janssen, SA, Leroux, T & van den Berg, F, 2016. Personal and situational variables associated with wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1455-1466. [URL]
[433] van den Berg, F, 2008. *Criteria for wind farm noise: Lmax and Lden*, Acoustics '08, 29 June – 4 July, Paris.
[434] Keith, SE, Feder, K, Voicescu, SA, Soukhovtsev, V, Denning, A, Tsang, J, Broner, N, Leroux, T, Richarz, W & van den Berg, F, 2016. Wind turbine sound pressure level calculations at dwellings. *Journal of the Acoustical Society of America*, 139 (3), 1436-1442. [URL]
[435] Kuwano, S, Yano, T, Kageyama, T, Sueoka, S & Tachibana, H, 2014. Social survey on wind turbine noise in Japan. *Noise Control Engineering Journal*, 62 (6), 503-520. [URL]
[436] Old, I & Kaliski, K, 2017. *Wind turbine noise dose response – comparison of recent studies*. Wind Turbine Noise 2017, 2-5 May, Rotterdam. INCE-Europe.

- They noted that differences in the sound exposure modelling assumptions adopted in the Health Canada study, and in the Sweden and Netherlands studies amounted to differences of -0.8 dB and -1.6 dB (respectively), compared with the reference model.
- They also noted that the measurement procedure used in the Japan study amounted to a difference of -5.4 dB, compared with the reference model.

Applying these adjustments to the CTL values originally reported by Michaud et al[432], alongside reversing the relevant conversion factors used in each study to produce L_{dn} or L_{den} estimations (ie, to arrive at worst-case downwind L_{Aeq}) and applying the same 2 dB adjustment to obtain worst-case downwind L_{AF90} leads to results that differ by around +5 dB to those produced by Davy et al[431], as shown in Figure 6-2. This exercise illustrates the uncertainties involved in converting sound level indices from studies employing varying assumptions.

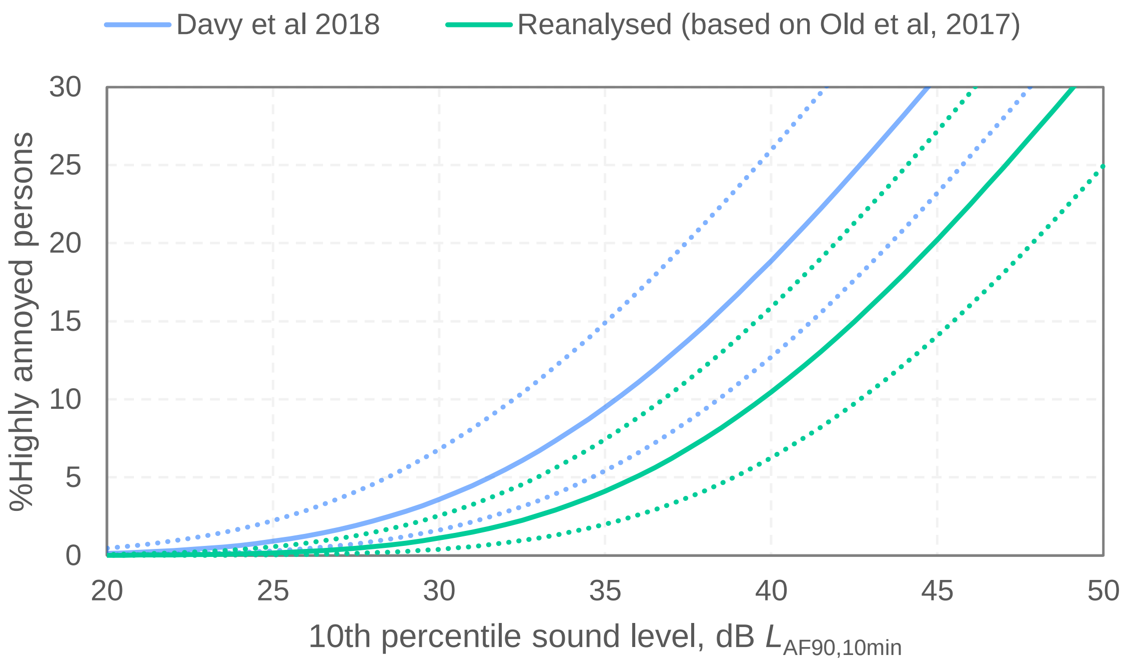


Figure 6-2: Community Tolerance Level model-based exposure-response curves combined from various studies, as proposed by Davy et al (2018)[431], and as reanalysed using assumptions based on normalising exposure estimations (using reference data from Old et al, 2017)[436]; solid lines: mean CTL curves; dotted lines: mean CTL curves ±1 standard deviation

Another example of difficulties encountered in converting between different sound level indices used in exposure-response relationships is found in the Draft Revised Wind Energy Development Guidelines (WEDG) published for consultation by the Government of Ireland in 2019[437]. The existing 2006 WEDG[438], contains a relatively brief section on noise, which sets out a regime of noise limits that is based on the ETSU-R-97 approach. The 2019 Draft Revised WEDG proposed a new approach by setting a maximum limit, which aims to ensure sound levels do not exceed the value

[437] Government of Ireland, 2019. *Draft revised wind energy development guidelines.* [URL]
[438] Government of Ireland, 2006. *Wind energy development guidelines* [URL]

‘conditionally’ recommended by the WHO in the 2018 ENGER[439] (as representing a level above which noise is associated with adverse health effects). The newly proposed maximum noise limit in the Draft Revised WEDG was underpinned by a detailed analysis[440], which provided a rationale for the conversion of the day-evening-night L_{den} level recommended by the WHO into the assessment metric used in the Draft Revised WEDG, the 10th percentile level $L_{AF90,10min}$. The consultation for the Draft Revised WEDG received a response from a group of 13 members of the IOA (several of whom had been involved in developing the IOA GPG) that challenged the approach employed and highlighted technical inaccuracies in the analysis used to convert between the sound level indices[441].

These examples illustrate some of the challenges in using simplistic sound level index conversion factors, and demonstrate that combining data based on varying assumptions and methods is fraught with uncertainties. Any future meta-analysis of existing exposure-response relationships would need to carefully consider the inter-study differences to avoid combining results using differing scales.

Recommendations

The regulations in many other countries and regions use L_{Aeq} to define controlling values for wind turbine sound. There is no indication in ETSU-R-97 that a systematic investigation was carried out to examine different options for measurement indices that would address the practical issues identified with measurements using L_{Aeq}. It could be valuable to undertake such a study, with the aim of identifying an optimal proxy measurement index, that has the benefit of being resistant to contamination from extraneous sources, while also maintaining a reasonably constant relationship with the L_{Aeq}, including during periods of relatively high magnitudes of AM. Whether the proxy measurement index used remains L_{AF90} or another index could be an outcome from the study.

In France, compliance tests of wind turbine sound levels employ the 50th percentile level L_{AF50} as a measurement index. It is noted in ETSU-R-97 that “*the use of L_{A50} was adopted during early work by the CEGB at the demonstration test facility at Carmarthen Bay*”[442] for the same reasons as were used to justify use of L_{AF90}. Following an extensive research programme, the government of Japan opted to use the L_{AF90} as a measurement proxy while setting controlling values for wind turbine sound in L_{Aeq}. However, the Japan study appears only to have considered L_{AF90} or L_{AF95} as potential candidate proxies – there is no scientific reason why alternative measurement indices should not be explored, as it may be found that a more effective index addressing both the contamination issue and the steady relationship with L_{Aeq} is identified.

As noted in ETSU-R-97[443], a drawback of percentile indices is that mathematically correct decibel addition or subtraction (eg, to compensate for the influence of residual or background sound) is more complicated than with L_{Aeq}. ETSU-R-97 cites research from a UK government-funded investigation in the context of road traffic sound[444], although ETSU-R-97 itself advises application of the simpler approximate logarithmic approach. It may be necessary to consider this further during any investigation of suitable indices for wind turbine sound.

---

[439] World Health Organization Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region.* [URL]
[440] RPS, 2018. *Draft wind energy guidelines wind turbine noise analysis.* Report MGE0713RP0001F01. [URL]
[441] Mackay, J, Singleton, J, Reid, M, Cand, M, Mahon, J, McKenzie, A, Keaney, D, Hayes, M, Bowdler, D, Kelly, D, Jiggins, M, Irvine, G, Lester, M, 2020. *Public consultation on the revised wind energy development guidelines: Joint consultation response.* [URL]
[442] ETSU-R-97, section 4, page 16
[443] ETSU-R-97, section 7, page 88
[444] Nelson, PM, 1972. *The combination of noise from separate time varying sources*. LR 526. Transport and Road Research Laboratory. [URL]

Considering the available evidence, it is recommended that limit or threshold values for wind turbine sound exposure should be defined in terms of L_{Aeq}, which is consistent with the majority of the available evidence on noise effects. For compliance measurement purposes, a separate proxy measurement index should be used to estimate the L_{Aeq}, to address the practical problems of measurement contamination from extraneous sources, while having a predictable relationship with wind turbine L_{Aeq} sound levels. This approach has the advantage of enabling greater flexibility if more advanced measurement techniques are developed in the future. Further study would be valuable to determine the most effective proxy measurement index. In advance of this evidence, the L_{AF90} index could be used, subject to adjustment for the potential divergence between L_{AF90} and L_{Aeq} during periods with relatively high AM depths.

The issue of potential underestimation of the L_{Aeq} while using L_{AF90} as a proxy measurement index during periods of high AM is discussed further in section 6.3.

Night-time minimum noise limit

The ETSU-R-97 night-time noise limit is one of the most frequently raised issues with the current guidance identified in the evidence review (see section 3.3) and during the stakeholder engagement exercise (see section 4.2.3).

Rationale in ETSU-R-97

The night-time minimum limit was rationalised by the threshold assumed in Planning Policy Guidance 24: *Planning and Noise* (PPG 24, which was withdrawn at the first publication of the NPPF in 2012) as representing avoidance of adverse effects on sleep, which itself was based on WHO guidance published in 1980[445] (discussed in section 6.2.2)[446]:

- The outdoor sound level was derived from the indoor value quoted by the WHO assuming 10 dB reduction from outdoor free-field levels to indoor levels (which is also consistent with the assumptions adopted in PPG 24).
- The justification presented the view that protection of external amenity becomes less important during the night, and so the aim of the limit is to avoid sleep disturbance.

Relevant information from evidence review and stakeholder engagement

Outdoor to indoor attenuation via open windows

It was assumed in ETSU-R-97 that an open window would provide around 10 dB attenuation of wind turbine sound considered in overall A-weighted decibels. Attenuation performance in terms of broadband levels is dependent on the source spectrum as well as spectral attenuation values. Investigations of outdoor to indoor attenuation of wind turbine sound via an open window are found in the literature. Of these, some focus only on the very low frequency part of the spectrum, which leads to low attenuation values[447,448]. However, it would be misleading to compare these studies with the ETSU-R-97 assumption, which was based on the broadband spectrum. Two studies that

[445] WHO, 1980. *Environmental Health Criteria 12: Noise*. World Health Organization. [URL]
[446] ETSU-R-97, section 6, page 61
[447] O'Neal, RD, Hellweg, RD & Lampeter, RM, 2011. Low frequency noise and infrasound from wind turbines. Noise Control Engineering Journal, 59 (2), 135-157. [URL]
[448] Hansen, KL, Hansen, CH & Zajamšek, B, 2015. Outdoor to indoor reduction of wind farm noise for rural residences. *Building and Environment*, 94, 764-772. [URL]

characterised open window attenuation of wind turbine sound over a suitable broadband range show good agreement:

- The Health Canada study, which included controlled test measurements at nine dwellings, found that the attenuation performance with partially open windows (gap width 100-150 mm) for a wind turbine sound spectrum averaged to 13.8 dB for outdoor (free-field) to indoor dB(A), with a standard deviation of 2.5 dB[449].
- The WiTNES study used laboratory test data for open window gaps, which equated to an overall attenuation of 13.4 dB for the outdoor (free-field) wind turbine sound spectrum dB(A)[450].

The 2006 UK investigation of wind turbine noise complaints measured the outdoor (free-field) to indoor attenuation of broadband A-weighted wind turbine sound at one dwelling with "*windows wide open*" [451] as 10 dB (standard deviation 1 dB).

This evidence supports the assumption in ETSU-R-97 of 10 dB open window attenuation of broadband wind turbine sound, and indicates it is probably conservative.

Sleep disturbance thresholds

As discussed further in section 6.2.2, the WHO 1980 recommendations[445] on sleep disturbance threshold values have been superseded by later evidence reviews and guidelines. It is now widely recognised that different types of sound source impart varying noise effects on people, including on sleep quality[452]. However, as discussed in the evidence review section 3.5.1, the evidence for wind turbine sound directly affecting sleep remains inconsistent, and specific threshold values have not yet been robustly established – this was also recognised in the WHO 2018 systematic review (of evidence up to 2015)[452].

The situation is complicated by differences in methodologies between studies, making direct comparisons uncertain. Moreover, several observational studies have identified links between subjective sleep disturbance and noise annoyance (ie, the more annoyed someone feels about wind turbine noise, the more likely they will report adverse effects on sleep quality), and these links appear to be more consistent than associations between sound levels and sleep disturbance. Naturally, at high enough exposure levels, sleep would be expected to be disturbed by any source, so these observations suggest that, for the study populations investigated, wind turbine sound is rarely at a high enough level to directly impact on sleep quality. Nonetheless, emerging evidence from experimental studies (discussed in section 3.5.1) indicates that indoor levels of wind turbine sound of ≥32 dB L_{Aeq} (ie at the sleeping position) or outdoor levels of ≥45 dB L_{Aeq} can induce some effects on sleep structure that are measurable using sensitive objective indicators, while indoor levels of 25 dB L_{Aeq} do not. The potential outcomes of such measurable effects for individual sleep quality are not yet fully understood.

A recent narrative review advised that a new systematic review and meta-analysis of evidence on associations between sleep disturbance and wind turbine sound exposure is warranted by the

[449] Keith, SE, Michaud, DS, Feder, KP, Soukhovtsev, V, Voicescu, SA, Denning, AR, Tsang, J, Broner, N & Richarz, WG, 2019. Wind turbine audibility calculations inside dwellings. *Journal of the Acoustical Society of America*, 145 (4), 2435-2444. [URL]
[450] Thorsson, P, Persson Waye, K, Smith, M, Ögren, M, Pedersen, E & Forrsén, J, 2018. Low-frequency outdoor–indoor noise level difference for wind turbine assessment. *Journal of the Acoustical Society of America*, 143 (3), EL206-EL211. [URL]
[451] Hayes McKenzie Partnership, 2006. *The measurement of low frequency noise at three UK wind farms*. Contract: W/45/00656/00/00 URN: 06/1412
[452] Basner, m & McGuire, S, 2018. WHO Environmental Noise Guidelines for the European Region: a systematic review on environmental noise and effects on sleep. *International Journal of Environmental Research and Public Health*, 15 (3), 519 [URL]

quantity and quality of studies published since 2014[453]. Such a review could potentially establish an exposure-response relationship, which would be valuable in informing a review of policy on UK wind turbine noise.

Overseas regulations on noise limits

An outline review of guidance on wind turbine noise regulations in other nations and regions with comparable wind energy industries indicates that the ETSU-R-97 night-time minimum limit tends to be less stringent than typically imposed overseas (see section 3.5.1). Furthermore, the situation of having a night-time limit that is less stringent than the daytime appears to be atypical and limited to only the UK and Ireland.

Amplitude modulation impact

The evidence review shows that AM prevalence is typically greater at night-time. The ETSU-R-97 minimum night-time noise limit therefore potentially enables a greater overall impact to occur at night, due to the combination of both higher sound levels and more frequently occurring AM.

Stakeholder engagement

Views received from stakeholders show that some consider the night-time minimum limit to be overly relaxed. Representatives of UK industry professional associations have also indicated that a lower night-time controlling value would probably not have a major impact on energy generation, as, under the existing guidance, it tends to be the daytime minimum limits that constrain operations.

Recommendations

Based on the evidence reviewed and the stakeholder engagement responses, it is recommended that night-time controlling values for wind turbine sound should be subject to further, evidence-based review, and it should not be assumed that higher (less stringent) values than applied during the daytime are appropriate.

Daytime minimum noise limit

Rationale in ETSU-R-97

- The rationalisation for the daytime minimum limit range incorporated substantial elements of professional judgement, alongside consideration of existing noise impact criteria available at the time[454]:
  - It was noted that existing daytime criteria reviewed (in particular, the WHO 1980 EHC 12 report) indicated a level of 50 dB L_{Aeq} outdoors was associated with annoyance, however the ETSU-R-97 working group felt this would be an entirely inappropriate limit (ie, too relaxed) to protect amenity in the quiet areas of the UK.
  - The ETSU-R-97 working group stated that the adopted approach represents their position that daytime limits "*should lie somewhere between that required to avoid sleep disturbance even if the occupant is outside of the property and the higher level that would still prevent sleep disturbance inside the property*"[455]. Based on the night-time limit rationale, the value assumed to represent the avoidance of sleep disturbance was 35 dB $L_{Aeq,10min}$, or ~33 dB $L_{AF90,10min}$.

[453] van Kamp, I, & van den Berg, F, 2021. Health effects related to wind turbine sound: An update. *International Journal of Environmental Research and Public Health*, 18 (17), 9133. [URL]
[454] ETSU-R-97, section 6, pages 62-66
[455] ETSU-R-97, section 6, page 63

- It was argued that a limit of 33 dB $L_{AF90,10min}$ (outside) would be a damaging constraint on wind energy development in the UK, and that several other factors indicated this would be unnecessarily stringent to protect outdoor amenity (which was the stated outcome intention).
- It was concluded that a level within the range 35-40 $L_{AF90,10min}$ (ie, approximately 37-42 $L_{Aeq,10min}$) would provide a "*reasonable degree of protection* [ie, to outdoor amenity]…*without placing unreasonable restriction on wind farm development*"[455]:
  - The selected value within this range is then to be determined by consideration of contextual factors:
    - the number of dwellings in the vicinity of the development (a larger number of dwellings indicating a greater adverse impact, implying that tighter constraints should be applied to developments with larger numbers of neighbouring receptors)
    - the effect of the selected value on the energy capacity of the development (it is noted that a single turbine would be expected to be given less weight in planning, implying that tighter constraints should be applied to smaller developments)
    - the duration and level of exposure (it is noted that receptors with lower background sound levels during wind turbine operations would be expected to have lower noise limits applied than receptors with higher background sound levels)

Relevant information from evidence review and stakeholder engagement

Noise annoyance thresholds

The evidence reviewed suggests that there is a greater quantity and quality of international evidence on noise annoyance associated with exposure to wind turbine sound than was available at the time of the WHO systematic review supporting the 2018 ENGER conditional recommendation. It has been recommended in a recent narrative review[456] that a new meta-analysis be carried out of the available evidence on annoyance. However, as discussed in section 3.5.1, annoyance responses vary considerably within studies and between studies, and are strongly influenced by personal and contextual factors. It was highlighted during the stakeholder engagement exercise that such factors themselves would probably be highly dependent on specific local circumstances. Furthermore, the differences in assumptions and methods employed to quantify response and exposure estimations across different studies can make comparisons and meta-analyses problematic, and this needs to be carefully considered. This suggests that further high-quality, UK-based study information would be valuable in informing policy on acceptability of wind turbine sound levels and expected degrees of noise annoyance.

Overseas regulations on noise limits

An outline review of guidance on wind turbine noise regulations in other nations and regions with comparable wind energy industries indicates that the ETSU-R-97 daytime minimum limit is broadly similar to the limits typically imposed overseas (see section 3.5.1).

Stakeholder engagement

It was noted in the stakeholder engagement that the intention to 'provide reasonable protection for amenity' is not clearly defined. Elsewhere in ETSU-R-97, much of the discussion focuses on annoyance, however in section 5 of the guidance, a 'survey of public reaction to noise from wind

[456] van Kamp, I, & van den Berg, F, 2021. Health effects related to wind turbine sound: An update. *International Journal of Environmental Research and Public Health*, 18 (17), 9133. [URL]

farms' is presented, which focusses on recorded complaints; it was highlighted in the engagement that complaints records may not be a meaningful indicator for annoyance, since some annoyed people may never make any complaints. There are many potential reasons why this may be, but one highlighted by stakeholders in the engagement exercise is that, in the UK, homeowners are required to notify potential purchasers of property about any disputes, such as noise complaints, which creates a financial incentive for homeowners not to make such complaints.

Recommendations

Based on the evidence reviewed and the stakeholder engagement responses, it is recommended that daytime controlling values for wind turbine sound should be subject to further, evidence-based review.

Relative noise limit

Rationale in ETSU-R-97

The relative limit is rationalised with reference to the since-withdrawn BS 4142:1990[457]. This standard was based on an assessment of the 'likelihood of complaints' associated with various degrees of impact, quantified as a margin of an industrial sound source level L_{Aeq} above the existing background sound level L_{AF90}. A margin of 5 dB was considered to be of 'marginal significance', while 10 dB would be an indication that complaints would be 'likely'. The ETSU-R-97 working group emphasised that the application of 5 dB as the acceptable margin of wind turbine sound L_{AF90} above background sound L_{AF90} (assumed to be equivalent to a margin of ~7 dB, in terms of L_{Aeq}) placed the guidance in the 'upper end' of the range that could be considered of 'marginal significance', ie, roughly halfway between the 'marginal significance' value and the 'complaints likely' value[458].

BS 4142 and relative impacts

The overall approach of BS 4142 has its origins in an appendix to the 1963 'Wilson Report', which presented the findings of a parliamentary committee tasked with investigating 'the problem of noise'. In the appendix, a procedure for assessing reactions to industrial noise was presented, which, with some modifications, became the first edition of BS 4142:1967, which was revised in 1990 to the version considered in ETSU-R-97.

Since then, BS 4142 was revised in 1997, again in 2014 and then the 2014 version was amended in 2019 (amendments comprising clarifications and corrections, rather than any revisions to the method). A notable change to the approach made in the 2014 revision was to remove references to 'likelihood of complaints', and instead align the relative margins above background sound level with 'adverse impact', which can be seen as an attempt to ensure consistency of the standard with the NPSE (published in 2010) and the first NPPF (2012).

The concept of 'adverse impact' used in the 2014 revision is ambiguous. It is stated that "*adverse impacts may include but not be limited to annoyance and sleep disturbance*", however, there is no link made between research on annoyance, sleep disturbance, or other adverse effects and the relative margins above background sound levels connected with the specified impact outcomes.

The evolution of the relative impact margins and the outcomes advised in the various BS 4142 revisions are presented in Table 6-1. Table 6-1 shows that, under the assessment outcomes

457 BSi, 1990. *BS 4142:1990 Method for rating industrial noise affecting mixed residential and industrial areas*. British Standards Institution. [URL]
458 ETSU-R-97, section 6, page 60

advised in the 2014 revision, the relative margin allowed under the ETSU-R-97 limit lies in between the indicators of 'adverse impact' and 'significant adverse impact' ('depending on the context').

Table 6-1: Summary of BS 4142 relative impact assessment outcomes

Relative impact L_{Aeq} - L_{AF90}	**BS 4142:1990**	**BS 4142:1997**	**BS 4142:2014+A1:2019**
Any ↑	N/A	*The greater this difference, the greater the likelihood of complaints*	*Typically, the greater this difference, the greater the magnitude of the impact*
Around 10 dB or more	*Indicates that complaints are likely*	*Indicates that complaints are likely*	*Likely to be an indication of a significant adverse impact, depending on the context*
Around 5 dB	*Is of marginal significance*	*Is of marginal significance*	*Likely to be an indication of an adverse impact, depending on the context*
Below 5 dB	*At a difference below 5 dB, the lower the value the less likelihood there is that complaints will occur*	N/A	N/A
Any ↓	N/A	N/A	*The lower the rating level is relative to the measured background sound level, the less likely it is that the specific sound source will have an adverse impact or a significant adverse impact*
0 dB	N/A	N/A	*An indication of the specific sound source having a low impact, depending on the context*
-10 dB	*A positive indication that complaints are unlikely*	N/A	N/A
< -10 dB	N/A	*A positive indication that complaints are unlikely*	N/A

There is no scientific evidence presented or referenced in BS 4142:1990 to support the relative impact margins proposed as representing specific outcomes in terms of complaints probability (or adverse impact), and this remains true of later revisions to the standard. It has been noted by AECOM (2011)[459] that the relative impact assessment approach of BS 4142 has never been underpinned by rigorous scientific research, but instead, as has been stated in its foreword since the 1997 revision, it is based on "*accumulated experience*", which can be viewed as representing the

[459] AECOM, 2011. *Wind farm noise statutory nuisance complaint methodology*. Contract no. NANR 277. Department for Environment, Food & Rural Affairs. [URL]

consensus professional judgement of a group of experts. In the 2014 revision, the foreword was updated to acknowledge that certain aspects, such as the reference methods for rating tonality and impulsivity sound characteristics, have been grounded on scientific research. However, this statement is not applicable to the overall relative impact assessment approach.

Prior to the 1997 revision, a programme of research was completed by the National Physical Laboratory (NPL), which comprised three parts: (i) a survey of local authority environmental health officer (EHO) experiences in applying the 1990 version to specific investigation cases, (ii) a review of overseas national practices in assessing industrial noise, and (iii) an experimental study aimed at quantifying the effects of specific sound characteristics comprising tonal components and impulsive sounds. The survey of EHOs showed that the majority (of 44 officers considering 113 cases) found the assessment to correspond 'fairly well' in their opinion with the actual occurrences of 'justified' complaints[460]. However, in the 'marginal cases' (where the assessment indicated a 'marginal significance' of the likelihood of complaints, ie, a margin of around 5 dB relative to the background sound), the correspondence was deemed to be poorer, with the method commonly either under- or overestimating the likelihood of complaints (in the officers' opinions).

AECOM (2011)[459] also highlighted research by Fields (1998)[461], who conducted a meta-analysis of a large, combined social survey dataset (57982 participants over 11 countries; 9 in Europe, plus the US and Canada) from studies that mainly addressed transportation sources, but also included 3 studies of impulsive industrial sources (comprising shunting yards, shooting ranges, shipyards, scrapyards, metalwork facilities, a dairy and a building site). It was shown from this meta-analysis that the influence on annoyance ratings of the difference between the residual sound levels and the 'target' source sound levels was non-significant, suggesting that the absolute sound level of the target source (rather than relative impact) was the dominant factor.

Fields[461] also investigated controlled laboratory studies, and found that the assumption that residual sound affects the subjective judgement of an intrusive noise was supported only in tests using a single sound event presentation (ie, tests with low ecological validity); tests with multiple sound events did not support the assumption. Fields surmised that it was only in a highly artificial context that such an effect might be observed, whereas in real situations, people tend to respond more to what they perceive the intrusive sound level would be in the absence of the residual sound. However, the applicability of these observations to wind turbine sound is uncertain.

Relevant information from evidence review and stakeholder engagement

Noise annoyance thresholds

It was identified in the first stage of the evidence review that some authors highlighted the margin above background sound level permitted by the ETSU-R-97 relative limit (a margin of ~7 dB in terms of $L_{Aeq,10min}$) is an indication of a potential adverse impact. It has also been noted that some national or regional regulations (Japan and Australia) impose a more stringent relative $L_{Aeq,10min}$ limit of 5 dB above background sound level (approximately equivalent in terms of $L_{AF90,10min}$ to ~3 dB above background sound level, ie ~2 dB more stringent than ETSU-R-97).

460 Porter, ND, 1995. *Study of the application of British Standard BS 4142:1990 "Method for rating industrial noise affecting mixed residential and industrial areas" (The data sheet study)*. RSA(EXT)0057A. National Physical Laboratory. [URL]

461 Fields, JM, 1998. Reactions to environmental noise in an ambient noise context in residential areas. *Journal of the Acoustical Society of America*, 104 (4), 2245-2260. [URL]

The base assumption for using relative impact thresholds or limits is that residual sounds will mask the target sound (ie, make it less detectable), or otherwise make it subjectively less annoying, due to psychological factors such as attitude or expectations. Experimental studies using wind turbine sound have shown that it is relatively easily detected among residual sounds, even for small signal-noise-ratios[462,463]. Furthermore, a study by Johansson et al (2019)[464] indicated that, once it is detected, annoyance responses to wind turbine sound start to increase. Yet, the study also showed that residual sounds *can* have some reductive effect on the annoyance associated with wind turbine sound – it was observed that natural forest sounds (leaves rustling) were less effective in this respect than motorway traffic or urban street sounds. Without further analysis of the original samples, the results of these studies cannot be directly compared with the 'margin above background sound level' approach taken in both ETSU-R-97 and BS 4142, however, as the signal-noise-ratio is calculated as the level difference between two energy time-average L_{Aeq} levels.

Overseas regulations on noise limits

An outline review of guidance on wind turbine noise regulations in other nations and regions with comparable wind energy industries indicates that the ETSU-R-97 relative limit is equal to those imposed in New Zealand, Ireland and the Australian states of Victoria and South Australia (see section 3.5.1). Japan and the Australian states of New South Wales and Queensland impose a more stringent relative limit, which appears to be connected with the choice of index applied to wind turbine sound levels. Some other nations (France and Italy) impose relative limits using a different type of relative impact metric (sound emergence), which is not directly comparable with the 'margin above background sound level' approach of ETSU-R-97.

Recommendations

Overall, the evidence reviewed suggests that, if relative impact is to continue to be used as a marker of acceptability for wind turbine sound, further evidence to support the approach would be valuable, to understand how relative margins between wind turbine sound and background sounds are associated with changes in annoyance or other effects. At present, evidence supporting the ETSU-R-97 relative limit, and the underlying approach of assessing relative impact, appears to be insubstantial, and would benefit from further research.

Financial involvement minimum and relative limits

Rationale in ETSU-R-97

The financial involvement minimum limit, and the recommendation for an undefined additional margin to be added to the relative limit for financially involved receptors, was rationalised on the basis that disturbance or annoyance depends on individual attitudes to the sound source[465].

[462] van Renterghem, T, Bockstael, A, de Weirt, V & Botteldooren, D, 2013. Annoyance, detection and recognition of wind turbine noise. *Science of the Total Environment*, 456-457, 333-345. [URL]
[463] Bolin, K, Nilsson, ME & Khan, S, 2010. The potential of natural sounds to mask wind turbine noise. *Acta Acustica united with Acustica*, 96 (1), 131-137. [URL]
[464] Johansson, A, Bolin, K, & Alvarsson, J, 2019. Annoyance and partial masking of wind turbine noise from ambient sources. *Acta Acustica united with Acustica*, 105 (6), 1035-1041. [URL]
[465] ETSU-R-97, section 6, page 66

Relevant information from evidence review and stakeholder engagement

Effects thresholds

The evidence review shows that economic benefits are sometimes associated with reduced noise annoyance, which lends some support to the general approach taken in ETSU-R-97 to apply more relaxed criteria in these cases, at least for daytime periods.

No evidence has been identified to indicate that sleep disturbance effects are directly influenced by economic benefits, although an indirect connection should not necessarily be ruled out, given the associations between noise annoyance and subjective sleep disturbance.

Overseas regulations on noise limits

An outline review of guidance on wind turbine noise regulations in other nations and regions with comparable wind energy industries indicates that less stringent limits are applicable to properties with financial involvement in the specific wind turbine development under consideration in Ireland, and the Australian states of Queensland, Victoria and South Australia.

Stakeholder engagement

Several stakeholders suggested that further guidance on the nature of what constitutes 'financial involvement', and how this affects future property ownership, would be valuable.

The issue of property ownership is potentially complex, and no further information on this aspect has been identified in the course of this study. If this aspect of noise controls is to be retained in future guidance, it is advised that further clarification of the appropriate interpretation of financial involvement be addressed, along with practical examples.

Recommendations

Based on responses to the stakeholder engagement, it is recommended that further guidance on the interpretation of 'financially involved' receptors for the application of noise controls (if this element is to be maintained) should be provided.

Wider policy compatibility

In England, the direction of NPS EN-1 towards the NPSE, and the direction of NPS EN-3 towards ETSU-R-97, raises the issue of compatibility of the ETSU-R-97 guidance on wind turbine noise limits with the NPSE (and NPPF) policies on adverse effects (see section 1.3.1). As outlined in section 4.3, some stakeholders were specifically asked to provide views on this, with some indicating there appeared to be an incompatibility, while others suggested that in this respect, ETSU-R-97 could be seen as applying a kind of preconceived judgement that may be interpreted as compatible.

To our knowledge and experience, the most common practice in wind turbine noise assessments for proposed development applications in the UK is to apply the ETSU-R-97 limits as compliance criteria; if the proposed development is demonstrated to be compliant with the limits (either with or without mitigation), then it is usually deemed to be acceptable in terms of noise impact[466], and no further mitigation is generally proposed. Based on the actions required by the NPSE and NPPF in response to the different effects levels, this practice suggests that the ETSU-R-97 limits could be interpreted as representing LOAELs. However, (again, to our knowledge and experience) since wind turbine development applications tend not to be advanced *unless* they have been mitigated to

[466] An exception to this was eventually made by the Welsh courts in the 'Gorsedd Bran judgement'; see section 4.4

demonstrate the likelihood of meeting the ETSU-R-97 limits, this suggests the limits could also be interpreted as SOAELs. This practice effectively removes any distinction between LOAEL and SOAEL as the concepts might be applied to wind turbine developments. For other types of sound-generating developments, the NPSE/NPPF policies on LOAELs and SOAELs require that applications need to demonstrate that any adverse impacts (falling in between the LOAEL and SOAEL) have been mitigated and minimised, within the context of sustainable development.

It was noted by one stakeholder in the engagement exercise that a 'pass/fail' system of noise limits rather than the 'effects thresholds and impact assessment' approach does offer the potential benefit of providing greater certainty for wind energy developers in terms of project risk. However, the NPSE is clear on the approach to be taken to noise in England, which is based on observed effects thresholds and mitigation actions (as outlined in section 1.3.1).

The policy situation in Northern Ireland is expected to be the same as in England, given the similarity of the NPSNI to the NPSE. However, the current PPS-18 preceded the publication of the NPSNI, and so no specific direction is made towards the NPSNI for wind energy developments. On the other hand, the 2015 SPPS advises planning authorities to pay "*due regard*" to the NPSNI for management of noise impacts, which indicates that the NPSNI should be given some weight in relation to noise from wind turbine developments.

In Wales and Scotland, no equivalent policy compatibility issue has been identified.

6.2.2 THE RELEVANCE OF WORLD HEALTH ORGANIZATION GUIDELINES

The WHO guidelines on sound levels thought to affect health and wellbeing were considered in the development of the ETSU-R-97 noise limits. They have also been frequently highlighted when issues are raised in relation to ETSU-R-97 within the literature identified in the evidence review, and by stakeholders in the engagement exercise. This section briefly considers the relevance to ETSU-R-97 and wind turbine noise assessment of the various guideline documents on noise published by the WHO, and the basis for the recommendations made.

1980 *Environmental Health Criteria 12: Noise*

This report for the WHO[467] was prepared by a task group that reviewed available evidence up to 1978. As noted in section 6.2.1, its main relevance to the current guidance in ETSU-R-97 is that its recommendations were used in developing night-time criteria for PPG 24, and the PPG 24 criterion was then adapted for use as the ETSU-R-97 night-time minimum limit. The WHO recommendation stated that:

> "*Although systematically collected field data on sleep disturbance are limited, there is some consensus of opinion that night-time noise levels of 35 dB(A) L_{eq}[468] or less will not interfere with the restorative process of sleep.*"

The WHO report narrative highlighted the results of three publications (one journal article and two from grey literature) that supported this recommendation, which comprised a USA aircraft noise guideline document based on earlier aircraft studies, an experimental study of heavy vehicle road traffic, and a study examining 'apartment noise'. None of these studies were cited in the evidence base that supported the later 1999 GCN (discussed below).

[467] WHO, 1980. *Environmental Health Criteria 12: Noise*. World Health Organization. [URL]
[468] Specified as an indoor 'bedroom' value

The relevant time period for averaging the night-time sound exposure is not specified in the 1980 WHO criteria, however in PPG 24 it was assumed the value referred to the 8-hour night period (taken as 2300-0700hrs). The ETSU-R-97 night-time minimum limit (specified in 10-minute periods) was then based directly on the 35 dB $L_{Aeq,8h}$ value, with assumed adjustments of 10 dB to account for transmission across an open window, and 2 dB to account for the difference between $L_{Aeq,10min}$ and $L_{AF90,10min}$, arriving at 43 dB $L_{AF90,10min}$.

The 1980 EHC 12 also advised that "*there will be few people seriously annoyed*" at daytime levels below 55 dB L_{Aeq}, and "*available data indicate that daytime levels of less than 50 dB L_{Aeq} cause little or no serious annoyance*". Although the origin of this recommendation is not made explicit, the narrative does refer to the highly influential exposure-response analysis of Theodore Schultz, who combined social survey data from transportation studies to determine a single function (later coined the 'Schultz curve'), as shown in Figure 6-3. The WHO EHC 12 guidance suggests that the L_{dn} index and L_{Aeq} can be considered interchangeable (which in general would be inaccurate), and this analysis provides an indication of the likely origin of the two daytime annoyance criteria.

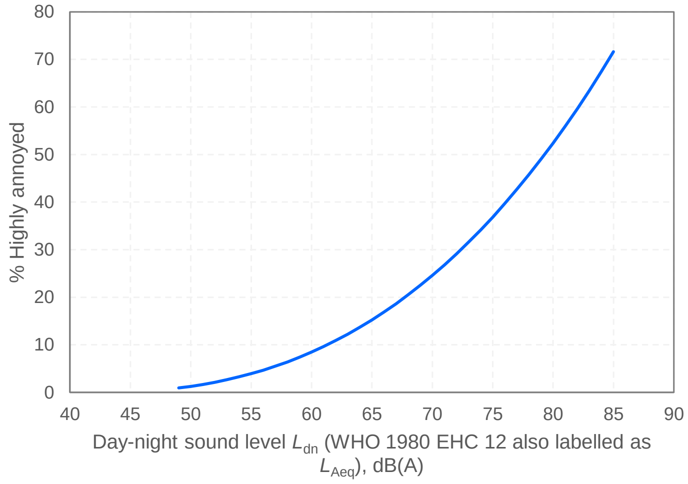


Figure 6-3: The 'Schultz curve' as presented in the WHO 1980 EHC 12 report[469,470]

ETSU-R-97 does not refer to the daytime values from the 1980 EHC 12 report, but instead refers to the 1993 External Review Draft of the *Community Noise* report, which reproduced the same values, as discussed below.

1993 External Review Draft of *Community Noise*

ETSU-R-97 also refers to the WHO 1993 'external review draft' of the report *Community Noise* (the final version of which was published in 1995[471] as an update to the 1980 EHC 12 report). The scope of what was considered to be 'community noise' was taken at the time to have a broad meaning encompassing transport, industrial, construction, and neighbourhood sound sources. Nonetheless, it is important to recognise that the evidence supporting the 1995 *Community Noise* primarily addressed industrial sound sources from the perspective of potential hearing damage, and not the risks of effects on communities, such as noise annoyance or sleep disturbance. The reviews of

[469] WHO, 1980. *Environmental Health Criteria 12: Noise*. World Health Organization. [URL]
[470] Schultz, TJ, 1978. Synthesis of social surveys on noise annoyance. *Journal of the Acoustical Society of America*, 64 (2), 377-407. [URL]
[471] Berglund, B & Lindvall, T (eds), 1995. Community Noise. *Archives of the Center for Sensory Research*, 2 (1), 1-195. [URL]

these effects considered the evidence that was available, which was mainly from transportation studies.

The *Community Noise* report included a proposed value of 30 dB L_{Aeq} indoors to avoid sleep disturbance. The ETSU-R-97 working group noted this criterion (which was still only in the draft form at the time), but decided that the 35 dB L_{Aeq} value from PPG 24 should inform the ETSU-R-97 night-time minimum limit.

The advice on daytime annoyance criteria in *Community Noise* remained almost the same as in the previous 1980 EHC 12, but the lower value of 50 dB L_{Aeq} was identified as an indicator of the onset of 'moderate annoyance', whereas 55 dB L_{Aeq} remained as an indicator for 'serious annoyance'. This revision from the 1980 guidance can be seen as an attempt to discern more clearly between the two annoyance indicator values, as the 1980 guidance (described above) could be read as being ambiguous in this respect. The 50 dB L_{Aeq} value from the external review draft of *Community Noise* was noted in ETSU-R-97 as an indicative daytime criterion for moderate annoyance.

1999 *Guidelines for Community Noise*

The 1999 GCN[472] also proposed guideline values for specific health effects of exposure to 'community noise'. The guideline values for these effects were again based on studies of transportation sound sources. It was also acknowledged that "*equal levels of traffic and industrial noises result in different magnitudes of annoyance*".

The guideline values provided for community effects were identical to the 1995 report, ie, 30 dB $L_{Aeq,8h}$ inside bedrooms at night to address the risk of sleep disturbance, and 50 dB $L_{Aeq,16h}$ outside during the daytime to address the risk of 'moderate' annoyance (with 55 dB $L_{Aeq,16h}$ as the indicator of 'serious' annoyance).

2009 *Night Noise Guidelines for Europe*

The 2009 NNGE[473] identified guideline values for night noise specifically intended to represent LOAELs. However, it was noted that "*for industrial noise there is an almost complete lack of information*", and the values recommended were developed from studies of transportation sound sources.

A further drawback from the perspective of considering UK wind turbine noise guidance is that the guideline values comprise annual average levels, or indoor maximum event levels, neither of which are directly relevant to the ETSU-R-97 approach. The NNGE includes a threshold value for complaints about night noise as 35 dB L_{night} (annual average night-time $L_{Aeq,8h}$ outdoors), which is lower than threshold values developed for any adverse effects on sleep quality. The overall recommendation for a night noise LOAEL was given as 40 dB L_{night} (outdoors), which, as noted in section 1.1.1, has subsequently been adopted as a LOAEL for some types of transportation infrastructure in the UK.

2018 *Environmental Noise Guidelines for the European Region*

The 2018 ENGER[474] is the first WHO guidance document to consider available evidence specifically addressing the effects of wind turbine sound exposure. As noted in section 3.5.1, the supporting systematic reviews rated the quality of evidence available as 'low', and the recommended value was

472 WHO, 1999. *Guidelines for community noise*. World Health Organization. [URL]
473 WHO Regional Office for Europe, 2009. *Night noise guidelines for Europe*. World Health Organization. [URL]
474 World Health Organization Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region.* [URL]

assigned a ‘conditional’ recommendation strength (reflecting the low quality of the evidence reviewed, the low burden on health, and less certainty about the effectiveness of the recommendation). The recommended value was based on evidence for noise annoyance, as evidence on other effects was too inconsistent to draw any conclusions.

The noise annoyance evidence comprised two publications covering data from two studies. As discussed in section 3.5.1, the meta-analysis used to support the recommendation took the two noise annoyance exposure-response functions and superimposed them directly to establish a value roughly corresponding with the 10% ‘highly annoyed’ response. However, the two functions had been derived using different methods, with differing exposure estimation and response modelling scales. The uncertainty implied by this approach was partially acknowledged but not addressed in the ENGER, which noted that “*it may be concluded that the acoustical description of wind turbine noise by means of* L_{den} *or* L_{night} *may be a poor characterization of wind turbine noise and may limit the ability to observe associations between wind turbine noise and health outcomes*”. The potential implications of combining studies with differing exposure estimation scales or response models have been discussed in sections 3.4.2 and 6.2.1, which demonstrate that different results can emerge from the data depending on the response models used, and the assumptions adopted in the exposure estimations.

Summary and recommendations

The various WHO guidelines, with the exception of the 2018 ENGER, have been based on evidence for sound sources that are dissimilar to wind turbines. It has long been recognised that different sound sources impart varying effects on people, and it would therefore be unsafe to apply such evidence to wind turbine sound.

The 2018 ENGER directly addressed wind turbine noise effects, but used an approach that directly compared data from studies employing differing methods, which may be misleading. As has already been noted in section 3.5.1, the quantity and quality of evidence has also increased since the reviews supporting the 2018 ENGER.

It is therefore advised that the existing WHO guidelines, including the 2018 ENGER, have limited relevance and are not considered to offer a robust platform for developing a framework of wind turbine noise effects thresholds.

6.2.3 CURRENT KNOWLEDGE AND FUTURE STUDY OF THE EFFECTS OF WIND TURBINE SOUND EXPOSURE AND CONTROL OF WIND TURBINE NOISE

The evidence review has demonstrated that there is now a substantial volume of research evidence concerning the effects of wind turbine sound exposure. The most studied and evidenced effect of exposure to wind turbine sound is noise annoyance; evidence for other effects at typical exposure levels is inconsistent (but less studied). In addition to the evidence reviewed in section 3.5.1, a further observational case-control study undertaken in Finland (and published during the preparation of this report), found no evidence of associations between exposure to wind turbine sound at worst-case levels up to 40 dB L_{Aeq} and a wide range of investigated health and wellbeing adverse effects, including chronic diseases and specific symptoms, with the exception of noise annoyance[475]. The same study found that exposure to road traffic sound at levels up to 65 dB $L_{Aeq,0700\text{-}2200}$ was

[475] Radun, J, Maula, H, Saarinen, P, Keränen, J, Alakoivu, R & Hongisto, V, 2022. Health effects of wind turbine noise and road traffic noise on people living near wind turbines. *Renewable and Sustainable Energy Reviews*, 157, 112040. [URL]

associated with increased likelihood of adverse health outcomes, including heart disease, heart palpitations, and other stress-related symptoms. These results appear to be in agreement with the weight of existing epidemiological evidence.

The quantity and quality of the evidence is now expected to be sufficient to develop an exposure-response relationship for noise annoyance, and possibly for sleep disturbance. However, in using evidence from overseas studies, it must be recognised that local circumstances that influence subjective responses to noise will inevitably affect the results of such synthesis and meta-analysis. This can be inferred from the exposure-response functions derived from different study data obtained in varying localities, such as shown in Figure 6-4, which illustrates that levels imparting equivalent modelled responses among the studies considered vary by up to nearly 10 dB.

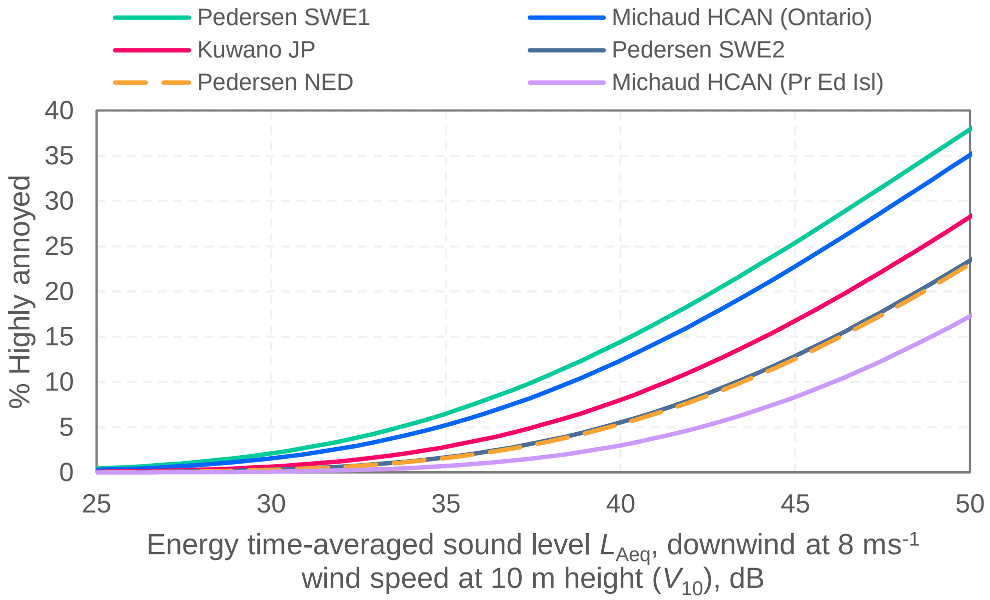


Figure 6-4: Community Tolerance Level model-based exposure-response curves from various studies adapted from CTL values derived by Michaud et al (2016)[476], reanalysed using assumptions based on normalising exposure estimations (using reference data from Old et al, 2017)[477]; see cited references and Table 3-3 for original study information

The potential influences of a wide range personal and contextual factors on responses to wind turbine sound exposure have been demonstrated in multiple studies. The interaction of visual and aural perception appears to be particularly influential in determining noise annoyance. From the perspective of further reviews of evidence with the aim of establishing guidance aimed at controlling the impact of wind turbine noise, it could be important to investigate this aspect further, considering any opportunities for synergistic approaches.

There has been very little scientific study of wind turbine noise effects on people in the UK, and research addressing this, especially in rural areas of the UK, would be valuable in supporting an

[476] Michaud, DS, Keith, SE, Feder, K, Voicescu, SA, Marro, L, Than, J, Guay, M, Bower, T, Denning, A, Lavigne, E, Whelan, C, Janssen, SA, Leroux, T & van den Berg, F, 2016. Personal and situational variables associated with wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1455-1466. [URL]

[477] Old, I & Kaliski, K, 2017. *Wind turbine noise dose response – comparison of recent studies*. Wind Turbine Noise 2017, 2-5 May, Rotterdam. INCE-Europe.

evidence-based approach to managing wind turbine noise. It is recommended that any such study also investigates the influence of prolongation and intermittency of wind turbine sound on responses, the adverse effects of AM (discussed further in section 6.3), and the influence of background and residual sound environments in terms of relative noise impacts.

Until such evidence is available, an interim position could be devised on the basis of meta-analysis of available data. As noted in section 3.5.2, it is important that inter-study differences are rigorously identified and accounted for, to avoid comparing or combining data based on differing scales of estimation. Studies often apply different methods and metrics for quantifying sound exposure, and varying response evaluation and modelling procedures, which would require careful consideration and normalisation when undertaking pooled data analysis.

As noted in section 3.4.2, another source of variation in the development of exposure-response relationships in different studies could lie in the exposure estimation uncertainty. This uncertainty has been shown to influence modelled response outcomes, which, in the context of wind turbine sound exposure, could typically lead to an overestimation of adverse responses[478]. The potential for this effect to have influenced existing study results should be considered, and any future studies should also investigate the uncertainty in the proposed estimation procedures, so that this effect can be addressed and minimised. Techniques intended to address this issue are emerging from scientific research[479].

The development of a framework of effects thresholds should also consider the relevance of the duration of exposure alongside the magnitude. One approach to this is found in the use of a 'dose' metric such as long-term average levels for day or night – in this approach, thresholds are fixed values. Another approach could be to establish varying thresholds associated with different exposure durations. An example of where this has been considered in recent noise assessment guidance is found in the Association of Noise Consultants Acoustics, Ventilation and Overheating Residential Design Guide[480]. This guidance considers the influence of the duration of exposure in determining an appropriate value for the SOAEL used in assessing noise impact, the concept of which is illustrated in Figure 6-5. This kind of approach could be based on statistical analysis of the occurrence frequency of the range of sound levels at a given receptor, with controls based on ensuring that the sound level distribution is within given threshold values for a specified duration (or occurrence probability, eg[481,482]).

Notwithstanding the outcome of these further studies, it appears likely that a suitable effects thresholds framework would be based on robust data for noise annoyance, and that the thresholds advised for night-time sound exposure would not be higher (ie, more relaxed) than those for daytime, which has been identified as a common criticism of the ETSU-R-97 approach.

[478] Horonjeff, RD, 2021. An examination of dose uncertainty and dose distribution effects on community noise attitudinal survey outcomes. *Journal of the Acoustical Society of America*, 150 (3), 1691-1701. [URL]
[479] Horonjeff, RD, 2022. Mathematical characterization of dose uncertainty effects on functions summarizing findings of community noise attitudinal surveys. *Journal of the Acoustical Society of America*, 151 (4), 2739-2750. [URL]
[480] ANC, 2020. *Acoustics, ventilation and overheating: Residential design guide*. Association of Noise Consultants. [URL]
[481] Ashtiani, P, 2013. *Generating a better picture of noise immissions in post construction monitoring using statistical analysis*. Wind Turbine Noise 2013, 28-30 August, Denver. INCE-Europe.
[482] Hansen, KL, Zajamsek, B, & Hansen, CH, 2018. Wind farm noise uncertainty: Prediction, measurement and compliance assessment. *Acoustics Australia,* 46, 59-67. [URL]

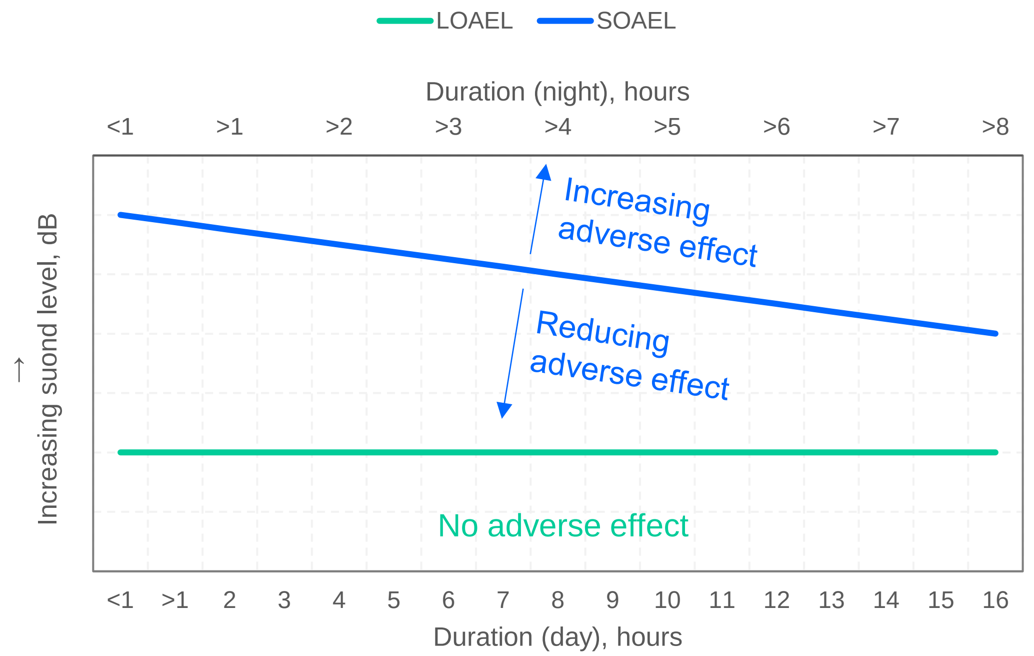


Figure 6-5: Conceptual example of consideration of duration of impact in determining adverse effects thresholds framework (adapted from ANC, 2020[480])

The selection of suitable thresholds of acceptability for subjective effects such as annoyance or self-reported sleep disturbance is not necessarily straightforward, and, as discussed in section 1.3, depends on the proportion of acceptability linked with the effects in the context of the relevant policies.

As noted in section 3.5.1, a review undertaken for the Australian government suggested setting controls based on limiting proportions of people expected to be 'highly annoyed' to ≤10%; according to the original analysis[483], this would effectively impose a maximum noise limit of 35 dB $L_{AF90,10min}$ (~37 dB $L_{Aeq,10min}$). However, it was shown in section 6.2.1 that this may be an overly-conservative estimate of the relevant threshold, as it is based on questionable assumptions, and combining data from studies that used varying exposure estimation methods. An alternative analysis presented in section 6.2.1, which was derived from the same data but applied normalisation to the exposure estimations, produced a value of 40 dB $L_{AF90,10min}$ (~42 dB $L_{Aeq,10min}$).

An approach taken in Switzerland is to consider the relative 'disability weight' values assigned to various adverse effects in determining an appropriate 'acceptable risk' – effects with high disability weight (such as heart disease) being assigned smaller acceptable risks than effects with low disability weights (such as annoyance)[484]. In that case, the acceptable risk for %HA was assigned 25%, based on a disability weight of 0.02, whereas a smaller acceptable risk (15%) was assigned to the proportion of people 'highly sleep disturbed' (%HSD), with a higher disability weight of 0.07. It should be noted that this approach was adopted for determining maximum noise limits that, in the Swiss legislative framework, are considered to mark the transition to levels of sound exposure that

[483] Davy, JL, Burgemeister, K & Hillman, D, 2018. Wind turbine sound limits: current status and recommendations based on mitigating noise annoyance. *Applied Acoustics*, 140 (2018), 288-295. [URL]
[484] Brink, M, Boegli, H, Walker, U, Artho, J, Wunderli, J-M, Röösli, M & Thomann, G, 2020. *Revision of Swiss noise exposure limits in the wake of the WHO environmental noise guidelines: Methodology matters*. Inter-noise 2020, 23-26 August, Seoul. I-INCE [URL]

are considered unacceptable, due to expected effects that are deemed to be ‘harmful or annoying, or significantly disturbing to wellbeing’ – this may be viewed as broadly analogous with levels exceeding the SOAEL defined in England and Northern Ireland (see Table 1-1). According to the reanalysed exposure-response curve presented in Figure 6-2, a maximum acceptable value for %HA of 25% would correspond with a level of 47 dB $L_{AF90,10min}$ (~49 dB $L_{Aeq,10min}$). Establishing proportions of impact acceptability relevant to the UK policy context would be another important step in determining a robust effects thresholds framework for assessments; the analysis of Brink et al (2020, as described here) illustrates one possible approach[484].

It has been noted in the evidence review that the weight of evidence appears to indicate that wind turbine infrasound has no adverse effects on human health at typical exposure levels. In the stakeholder engagement it was suggested that a clear guiding statement on the relevance of infrasound to wind turbine noise assessments would be helpful for assessors and decision takers to understand the appropriate scope of noise assessments. At present it appears that an evidence-based statement could be robustly justified, with the effect that considering wind turbine infrasound would not normally be necessary when determining development applications, until such time that the position is reviewed against newly emerging evidence.

Reviews of the effects of exposure to low frequency sound from wind turbines currently suggest these are limited to annoyance, at typical exposure levels. It was found in a previous UK study of reported ‘low frequency noise’ issues associated with wind turbines, that disturbances reported were more likely to be due to audible AM rather than low frequency sound[485]. Moreover, the evidence currently suggests that, due to the inherent characteristics of wind turbine sound, suitable controls on A-weighted sound levels are expected to also provide sufficient control for the potential impact of low frequency noise.

6.3 AMPLITUDE MODULATION CONTROL

The evidence review and the stakeholder engagement have both identified the control of AM in wind turbine sound as a priority area of concern with the current guidance. The field measurements taken have also indicated that measurements of AM are practical using available tools, and tentatively indicate that the presence of detectable AM at typical receptor distances is probably not unusual (although generalisation about AM prevalence would require a more substantial dataset than has been acquired during this study). This indication is supported by more extensive measurement data acquired overseas, some of which has been identified in section 3.5.1, and is also discussed further below.

6.3.1 CURRENT GUIDANCE ON AM

ETSU-R-97 identifies that amplitude modulation is characteristic of wind turbine sound, and that its presence increases the distinctiveness of wind turbine sound against residual sounds[486]. It also acknowledges that AM has a range of sound descriptions associated with it, including “*swishing, whooshing, chomping and thumping*”. ETSU-R-97 notes that “*blade thump*” had been identified as a disturbing characteristic at one wind farm that was known at the time[487]. However, the guidance focusses on the ‘blade swish’ characteristic, identifying that, although all turbines exhibit ‘blade

[485] Hayes McKenzie Partnership, 2006. *The measurement of low frequency noise at three UK wind farms*. Contract no. W/45/00656/00/00 URN no. 06/1412. Department of Trade & Industry. [URL]
[486] ETSU-R-97, section 3, page 11
[487] ETSU-R-97, section 5, page 40

swish'[488], it is predominantly audible at close range to turbines (ie, "*most apparent when standing close to a wind turbine, less than 50 metres from the base of a supporting tower*"), and is focussed on the 800-1000 Hz frequency range[489]. ETSU-R-97 states that the modulation depth of 'blade swish' has been measured as up to 3 dB depth in the broadband A-weighted signal, but also up to 6 dB in a position where reflections from nearby surfaces contributed to the total signal[487]. It notes that 'blade swish' can "*under certain circumstances*" (which are not specified) increase adverse impact[487], and suggests that the noise limits devised in ETSU-R-97 include a provision for this increased impact, but no details of the underlying considerations are provided[488]. It is also noted that knowledge about AM was limited at the time, with "*insufficient data available…to formulate an accurate measurement methodology for blade swish where it occurs*" and that it was "*envisaged that further research will be required to enable proper measurement and assessment to be devised, if in the future this is felt to be necessary*"[488].

6.3.2 CURRENT KNOWLEDGE AND FUTURE STUDY OF AMPLITUDE MODULATION

Research, as discussed in section 3.5.1, has confirmed that there is more than one form of AM, and a wide range of complex interacting factors can influence its generation and character. It has also been demonstrated that annoyance responses are influenced by AM characteristics in wind turbine sound, and that AM may be the most annoying characteristic of wind turbine sound.

Measurement and control schemes intended to quantify AM and characterise the additional annoyance expected have been devised. The IOA Reference Method for AM measurement has been shown to be a robust and practical approach to quantifying AM within large field measurement datasets. Other methods have also been developed and are in use, and the differing quantification procedures for AM makes inter-study comparisons uncertain and potentially misleading. Recent work has focussed on revisiting existing experimental exposure-response results using the IOA metric to provide a common platform from which to make direct comparisons and to combine data from different studies.

There remains very little scientific evidence concerning the impact of AM as experienced by wind farm neighbours in their homes, and as such there could be considerable value in further study of this aspect[490].

Causal factors contributing to amplitude modulation occurrence

Theoretical and empirical studies indicate that wind turbine non-TEDCAR-AM may be generated by several different factors, any of which could contribute to AM perceived at receptor locations, depending on local site conditions.

The evidence review summarised in section 3.5.1 highlighted evidence in support of the following mechanisms contributing to AM occurrence:

- transient blade stall
- turbulent inflow variation

[488] ETSU-R-97, section 6, page 68
[489] ETSU-R-97, section 3, page 12
[490] During the preparation of this report, the results of a study funded by the German Environment Agency (Umweltbundesamt) were published, which included an observational field study component surveying the responses of 468 residents within 3 km of wind turbines in 5 areas in different geographic regions. The survey included questions about sound characteristics that included descriptions associated with AM, such as 'whooshing' (alongside other descriptions not associated with AM). Of the various characteristic descriptions, 'whooshing' produced the strongest correlation with reported noise annoyance. Details are found in: Schmitter, S, Alaimo Di Loro, A, Hemmer, D, Schreckenberg, D, Großarth, S, Pörschmann, C & Kühner, T, 2022. *Noise effects of the use of land-based wind energy*. Project Number 3717 43 110 0 Report No. FB000656/ENG (Final report). Umweltbundesamt. [URL]

- turbine wake effects
- partial refractive rotor 'shading'

These mechanisms are influenced by atmospheric factors (which are intrinsically linked with the varying meteorological conditions that tend to occur during different parts of the day), turbine operational behaviour, and other factors including site topography. It is noted that some of these mechanisms could be inherently linked with the size of turbines (both the hub height and the rotor span), however the evidence review did not identify any studies that systematically investigated this potential factor.

It has also been suggested, based on theoretical analysis, that the ground surface acoustic properties may play a further role in non-trivial frequency-dependent AM occurring at ranges of up to around 500 m from turbines[491].

Measurements of amplitude modulation

Long-term measurements of AM at overseas sites in varied environments have confirmed that AM is more prevalent during evening, night, and early morning, as illustrated in Figure 6-6. This phenomenon is primarily due to the influence of the atmospheric conditions that tend to prevail at these times, but is probably also linked with lower residual sound levels.

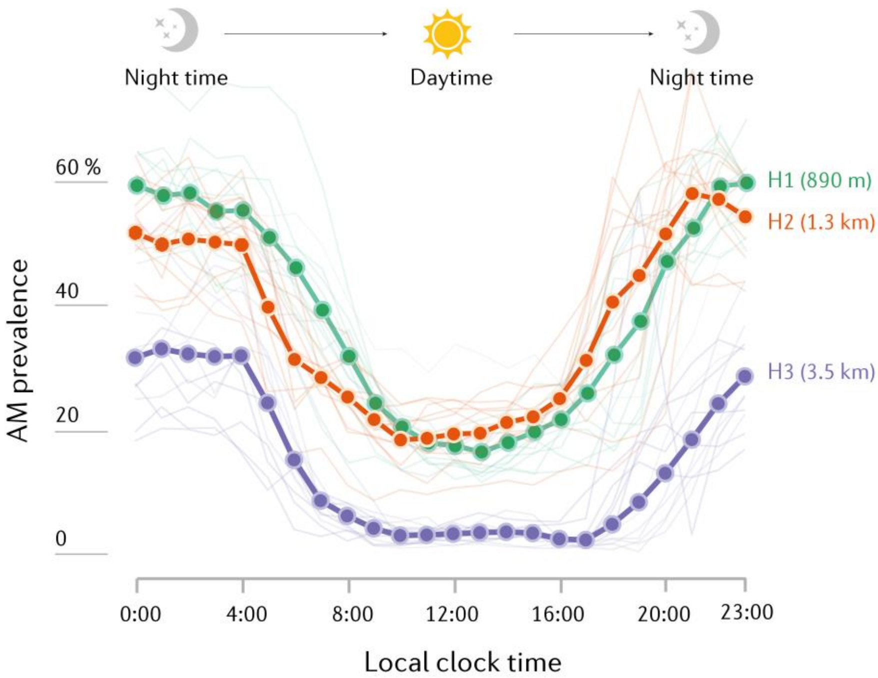


Figure 6-6: Measured AM prevalence across the day at three residential locations over one year in Australia (data from Nguyen et al, 2021[368]; image © 2021 Elsevier Ltd)

Measurements have also indicated that the distribution of AM depth typically has a low-skewed normal form (see example in Figure 6-7 – note that the AM depth metric used in Figure 6-7 is not the IOA metric). This is consistent with the AM measurements from the Japan study, which are shown

[491] Ecotière, D, 2015. *Can we really predict wind turbine noise with only one point source?* Wind Turbine Noise 2015, 20-23 April, Glasgow. INCE-Europe.

for comparison in Figure 6-8 (note that Figure 6-8 shows axis scaling for both the Japan D_{AM} metric and the approximate corresponding values for the IOA metric, which have been estimated from published regression relationships[492]).

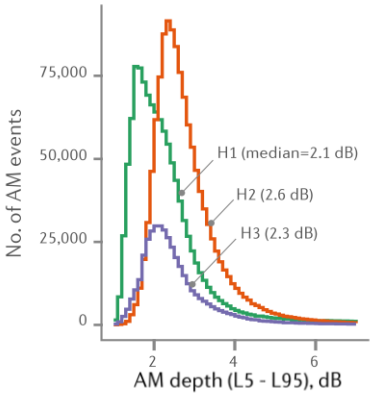


Figure 6-7: Measured AM depth distributions at three residential locations over one year in Australia (data from Nguyen et al, 2021[494]; image © 2021 Elsevier Ltd)

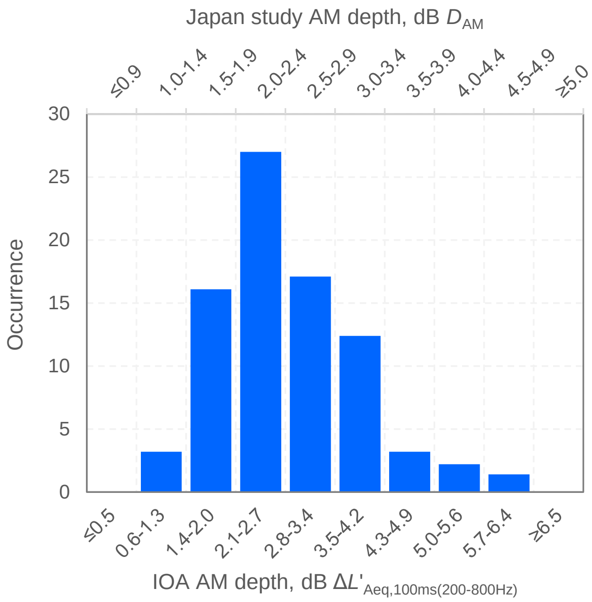


Figure 6-8: Measured AM depth distributions at 81 locations around 18 wind farm sites in Japan (data from Tachibana et al, 2014[495]; IOA AM depth axis scaling estimated using data from Fukushima et al, 2017[492])

[492] Fukushima, A & Tachibana, H, 2017. *Comparison of the IOA method and Japanese F-S method for quantitative assessment of amplitude modulation of wind turbine noise – A study based on the field measurement results in Japan*. Wind Turbine Noise 2017, 2-5 May, Rotterdam. INCE-Europe.
[494] Nguyen, P, Hansen, K, Catcheside, P, Hansen, C, & Zajamsek, B, 2021. Long-term quantification and characterisation of wind farm noise amplitude modulation. *Measurement,* 182, 109678. [URL]
[495] Tachibana, H, Yano, H, Fukushima, A & Sueoka, S, 2014. Nationwide field measurements of wind turbine noise in Japan. *Noise Control Engineering Journal*, 62 (2), 90-101. [URL]

The limited measurements undertaken in this study also exhibit a similar distribution (see section 5.5). These datasets indicate that, when present, AM tends towards lower depths, but there are occurrences when AM depths are considerably greater than the median values.

It is noted that AM measurements in another study over 2 months in Australia showed much higher AM depths (typically 7-10 dB $\Delta L'_{Aeq,100ms(50Hz)}$, quantified using a modified version of the IOA Reference Method), but these corresponded with a specific low frequency tonal form of AM, the relevance of which to other areas is not apparent in the evidence reviewed[496].

It should be emphasised that, in view of the ranges, wind directions and frequency ranges involved in the measurements described above, the data considered are all thought to be examples of non-TEDCAR-AM, which is not addressed in the ETSU-R-97 guidance.

Evidence and experience suggest that, of the various AM measurement methods currently available, the IOA Reference Method offers the best balance between reliability and practicality. It is also known that this metric is currently incorporated (with some proposed refinements or clarifications) into the working draft of the forthcoming IEC 61400-11-2 standard, which addresses measurements of wind turbine sound at receptor locations[497]. It is therefore recommended that the IOA metric is adopted in future guidance as the appropriate AM measurement method, and any modifications of the method proposed in the IEC standard or in relevant research (see section 3.5.1) should also be considered for integration.

Effects, and approaches to amplitude modulation control

Responses to AM have typically been studied in controlled, experimental conditions with relatively small participant samples. Several studies have demonstrated that participant noise annoyance ratings increase in the presence of AM in wind turbine sound, and research has also shown that annoyance ratings are influenced by modulation depth and modulation frequency (see section 3.5.1).

A smaller number of experimental studies have investigated the potential for effects of AM wind turbine sound on objective and subjective sleep quality. These suggest the potential for a slight effect on some objective sleep indicators, but further research is needed to investigate this. On the other hand, AM wind turbine sound in the context of a controlled laboratory sleep study has been associated with self-reported measures of sleep disturbance.

The need for official guidance on the control of AM in wind turbine sound was the single most commonly raised theme in the engagement responses to the question asking stakeholders to suggest what updates to the current guidance may be required.

The 2016 review of response to AM[498] concluded that a character penalty scheme would be appropriate to include in planning conditions, which would entail measuring sound levels and AM in response to noise complaints, and adjusting the measured levels according to the magnitude of AM to reflect the additional impact. This is analogous with the way in which tonality characteristics in wind turbine sound are addressed in ETSU-R-97 and the IOA GPG. This type of approach is largely supported by the experimental evidence, which indicates that AM is secondary to the overall sound

[496] Hansen, K, Nguyen, P, Zajamsek, B, Catcheside, P, & Hansen, C, 2019. Prevalence of wind farm amplitude modulation at long-range residential locations. *Journal of Sound and Vibration,* 455, 136-149. [URL]
[497] Broneske, S & Søndergaard, B, 2021. *Development of IEC/TS 61400-11-2: Measurement of wind turbine noise characteristics in receptor position*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe.
[498] WSP | Parsons Brinckerhoff, 2016. *Wind turbine AM review: Phase 2 report.* 3514482A Issue 3. Department for Business, Energy & Industrial Strategy. [URL]

level in determining subjective responses, and that the added impact of AM can be quantified as a change in the equivalent sound level.

It has been shown that AM depth and modulation frequency both have an influence on noise annoyance, and, since these parameters are both reliably measurable, it follows that they should be included in a character penalty scheme – a penalty scheme has been proposed that addresses both these aspects[499], which employs the IOA Reference Method to quantify AM.

A further consideration is the influence of the sound level index used to quantify the overall wind turbine sound levels, as discussed in section 6.2.1. It has been noted that increasing AM depth can lead to a slight increase in the difference between $L_{Aeq,10min}$ and $L_{AF90,10min}$, over and above the ETSU-R-97 assumed range of 1.5-2.5 dB. For AM depths up to 10 dB $\Delta L'_{Aeq,100ms(BPmax)}$ the typical difference may increase up to ~3.5 dB. Further measurement investigation of this effect could be valuable to expand the evidence and understand the uncertainties. However, to address this issue for sound level measurements made using the $L_{AF90,10min}$ index, it has been proposed that the addition of a sliding margin dependent on the measured AM depth could be added on top of an AM penalty, for application to measured $L_{AF90,10min}$[500]. The available evidence (see section 6.2.1) indicates that the sliding scale would take an approximate magnitude of 0-1.5 over the range 4-10 dB $\Delta L'_{Aeq,100ms(BPmax)}$.

Another aspect that requires consideration is the combination of character penalties for different characteristics (eg, AM and tonality). This is complicated further in the case of wind turbine sound, due to its inherent variability, and the potential for characteristics to be detected at different times as well as simultaneously. This issue requires further research and has remained unresolved throughout the revisions of BS 4142[501], which currently advises arithmetic combination of penalties – however, the simplistic additive approach has been shown in experiments not to reliably represent subjective impressions[502,503]. An alternative approach is taken in the New Zealand standard[504], which 'caps' the combined characteristic penalty; this approach may be more consistent with available research, but further investigation is needed to confirm the most representative method.

In practice, the details of applying such a penalty scheme are complicated by the complexities of wind turbine sound measurements. These often involve a considerable amount of data filtering and data aggregation to address the practical difficulties of measuring a highly variable source, which is often also at a level that is relatively low compared with other, fluctuating residual sounds present in the acoustic environment. Such details will need to be carefully considered in further study, and the example planning condition proposed by a group of IOA members in 2017[505] should be considered as a starting point. The final form of a scheme will also depend on how any future guidance addresses compliance determination, which is discussed further in section 6.4.

---

[499] Lotinga, M, & Lewis, T, 2021. *Subjective responses to wind turbine noise amplitude modulation: Pooled analysis of laboratory listening studies and synthesis of an AM character rating penalty*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe. [URL]
[500] Bowdler, D, Cand, M, Hayes, m & Irvine, G, 2018. *Wind turbine noise amplitude modulation penalty considerations*. Acoustics 2018, 23-24 April, Cardiff. Institute of Acoustics. [URL]
[501] BSi, 2019. *BS 4142:2014+A1:2019 Methods for rating and assessing industrial and commercial sound*. British Standards Institution. [URL]
[502] Porter, ND, 1995. *The assessment of industrial noise – Subjective listening tests and objective assessment procedures*. RSA(EXT)0057C. National Physical Laboratory. [URL]
[503] Youdale, C, Woodcock, J & Waddington, D, 2016. Perceptual evaluation of the BS 4142:2014 penalty method for multiple sound characteristics. *Proceedings of the Institute of Acoustics*, 38 (1), 173-180. [URL]
[504] Standards New Zealand, 2010. *NZS 6808:2010 Acoustics - Wind farm noise*. [URL]
[505] McKenzie, A, Cand, M, Bowdler, D, Jiggins, M, Irvine, G, Reid, M, Perkins, R, Lotinga, M, Hayes, m & Bullmore, A, 2017. A planning condition for wind turbines. *Acoustics Bulletin*, 42 (6), 56-60. [URL]

The stakeholder engagement highlighted that some respondent Northern Ireland LPAs "*have concerns about the use of penalty planning conditions to address tonality and amplitude modulation impacts that may occur on a site-specific basis. This provides no certainty that adverse noise impacts will not occur and places huge uncertainty on the ability of the operator to comply. This is particularly the case for single turbine schemes with machines that may be less capable of adjustment.*". It should be noted that there is no noise management government policy in place in Northern Ireland that requires 'certainty' that adverse impacts from wind turbine noise will not occur (see section 1.3.3); the NPSNI requires adverse impacts to be mitigated and minimised while taking into account the guiding principles of sustainable development – the NPSNI notes that "*this does not mean that adverse effects cannot occur*". Nonetheless, establishment of controls for the impact of sound characteristics should carefully consider the practicability from the perspective of wind turbine operators.

6.4 OTHER ISSUES

6.4.1 COMPLIANCE DETERMINATION AND ENFORCEMENT

The stakeholder engagement highlighted that many stakeholders find compliance assessment to be overly difficult, complex and costly, and can sometimes result in ambiguity over the compliance status of developments, when it cannot be robustly established whether compliance is achieved or not.

It has also been suggested that an approach comprising the use of proxy measurement locations nearer to turbines alongside predicted propagation should be considered, to address some of the issues involved in compliance assessments such as low sound levels, and the cumulative contributions from multiple developments. One stakeholder expressed the view that the general propagation prediction approach set out in the GPG is robust and conservative, and this view has been supported by research evidence examining predictions of wind turbine sound for sites in Scotland[506]. A similar approach is used in the Netherlands, which employs in-situ sound power level verification measurements alongside predictions of propagation (and also takes into account the expected annual distribution of sound associated with varying wind conditions).

6.4.2 CUMULATIVE IMPACTS

Several stakeholders identified that the increasing complexity of assessing cumulative impacts from multiple developments is problematic, and further guidance would be valuable. Subsequent to the publication of the IOA GPG (which includes guidance on assessment of cumulative impacts), a group of UK consultants and LPA officers published an 'agreed view' on factors affecting cumulative assessments, within the context of the ETSU-R-97 assessment method and the IOA GPG recommendations[507]. This included proposed approaches to some of the complexities that require interpretation of the existing guidance, as well as identifying other, unresolved, issues that may arise in assessing cumulative impacts. This evidence could be used to inform the development of further guidance on cumulative impact assessments.

In addition, it has been noted that the encirclement of receptors by multiple wind turbine developments could potentially result in more sustained noise impacts, which indicates that

[506] SLR & Hoare Lea, 2015. *Wind Farm Impacts Study: Review of the visual, shadow flicker and noise impacts of onshore wind farms.* Final report: 405.04528.00001. ClimateXChange. [URL]
[507] Bowdler, D, Branney, E, Cand, M, Carmichael, B, Carter, R, Farmer, L, Irvine, G, Jiggins, M, Leventhall, G, McKenzie, A, Richard Perkins, R, Reid, m & Travis, P, 2016. Wind farms cumulative impact assessment. *Acoustics Bulletin*, 41 (1), 44-48. [URL]

consideration of the duration of impacts should be incorporated into the assessment approach and the development of a framework of effects thresholds (as discussed in section 6.2.3).

6.4.3 DEVELOPMENT VALUE PRIORITISATION

The stakeholder engagement highlighted that policy and guidance on wind turbine developments should prioritise larger developments that contribute the most value to renewable energy policy objectives. In ETSU-R-97, this has been attempted (to an extent) by the flexibility available in assigning a daytime minimum noise limit (as discussed in section 6.2.1). Consideration of a noise effects thresholds framework in future guidance should also examine how flexibility in controlling values enables prioritisation of developments according to their energy capacity, with reference to the relevant aspects of government policies (eg, the sustainable development guiding principles set out in the NPSE – see section 1.3.1).

6.4.4 DATA AGGREGATION AND TREATMENT OF UNCERTAINTY

Some stakeholders suggested that more guidance on the treatment of uncertainty would be valuable. It was also noted that there are several potential sources of uncertainty in wind turbine noise assessments, although there was no clear agreement on whether or not the current guidance adequately addresses these or not. The ETSU-R-97 assessment approach involves data aggregation, primarily in the derivation of prevailing background sound levels used to establish the relative noise limit. The stakeholder engagement and the evidence review indicated that some take the view that the approach to aggregation in ETSU-R-97 does not represent a reasonable worst-case. The IOA GPG addresses uncertainty in wind turbine sound predictions, which, as noted in section 6.4.1, are considered conservative. But it does not explicitly consider uncertainty inherent in other aspects of the assessment procedure.

ETSU-R-97 is not definitively prescriptive on the aggregation approach to be applied to background sound level data. It indicates that a least-squares method should be used to fit a curve to the data[508], and that where data exhibits considerable scatter, 'binning' data into integer wind speeds could be applied (to 'smooth' the data before curve fitting). From a statistical analysis perspective, this advice allows considerable flexibility in selecting the most appropriate technique to apply, since a 'least squares' approach is used in a wide range of statistical curve fit analyses, including linear[509] (also known as 'ordinary') and non-linear least squares regression models. The apparent flexibility afforded by ETSU-R-97 in this respect has subsequently been effectively narrowed in practice by the guidance in the IOA GPG (and associated SGN2), which advises only on the use of linear (usually polynomial) least squares regression.

As such, an issue with the current guidance on data aggregation is that the statistical modelling technique to be applied is prescribed, rather than selecting the technique that best represents the actual data. This can be seen as an attempt to balance rigour with practicality and consistency, in view of the likelihood that most assessors will not be experts in statistical analysis. However, the approach can lead to anomalous results, such as models that predict increasing sound levels at very low wind speeds and reducing sound levels at very high wind speeds – the IOA GPG addresses this

[508] ETSU-R-97, section 8, page 101
[509] Here, 'linear' and 'non-linear' are used in the strict statistical sense of the manner in which regression model equation terms are combined, and does not refer to the 'straightness' or 'curviness' of the line produced by the model fit. In this sense, least squares regression models defined using a polynomial equation (of any order) are considered linear regression models, as the terms are linear combinations. This definition is distinct from the terminology used in the IOA GPG (which uses 'linear' to mean a 'straight line' model – ie, an 'affine linear' function –, which can also be considered as a polynomial equation of order 1).

particular issue (which is usually due to regression model 'overfitting') by advising that regression curves are manually truncated, but this avoids addressing the underlying issue, which is poorly-fitted models that do not accurately represent the underlying relationships.

An alternative approach would be to select a different type of model, but this is not accommodated by the current guidance in the IOA GPG, which prescribes polynomial regression models of order 1-4.

If the use of background sound measurements and data aggregation is to be retained in future assessment guidance, it would be beneficial to undertake a review of the approach, and such a review should be undertaken by experts that include representatives with the appropriate specialist competency in applied statistical methods, to enable a robust approach to be developed that is also sufficiently practical for implementation. If the methods recommended involve greater complexity, this should be addressed in guidance using worked examples.

Another issue raised by data aggregation is whether the assessment represents a reasonable worst-case. The use of a least-squares regression model gives an estimate of a value near the middle of a set of possible values, which for normally distributed data would be equal to the mean (and median). In simple terms this means that roughly half the measured levels would be above and half would be below (ie, around 50% of the time), with the degree of error in the estimate being proportional to the scatter (the variance) in the measured data. Some authors proposed that this be considered by subtracting a margin from estimates of the background sound levels to produce a low-weighted estimate. However, such an approach would largely overlook the fact that in many cases the predicted wind turbine sound levels represent a worst-case, and (with the possible exception of the type of cumulative encirclement situations discussed in section 6.4.2), the wind turbine sound levels will also be lower for substantial periods of time, due to natural fluctuations in wind conditions. If relative impacts of wind turbine sound continue to be considered in noise assessments, a more balanced approach might be to consider what proportions of time wind turbine sound is expected to be at specific margins relative to background sound. The far more simplistic approach of subtracting margins from background sound level data to provide a more worst-case estimate could easily result in assessments that are highly restrictive on wind energy development, which may not be compatible with policies on sustainable development and Net Zero – this would need to be carefully considered.

6.4.5 SOUND AND WEATHER MEASUREMENT

The evidence review indicated that two issues are raised with the current guidance concerning sound measurement instrumentation: sound level meter microphone wind shield performance specification, and sound level meter self-noise influence on measurements in low sound level environments.

The stakeholder engagement also highlighted two instrumentation issues in need of further guidance: sound level meter microphone wind shielding, and weather measurement techniques. The IOA GPG explicitly recognises that further research and guidance is required to resolve issues around wind shield performance and testing, while providing recommendations on the approach to be followed until further advice is made available[510].

[510] IOA GPG SGN1, section 2.4, pages 5-6,

Research studies aimed at investigating the performance of various wind shielding devices have been undertaken since the development of the IOA GPG, including studies in Australia[511] and in Japan[512]. The results of this research should be reviewed, and the need for any further study identified to support the development of further guidance on the specification of wind shielding.

The issue raised on weather measurements primarily concerned appropriate siting of instrumentation, and the need for further guidance on this aspect, which could be considered in future guidance development.

6.4.6 EVALUATION AND CONTROL OF TONALITY CHARACTER

The stakeholder engagement highlighted that the tonality assessment methods in ETSU-R-97 and the IOA GPG should be reviewed against contemporary standardised methods. In particular, it is known[513] that the working draft of the forthcoming IEC 61400-11-2 standard for measurement of wind turbine sound at receptor locations currently includes the ISO/PAS 20065[514] method, with some proposed modifications[515].

A known issue with the current ETSU-R-97 tonality evaluation approach is that for compliance assessments, it specifies that measured tonal audibilities should be aggregated *before* assigning an overall tonal penalty[516]. Due to the construction of the tonal penalty, this can result in situations in which tonal audibility could consistently occur at relatively low values but attract no overall penalty, due to the tonal audibility aggregation process. As has been noted in relation to the recommendations of the 2016 AM review, it would be more robust to ensure that sound character evaluations are based on aggregation of the penalty values assigned to individual periods[517] (ie, rather than assigning a penalty value to an aggregated tonal audibility), to ensure that the presence of sound characteristics that increase adverse impact is always penalised.

As discussed in section 6.3.2, the practicability of controls proposed for sound characteristics should be carefully considered, and examples provided to illustrate the appropriate application in a suitable range of scenarios.

6.4.7 EVALUATION AND CONTROL OF INTERMITTENCY CHARACTER

Two LPA stakeholders responding to the engagement exercise highlighted that the inherent variability of wind turbine sound may be a characteristic that increases adverse impact, citing the penalty proposed in BS 4142 for intermittency that "*is readily distinctive against the residual acoustic environment*"[518]. This aspect has not been systematically investigated in this review, but it is noted that there are no specific studies cited within BS 4142 that provide direct evidence supporting the

[511] Hansen, K, Zajamšek, B & Hansen, C, 2014. Identification of low frequency wind turbine noise using secondary windscreens of various geometries. *Noise Control Engineering Journal*, 62 (2), 69-82. [URL]
[512] Tachibana, H, Yano, H, Fukushima, A & Sueoka, S, 2014. Nationwide field measurements of wind turbine noise in Japan. *Noise Control Engineering Journal*, 62 (2), 90-101. [URL]
[513] Broneske, S & Søndergaard, B, 2021. *Development of IEC/TS 61400-11-2: Measurement of wind turbine noise characteristics in receptor position*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe.
[514] ISO, 2016. *ISO/PAS 20065:2016 Acoustics – Objective method for assessing the audibility of tones in noise – Engineering method*. International Organization for Standardization. [URL]
[515] Woodward, R, 2021. *An implementation of ISO/PAS 20065:2016 for the analysis of wind turbine sound at receptor distances*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe.
[516] ETSU-R-97, section 7, page 89
[517] Lotinga, M, Perkins, R & Lewis, T, 2017. Perception and control of amplitude modulation in wind turbine noise. *Acoustics Bulletin*, 42 (2), 41-46. [URL]
[518] BSi, 2019. *BS 4142:2014+A1:2019 Methods for rating and assessing industrial and commercial sound*. British Standards Institution. [URL]

proposed penalty for intermittency. The issue is discussed in one of the cited NPL studies[519], but this provided only indirect, anecdotal evidence, in the form of reports from EHOs concerned about intermittency. Furthermore, examination of the worked examples in appendix A of BS 4142 show that 5 of the 11 examples address sound sources described as 'intermittent', yet none of these examples demonstrate the application of a character penalty for intermittency. This suggests that the intermittency penalty proposed in BS 4142 is not well supported by robust evidence.

One experimental study has investigated the influence of intermittency in relation to responses to wind turbine AM sound, which noted that intermittent periods of non-TEDCAR-AM were not rated as more annoying than sustained periods of TEDCAR-AM[520] by the 13 participants. However, this evidence only indirectly addresses the concern raised by the stakeholders. This issue could benefit from further review and investigation in experimental and observational studies, but, based on this initial consideration, there does not appear to be a strong case at present for incorporating any penalty for this sound characteristic into wind turbine noise assessment guidance.

6.4.8 SOUND PREDICTIONS

It was highlighted in the stakeholder engagement that validation examples for wind turbine sound prediction procedures would be valuable.

The IOA GPG provides some literature references to demonstrate that the recommended procedures are considered to be robust, and it has been shown that the IOA GPG recommendations lead to more conservative predictions than common assumptions previously adopted in planning assessments[521]. On this basis, there does not appear to be a strong case for further effort on this aspect at present for predictions made under assumed (reasonable worst case) downwind conditions.

For predictions made for emissions in other (crosswind or upwind) conditions, the IOA GPG refers to evidence from research undertaken in the 1980s-90s[522,523,524,525]. In two of these studies[522,525], stationary omni-directional loudspeaker sound sources were used to investigate sound propagation and directivity, while in the other[523,524], the field-measured directivity patterns corresponded with a 2-bladed, downwind-rotor turbine (the 'WTS-4' used for research by the US federal government). Further evidence is now available, including from theoretical[526] and experimental field studies[527] (addressing conventional 3-bladed, upwind-rotor turbines), against which the existing guidance should be reviewed.

---

[519] Porter, ND, 1995. *Study of the application of British Standard BS 4142:1990 "Method for rating industrial noise affecting mixed residential and industrial areas" (The data sheet study)*. RSA(EXT)0057A. National Physical Laboratory. [URL]
[520] Ioannidou, C, Santurette, S & Jeong, C-H, 2016. Effect of modulation depth, frequency, and intermittence on wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1241-1251. [URL]
[521] SLR & Hoare Lea, 2015. *Wind Farm Impacts Study: Review of the visual, shadow flicker and noise impacts of onshore wind farms.* Final report: 405.04528.00001. ClimateXChange. [URL]
[522] Wyle Research, 1988. *Measurement and evaluation of environmental noise from wind energy conversion systems in Alameda and Riverside Counties*. WR 88-19. Alameda County Division of Environmental Health & Riverside County Planning Department.
[523] Shepherd, KP, Willshire, WL & Hubbard, HH, 1989. *Comparison of measured and calculated sound pressure levels around a large horizontal axis wind turbine generator*. NASA Technical memorandum 100654. National Aeronautics and Space Administration. [URL]
[524] Hubbard, HH & Shepherd, KP, 1990. *Wind turbine acoustics*. NASA Technical paper 3057. National Aeronautics and Space Administration. [URL]
[525] Bass, JH, Bullmore, AJ & Sloth, E, 1998. *Development of a wind farm noise propagation prediction model*. Non-Nuclear Energy Programme JOULE III. JOR3-CT95-0051 Final Report. The European Commission. [URL]
[526] Barlas, E, Zhu, WJ, Shen, WZ, Dag, KO, & Moriarty, P, 2017. Consistent modelling of wind turbine noise propagation from source to receiver. *Journal of the Acoustical Society of America*, 142 (5), 3297-3310. [URL]
[527] Okada, Y, Yoshihisa, K, Higashi, K & Nishimura, N, 2016. Horizontal directivity of sound emitted from wind turbines. *Acoustical Science and Technology*, 37 (5), 239-246. [URL]

Some stakeholders highlighted during the engagement that further consideration should be given to the approaches provided in the IOA GPG for predicting sound propagation over concave terrain (eg, valleys) and over large bodies of water. Although these aspects have not been systematically investigated in this study, it is known that research on both topics has been published since the IOA GPG, which should also be reviewed in future guidance development[528,529].

6.4.9 SMALLER TURBINES

The scope of this study has not included specifics of wind turbine sound emissions and noise impact that may be associated with small turbines with relatively low power ratings. The stakeholder engagement highlighted that small and single turbines are a particular concern in Northern Ireland, where it has been reported that there are three times as many single turbines than in the rest of the UK[530], and statistics for Northern Ireland councils[531] show that the number of noise complaints about single turbines has increased steadily each year since 2015. The IOA GPG specifically excludes turbine developments with power ratings ≤50 kW, and the ETSU-R-97 approach is not generally applied to small turbines. The development of further guidance may need to consider whether specific guidance for small turbines is warranted.

6.5 BEIS RESEARCH QUESTIONS

In this section, the research questions motivating the project are directly addressed.

6.5.1 DO CONTEMPORARY ACOUSTIC MEASUREMENT METHODOLOGIES CHALLENGE THOSE THAT ARE USED IN ETSU-R-97?

There are several relevant aspects of sound measurements that have advanced since ETSU-R-97 was devised:

- The research shows that several methods have been developed to detect and quantify the magnitude of AM in wind turbine sound. Of those reviewed in this study, the IOA Reference Method, which was developed following a technical review of existing approaches, is believed to offer the best balance between robustness and practicality for use in the field. It is also known that the method has been incorporated into the working draft of the forthcoming IEC 61400-11-2 standard[532], albeit with some amendments[533], and refinements of the method have also been proposed during research applications.
- Research has shown that, during periods of AM with large modulation depths, the assumptions made in ETSU-R-97 supporting the choice of sound level index used to define the noise limits may not hold (see section 6.2.1). The rationale outlined in ETSU-R-97 to justify the choice of index is based on practical difficulties of measuring wind turbine sound, and remains valid. Therefore, this study recommends that the sound level index used to define controlling values is changed to the energy time-averaged sound level L_{Aeq}, and a suitable proxy measurement index is investigated and confirmed from further study.

---

528 van Renterghem, T, 2017. Sound propagation from a ridge wind turbine across a valley. *Philosophical Transactions of the Royal Society A*, 375, 20160105. [URL]
529 Søndergaard, LS, Thysell, E, Claumarch, C, Vignaroli, A, Thomsen, C & Hansen, KS, 2021. *Long distance noise propagation over water for an elevated height-adjustable sound source*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe.
530 https://www.bbc.co.uk/news/uk-northern-ireland-55279337
531 http://www.daera-ni.gov.uk/publications/noise_complaint_statistics_ni_2018_2019
532 At the time of preparing this report, the IEC 61400-11-2 standard is at drafting stages, and the standards development procedures mean it is unlikely to be published sooner than late-2022 or early-2023 [URL]
533 Broneske, S & Søndergaard, B, 2021. *Development of IEC/TS 61400-11-2: Measurement of wind turbine noise characteristics in receptor position*. Wind Turbine Noise 2021, 18-21 May, Remote from Europe. INCE-Europe.

- It was noted during the stakeholder engagement that there are several standardised methodologies available for evaluating tonality characteristics in sound immissions, which indicates that a review of these methods in comparison with the ETSU-R-97 approach should be undertaken.
- Researchers in Italy have devised a method for determining compliance of wind turbine sound immission levels with controlling values in the presence of residual sound, without the need to impose shutdowns on operations[534,535]. This type of procedure could have benefits for reducing the costs of undertaking compliance tests, and could be considered in future guidance development.

6.5.2 DO MODERN ONSHORE WIND TURBINES (COMPOSITE BLADES, GEARLESS TRANSMISSION) EMIT MORE, LESS, OR DIFFERENT CHARACTERISTICS OF NOISE THAT ETSU-R-97 GUIDANCE DOES NOT CURRENTLY ACCOUNT FOR?

Information gained during the stakeholder engagement has provided insights concerning this question:

- It was suggested that developments in turbine operational systems have influenced the sound emission profile of modern turbines: variable speed, pitch regulated turbines 'cut-in' with a relatively low sound level, which rises rapidly with wind speed, and 'plateaus' at or around rated power for the turbine; by contrast, sound emissions from the older fixed or dual-speed, stall regulated turbines more common at the time of ETSU-R-97 tend to increase steadily with wind speed, and do not plateau at rated power, as blade stall (which increases sound emissions) is used to regulate the turbine lift force at high wind speeds, to prevent damage.
- Stakeholders noted the increasing size of onshore turbines compared with those that were common when ETSU-R-97 was published has several potential implications:
  - The greater height means that wind speeds at blade and hub heights are typically higher for a given ground level wind speed. This may lead to situations in which, compared with a smaller turbine, larger turbines are generating similar sound immission levels, but wind-induced residual sound levels at receptors may be lower (due to the reduced ground level wind speed corresponding with a given hub height wind speed), which could lead to increased relative noise impact.
  - The larger rotor sizes may have two implications for AM characteristics at receptors:
    - the variation in the wind speed profile across the rotor span could be greater, which may contribute to transient blade stall, which in turn is associated with AM at long ranges
    - 'partial refractive shading' of the rotor could be greater, which could also lead to increased AM at long range (this was not raised in the engagement, but is discussed in the evidence review section 3.5.1)
  - Larger turbines lead to reduced turbine density for the same power capacity, which means that total sound emission levels tend to be similar to smaller turbine installations.

---

[534] Gallo, P, Fredianelli, L, Palazzuoli, D, Licitra, G & Fidecaro, F, 2015. A procedure for the assessment of wind turbine noise. *Applied Acoustics*, 114, 213-217. [URL]
[535] Fredianelli, L, Gallo, P, Licitra, G & Carpita, S, 2017. Analytical assessment of wind turbine noise impact at receiver by means of residual noise determination without the wind farm shutdown. *Noise Control Engineering Journal*, 65 (5), 417-433. [URL]

- Larger turbines also mean increased distances between turbines and receptors, which may result in a more low-frequency sound immission character at long ranges, due to atmospheric effects on sound propagation.
- It was also suggested (citing research evidence[536]) that larger turbines may emit lower frequency tones than smaller turbines, when tones are present in the sound.
- Research evidence on the general low frequency character of the sound emissions from larger, more powerful turbines is conflicting. A study undertaken for the Danish government produced differing interpretations of the measurement data by two of the project partners: one concluded[536] that increasing turbine size and power ratings was not associated with a systematic increase in the proportion of low frequency sound emissions; another analysed the same dataset and reached the opposite conclusion[537]. Further analysis was later undertaken on an expanded dataset, which again concluded that the notion that larger turbines systematically emit a greater proportion of low frequency sound energy compared with smaller turbines is not supported by the available evidence[538,539].

- It was highlighted that developments in turbine design features also have potential implications:
  - Several options for noise mitigation measures are available as standard on many commercial turbines, which include reduced sound operating modes and blade attachments, such as serrations, stall strips and vortex generators.
  - It was suggested that tonality characteristics in the sound emissions from modern turbines have been effectively addressed by improved technology and attention from manufacturers. However, it was also noted that the design features or mitigation measures introduced to reduce the overall broadband sound emissions could potentially mean that tones could 're-emerge' within the expected sound immissions from wind turbines.

Commercial onshore wind turbines employing direct drive transmission apparently remain relatively unusual. Although direct drive technology has been increasingly used for offshore turbines, it has not received widespread adoption for onshore applications, and it remains unclear whether gear-based or direct drive technology will be more dominant in the future of onshore wind energy[540,541]. Inspection of the onshore product portfolios for major wind turbine manufacturers (General Electric, Nordex, Siemens Gamesa and Vestas) has shown that, at the time of preparing this report, none of the current onshore turbine models available from these manufacturers employ direct drive technology, although it is found in some discontinued onshore products (and available in current offshore turbines). This suggests that, while there was some commercial interest in direct drive transmission for onshore turbines in the recent past, demand for the technology in onshore applications has waned, and it is unclear whether it will be revived. From an acoustics perspective, there may be a slight advantage to direct drive transmission, in avoiding gear meshing sound.

---

536 Madsen, KD & Pedersen, TH, 2010. *EFP-06 project: Low frequency noise from large wind turbines*. Final report. AV 1272/10. Danish Energy Authority.
537 Møller, H & Pedersen, CS, 2011. Low-frequency noise from large wind turbines. *Journal of the Acoustical Society of America*, 129 (6), 3727-3744. [URL]
538 Søndergaard, B, 2014. *Noise and low frequency noise from wind turbines*. Inter-noise 2014, 16-19 November, Melbourne. I-INCE [URL]
539 Søndergaard, B, 2015. Low frequency noise from wind turbines: do the Danish regulations have any impact? An analysis of noise measurements. *International Journal of Aeroacoustics*, 14 (5-6), 909-915. [URL]
540 van de Kaa, G, van Ek, M, Kamp, LM & Rezaei, J, 2020. Wind turbine technology battles: Gearbox versus direct drive - opening up the black box of technology characteristics. *Technological Forecasting and Social Change*, 153, 119933. [URL]
541 Osmanbasic, E, 2020. *The future of wind turbines: Comparing direct drive and gearbox*. [URL]

However, directly driven generators still produce tonal sound and vibration[542], and since the dominant part of the sound emission from turbines is generated by aerodynamic mechanisms, any acoustical advantage offered by direct drive transmission may be inconsequential.

6.5.3 DO ANY CHANGES IN THE WAY MORE MODERN TURBINES ARE SITED IN NEWER WIND FARMS RESULT IN MORE, LESS OR DIFFERENT CUMULATIVE NOISE LEVELS, BOTH WITHIN THE WIND FARM AND ALSO WHERE THESE NEWER WIND FARMS ARE LOCATED IN PROXIMITY TO OTHER WIND FARMS?

Responses to the stakeholder engagement suggested that the increased density of wind energy developments may have resulted in some situations in which properties become 'encircled' by wind turbines. This has the potential consequence that wind turbine sound could be incident from several directions, meaning that periods of 'respite', during which residents may otherwise have expected lower levels of wind turbine sound, would potentially be diminished, resulting in more prolonged impact.

Evidence from research identified during this study has suggested that wind turbine wakes, especially in stable atmospheric conditions, can enhance wind turbine sound propagation and the potential for AM. This indicates that turbine layouts could have some influence on sound emissions and character that may not yet be fully understood.

6.5.4 DO MODERN ONSHORE WIND TURBINES PRODUCE EXCESSIVE AM, TO WHAT EXTENT, AND TO WHAT EFFECT?

The term 'excessive' is not a well-defined descriptive term to use for AM sound characteristics. In this study, we have chosen to use the term 'TEDCAR-AM' to signify 'trailing edge directivity and convective amplification-related' AM (also known as 'blade swish' or 'normal AM'), and 'non-TEDCAR-AM' to signify AM that is primarily influenced by other factors (also known as 'other AM'). This is because the latter can be affected by a wide range of complex interacting factors, including turbine operational parameters (and potentially, size), atmospheric effects, refraction, and turbine wake effects. The terms used in this study have the benefit of being related to an objective description of the generation mechanisms of what is commonly known as 'blade swish'. Research indicates that the occurrence of non-TEDCAR-AM (which, although apparently acknowledged in ETSU-R-97 in the form of 'blade thump' described as having been identified at one site, was not the focus of the guidance), is likely to be more prevalent at night-time than during the day, and potentially increases the noise annoyance impact of wind turbine sound when it is present.

We undertook a limited field measurement exercise that showed detectable AM at distances and in wind directions that would not be considered as consistent with the more predictable TEDCAR-AM. This tentatively indicates that detectable non-TEDCAR-AM is probably not an unusual occurrence at the sites visited, although a larger dataset would be necessary to draw generalised conclusions about prevalence.

Evidence from the research identified during this study indicates that audible AM increases the distinctiveness of wind turbine sound and aggravates noise annoyance responses. The impact of AM is influenced by the modulation depth, as well as by its modulation frequency.

[542] Schneider, L & Hanus, K-H, 2017. *Origin, transfer and reduction of structure-borne noise in wind turbines*. Wind Turbine Noise 2017, 2-5 May, Rotterdam. INCE-Europe.

6.5.5 IS THERE EVIDENCE OF THE NEED FOR A MORE COMPREHENSIVE MEASUREMENT CAMPAIGN FOR AM FROM NEW TURBINE TYPES?

This study has not identified evidence to indicate that 'new turbine types' are associated with different AM characteristics. While some evidence suggests that larger turbines may be subject to increased risk of non-TEDCAR-AM occurrence, due to potential factors connected with turbine dimensions (including wind speed variation over the rotor span, partial refractive shading of the rotor disc, and wake effects), no studies have been identified that systematically investigated this possible connection, which therefore remains uncertain. On the other hand, the research indicates that modern turbines enable accurate control of blade pitch angle – this can be used to reduce the risk of blade stall occurrence, which is also associated with non-TEDCAR-AM.

This study has identified previous long-term campaigns comprising field measurements of AM in Australia (see sections 3.5.1 and 6.3.2) and in Japan (section 6.3.2). Based on the findings from the evidence review and the stakeholder engagement, the potential value of such a campaign in the UK may lie more toward investigating wind turbine noise effects and responses to AM than in trying to establish whether particular turbine types, models or ages are more or less associated with AM occurrence or severity. This is because there are multiple complex factors that appear to influence AM generation, which could make it unlikely that any firm conclusions regarding the influence of specific turbine distinctions can be reached. It has also been highlighted in the stakeholder engagement that the challenges involved in attempting to obtain sufficiently robust data should not be underestimated (see section 4.2.4), and there could be no guarantee of achieving the objective.

6.5.6 DOES THE EXTENT OF AM CHANGE AS TURBINES GET OLDER OR SUFFER MORE WEAR AND TEAR?

The stakeholder engagement identified some evidence addressing this question: a member of an industry professional association shared their experience that delamination (roughening) of wind turbine blades over a period of 10 years led to increased AM identified at 2 sites. It was found that repairs were straightforward and resolved the issue.

The general consensus among stakeholders responding to the part of the engagement survey that addressed this question was that there is a commercial incentive for operators to maintain turbines, as degradation that adversely affects sound emissions also impacts on power generation. Routine maintenance and repairs can avoid or resolve such issues when they arise.

6.5.7 DO INTERNATIONAL COMPARISONS SUGGEST THAT ETSU-R-97 GUIDANCE, METHODOLOGIES AND RATINGS ARE NOT UP TO DATE, OR CAN BE ADAPTED?

The research showed that the most apparent difference between ETSU-R-97 and overseas national or regional guidance and regulations is that the ETSU-R-97 night-time minimum noise limit is less stringent than the daytime. This study has found that this situation appears to be unique to the UK and Ireland (among the territories considered – see section 3.5.1). In 2019, the Government of Ireland published draft revised guidelines that indicated it is proposing to replace the existing noise limits with a regime that would effectively ensure that night-time limits are lower (more stringent) than the daytime[543]. However, at the time of preparing this report, the finalised guidance had not been published.

[543] Government of Ireland, 2019. *Draft revised wind energy development guidelines.* [URL]

The research has also shown that the ETSU-R-97 daytime minimum noise limits appear to be similar to those imposed in overseas territories.

Comparison of relative 'margin above background sound level' limits indicates that the ETSU-R-97 approach is also taken in New Zealand, Ireland, and the Australian states of South Australia and Victoria, while Japan, and the states of New South Wales and Queensland impose a more stringent relative limit. This appears to be connected with the use of L_{Aeq} to characterise wind turbine sound immissions instead of L_{AF90}. France and Italy impose relative limits based on a different system known as 'sound emergence', which is not directly comparable with the 'margin above background sound level' approach. Research on the sound emergence approach indicates that it may not be a useful characterisation of relative impact[544]. However, there also appears to be very little (if any) scientific evidence supporting the margin above background approach taken in the other territories that apply relative impact controls (as discussed in section 6.2.1).

It is notable that the Japanese regulations were introduced following an extensive research programme involving observational epidemiological field studies and experimental studies of sound characteristics, including AM, tonality, and low frequency sound. The overall approach is very similar to ETSU-R-97, being based on a combined regime of absolute and relative limits. However, the controlling values tend to be slightly more stringent, and the sound level index used to control wind turbine sound is L_{Aeq} rather than L_{AF90} (although L_{AF90} is used as a proxy measurement index)[545].

A more detailed review of overseas national and regional guidelines on wind turbine sound and noise assessment could be valuable in providing further context for decisions on the policy balance between noise control and enabling renewable energy development. However, vigilance should be exercised in considering overseas guidance and regulations; the underlying scientific evidence and any professional judgements should be identified and considered, and if evidence or judgements are not clear, the information should be treated with caution.

6.5.8 TAKING THE ABOVE INTO ACCOUNT, SHOULD BEIS CONSIDER REFRESHING ETSU-R-97 GUIDANCE AND, IF SO, HOW?

In view of the results of the evidence review, the stakeholder engagement and the field measurement exercise, this study concludes that the identified aspects of the current guidance should be reviewed and updated. To an extent, this could be supported by the currently available research evidence (some of which has been summarised in this report), alongside the relevant experience of stakeholders. However, this study has also highlighted gaps in the state of knowledge, which should be addressed by further research to support any updates to the guidance.

Our recommendations for aspects of the guidance that should be reviewed and updated are summarised in section 7.

[544] Dutilleux, G, & Fosset, J, 2020. Comparing sound emergence and sound pressure level as predictors of short-term annoyance from wind turbine noise. *Acta Acustica*, 3 (4), 10. [URL]
[545] Shimada, A & Nameki, M, 2017. *Evaluation of wind turbine noise in Japan*. ICBEN 2017, 18-22 June, Zurich. International Commission on Biological Effects of Noise. [URL]

7

CONCLUSIONS & RECOMMENDATIONS

7 CONCLUSIONS & RECOMMENDATIONS

This section first outlines the conclusions of the study, and the summarises the recommendations alongside the rationale and signposting to the relevant supporting evidence and information contained in other parts of this report.

7.1 DOES THE GUIDANCE REQUIRE UPDATING, AND IF SO, WHICH PARTS?

The evidence reviewed in this study, combined with the responses from the stakeholder engagement, indicates that the guidance would benefit from further review and updating of the aspects identified. Views from stakeholders on the extent of the updates required vary, with roughly half whose view is that the guidance requires some updating, and almost the same proportion whose view is that it requires substantial revision. Between these two viewpoints, there is consistency on the aspects of the guidance that the engagement respondents feel should be updated. These aspects are consistent with the findings of the evidence review, which has identified a substantial body of evidence published since both ETSU-R-97 and the IOA GPG that could inform updating of the areas in question. There are two primary aspects that this study has identified, which indicate the guidance requires updating; each is addressed in turn below.

7.1.1 ETSU-R-97 NOISE LIMITS

- The research indicates that the underlying basis for the ETSU-R-97 limiting values is outdated; there is now a volume of scientific evidence on the effects of exposure to wind turbine sound, which was unavailable at the time of ETSU-R-97, but now could be used to support the development of an up-to-date framework of evidence-based effects thresholds:
  - The WHO 2018 ENGER specifically addressed wind turbine noise effects, however the recommendation made was based on the evidence available up to the end of 2014; our review, and several others, have identified that the quantity and quality of evidence has expanded from 2015, such that the 2018 WHO recommendation is not recommended as a basis for developing new guidance on wind turbine noise. There are also valid technical concerns over the procedure used to arrive at the value recommended in the ENGER, which are symptomatic of the challenges involved in combining data from different studies that employ differing methods.
  - A fresh, systematic review and meta-analysis of evidence on exposure-response relationships for wind turbine sound and noise annoyance is now considered likely to produce informative results. However, it must also be recognised that the nature of noise annoyance is that responses can be strongly influenced by personal and contextual factors that may not have any direct relationship with sound exposure; these factors vary from study to study and will depend somewhat on local circumstances. This suggests that there will be inherent uncertainty in applying generalised exposure-response data from overseas areas to people in the UK. Nonetheless, such information could provide a justifiable basis for establishing a framework until further UK studies have been undertaken. This study has also shown that any meta-analysis of existing studies must take careful account of inter-study differences in the approaches taken to estimating exposures and quantifying responses.
  - The evidence on sleep disturbance from wind turbine sound is less clear, and this is an area of research in which new evidence is continuing to emerge. It does seem clear that there is a

well-established relationship between noise annoyance and self-reported sleep disturbance, which indicates that a control framework established to address annoyance will also help to control against sleep disturbance. The emergence of new evidence should be kept under review in developing future guidance.
  - Effects thresholds should be based on the energy time-averaged sound level index L_{Aeq}. This has the primary benefit of compatibility with the majority of the research evidence. The use of a convenience proxy index for measurement purposes is supported on the basis that measuring the L_{Aeq} of wind turbine sound can often be problematic in the field. The proxy index could either remain as L_{AF90}, or otherwise the most advantageous index could be determined from further study.
  - The use of a relative impact threshold (ie, assessing the wind turbine sound level relative to background sound levels) is not firmly supported by the research evidence identified. Although some influence of the residual sound environment on subjective responses is expected, only indicative evidence appears to be available at present, and further research to review and quantify this effect would be valuable. On the other hand, the relevance of using a relative impact margin in the context of the increasing size of turbines has been questioned in the stakeholder engagement. This is because larger turbines may reach rated power while wind speeds at ground level remain relatively low, which could mean that wind-induced sound at receptors could be negligible. In these cases, it would be simpler to assess impacts against absolute thresholds, and the potential benefits of this approach should also be explored.
- The research also indicates that the common application of the ETSU-R-97 noise limits as a binary test of acceptability is considered to be inconsistent with the wider policy frameworks in England and Northern Ireland:
  - The approach in the NPSE, NPSNI and the NPPF is based on a hierarchy of effects thresholds, the different levels of which determine how impacts are to be addressed by mitigation, within the context of guiding principles on sustainable development; this is not represented in the ETSU-R-97 assessment method, which is commonly applied as a pass/fail system of noise limits.
  - The application of ETSU-R-97 is not necessarily inconsistent with wider policies in Scotland or Wales, although it is noted that relevant policy and guidance documents in both countries are in the process of being updated. These updates would need to be kept under review to consider ongoing consistency and compatibility with any new guidance developed.

7.1.2 THE APPROACH TO CONTROLLING THE IMPACT OF AM

- The research indicates that the current guidance does not fully address the potential impact of AM in wind turbine sound. The evidence identified in this study suggests that the assumptions about AM adopted in ETSU-R-97 do not adequately represent the nature of AM as experienced and measured. This study has identified evidence that could be used to develop a suitable control for AM, and stakeholder views indicate that official guidance on this issue would be welcomed:
  - It has been shown that it is possible to simulate AM occurring at long ranges using computationally intensive numerical and analytical methods that incorporated coupled source and propagation models. These simulations have provided substantial insights and evidence that AM over long ranges can be influenced by a wide range of complex and interconnected factors, including operational, atmospheric and topographical variables. However, these types

of models require highly detailed information on a wide range of parametric inputs, and are likely to be very sensitive to the model assumptions. This indicates that reliable predictions of AM in the context of development planning and noise assessment guidance are unlikely to be practically feasible in the near future.

- This study has identified a range of methods of detecting and measuring AM in wind turbine sound. At present the most advantageous appears to be the IOA Reference Method, and application of this approach in future guidance is supported by the stakeholder engagement responses. There may be modifications that could be made to the Method to refine or clarify some aspects of its implementation, and this should be considered further.
- Research on the effects of AM demonstrate that its audibility increases adverse impact, but the effect is secondary compared with the overall sound level. This indicates that a character penalty is a suitable control approach, and proposed penalty schemes are evident in the literature. A study should be undertaken to confirm the most effective approach. The practical application of the scheme in terms of compliance measurements would also require careful consideration and guidance.
- Responses to the stakeholder engagement indicate that turbine suppliers are aware of the importance of ensuring that operational mitigation for AM is available on modern turbines.

7.1.3 OTHER ASPECTS

Several other aspects have been identified during this study as potentially benefitting from review and updates against the current state of understanding, primarily from the stakeholder engagement exercise. The main aspects are summarised in section 7.2, however future guidance development should also include review and consideration of the other suggestions made during the stakeholder engagement, as detailed in sections 4.2, 4.3, 4.4 and Appendix C3 section 12.2, and as discussed in section 6.

7.2 SUMMARY OF STUDY RECOMMENDATIONS

The recommendations of this study are summarised in Table 7-1, with the recommendations addressing the two main issues identified highlighted with light green shading.

In making these recommendations, we recognise that the delivery of further work is dependent upon a range of factors and constraints, and that the parties best placed to promote and progress the work may depend on its nature and scope, the availability of funding, and any wider potential benefits that might be associated with their involvement.

Table 7-1: Summary of study recommendations

Recommendation	Rationale and justification	Supporting evidence and information
A review and update of the current guidance should be undertaken.	The review has identified that evidence on relevant aspects of wind turbine sound has expanded and improved in quality since the guidance was developed.	Sections 3.4, 3.5.1
	The engagement exercise confirmed that the majority (28 / 31) of respondent stakeholders agree that the current guidance requires updating, with a roughly even split between those who think some updating or amendment is required, and those whose view is that it requires substantial revision.	Section 4.2.3
	The evidence review and the stakeholder engagement were largely consistent in identifying the primary issues with the current guidance:	
	▪ The ETSU-R-97 noise limits are based on outdated or insubstantial evidence.	Sections 3.5.1, 4.2.3, 6.2, Appendix B sections 9.1.1, 9.2.1
	▪ The current guidance does not adequately address the adverse impact of amplitude modulation (AM), which increases noise annoyance, and is an expected characteristic of wind turbine sound immissions.	Sections 3.3.2, 3.5.1, 4.2.3, 6.3.2, Appendix B sections 9.1.2, 9.2.2
The review and updates should address the main areas identified as a priority, and should also consider the range of other issues and suggestions raised during this study, including:		

Recommendation	Rationale and justification	Supporting evidence and information
▪ A systematic review and meta-analysis of noise effects evidence on noise annoyance and sleep disturbance should be undertaken, with the aim of developing a robust framework of effects thresholds on which to base controls for wind turbine noise, which is consistent and compatible with wider national policy frameworks on noise. The review should include consideration of the influences of personal and contextual factors on subjective responses.	▪ Noise policy frameworks in England and Northern Ireland are based on 'observed effects levels' (effects thresholds).	Section 1.1.1
	▪ The quantity and quality of available evidence is now thought to be sufficient to obtain meaningful results from a meta-analysis of studies of wind turbine noise annoyance, and possibly also sleep disturbance.	Sections 3.5.1, 6.2.3, Appendix B section 9.2.1
	▪ Existing controlling values and guidelines for wind turbine sound levels are based on evidence and guidance that is outdated and may be unreliable.	Sections 6.2.1, 6.2.2, Appendix B section 9.2.1
	▪ The way in which ETSU-R-97 noise limits are applied in common practice is inconsistent with the wider framework of noise policies in England and Northern Ireland.	Sections 4.2.3, 4.3, 6.2.1
▪ Meta-analysis of exposure-response relationships for wind turbine sound should carefully consider the inter-study variation in methodologies for exposure and response estimations, and, where necessary, develop robust normalisation procedures to avoid combining or comparing data that use differing scales.	▪ The evidence review identified that varying exposure estimation and response modelling procedures are used in different studies.	Section 3.4
	▪ It has also been shown that these methodological differences have non-trivial implications for the exposure-response relationships developed.	Sections 3.4.2, 6.2.1
	▪ Some previous studies and guidance have combined or compared exposure-response relationships that are based on differing scales, which could be misleading.	Sections 3.5.1, 6.2.1, 6.2.2

Recommendation	Rationale and justification	Supporting evidence and information
▪ The existing WHO guidelines should not be used as a basis for developing a framework of effects thresholds for wind turbine sound.	▪ The evidence reviewed in WHO guidance up to and including 2009 did not include wind turbine sound, and it is widely recognised that different sound sources impart varying effects.	Section 6.2.2
	▪ The 2018 WHO ENGER made a 'conditional' strength recommendation on noise annoyance from wind turbine sound, which was based on a direct comparison of exposure-response functions from studies that employed differing methods, which consequently may be misleading.	Sections 3.5.1, 6.2.2, Appendix B section 9.2.1
	▪ The evidence reviews supporting the 2018 ENGER included studies up to 2014-15; the quantity and quality of studies have expanded since the reviews were completed.	Sections 3.5.1, 6.2.2, Appendix B section 9.2.1
▪ A study should be undertaken to (i) consider the relative impact control approach and whether this should remain a component of wind turbine noise assessment, and (ii), if it is to be retained, to identify effects thresholds, either in existing evidence, or otherwise gather new evidence (eg, via experimental testing) to support the approach.	▪ The ETSU-R-97 relative limit, and the relative impact assessment approach, appears to be historically based on consensus opinion, but has not been supported by scientific evidence.	Sections 3.5.1, 6.2.1, Appendix B section 9.2.1
	▪ Nonetheless, some emerging evidence on wind turbine sound masking does indicate that an influence of relative levels may be expected, although the potential magnitude of this effect has not been firmly established and may be smaller than previously assumed.	Sections 3.5.1, 6.2.1, Appendix B section 9.2.1
	▪ It is unclear whether a relative impact approach remains appropriate for the increasing size of turbines, which is connected with the background sound levels at which wind turbines are operational.	Sections 4.2.3, 4.4, 6.5.2

Recommendation	Rationale and justification	Supporting evidence and information
▪ A more detailed review of overseas national and regional wind turbine noise guidelines should be undertaken to provide context for decisions on the policy balance between noise control and enabling renewable energy development (to achieve Net Zero), which should also ensure that underlying scientific evidence and professional judgements are identified (and any guidelines for which evidence or judgements are unclear should be treated with caution).	▪ This study has provided an outline review of overseas national and regional guidelines, mainly extracted from secondary literature sources; a further review could confirm the details from the primary documents, and identify the underlying rationale, including scientific evidence and professional judgements. ▪ Some territories are in the process of developing new guidelines, which may provide helpful information for development of UK guidance.	Sections 3.5.1, Appendix B section 9.1.1 Section 3.5.1
▪ A UK-based observational study of effects of wind turbine sound exposure should be undertaken, including investigation of rural areas, the influence of prolongation and intermittency of exposure, and the impact of AM.	▪ There is very little UK-based evidence from observational studies of effects of wind turbine sound exposure. ▪ It is expected that subjective responses to wind turbine sound will be influenced by local circumstances and attitudes. ▪ There is very little evidence on the influence of prolongation and intermittency of exposure to wind turbine sound and effects. ▪ There is also very little evidence on AM impacts from observational studies (most of the evidence on responses to AM comes from experimental studies).	Sections 3.5.1, 3.5.2, 6.2.3, Appendix B section 9.2.1 Sections 3.5.1, 3.5.2, 4.3, 6.2.1 Sections 3.5.2, 4.4, 6.2.3, 6.4.7 Sections 3.5.1, 3.5.2, 6.3.2, Appendix B section 9.2.2

Recommendation	Rationale and justification	Supporting evidence and information
▪ Controlling values for noise during the night should not be higher (ie, less stringent) for night-time than during the day.	▪ This feature of the ETSU-R-97 noise limits appears to be unique to the UK and Ireland (which implements wind turbine noise guidance developed from ETSU-R-97).	Sections 3.5.1, 6.2.1, Appendix B section 9.1.1
	▪ AM prevalence is typically greater at night, which, combined with the higher minimum limit means overall night-time impacts could be increased compared with daytime.	Sections 3.5.1, 6.3.2, Appendix B section 9.2.2
▪ Consideration should be given to how to use noise controls to ensure that developments are prioritised according to renewable energy capacity value.	▪ The stakeholder engagement highlighted that the current guidance may result in larger, more valuable development proposals being made unviable due to the noise impact of smaller, less valuable, developments.	Sections 4.2.3, 4.4, 6.4.3
▪ Further clarification on the interpretation of 'financially involved' receptors for the application of noise controls, along with relevant examples, should be provided.	▪ The evidence review highlighted that some evidence supports the notion that financial involvement or direct economic benefits are associated with reduced annoyance.	Sections 3.5.1, 6.2.1, Appendix B section 9.2.1
	▪ The stakeholder engagement highlighted that some LPAs consider further guidance on the extent, nature and implications of financial involvement is required.	Sections 4.2.3, 4.4, 6.2.1

wsp

Recommendation	Rationale and justification	Supporting evidence and information
▪ A study should be undertaken to determine the most effective way to control the impact of AM, which should be based on the IOA Reference Method for measuring AM – the method itself should be reviewed in light of any refinements proposed (eg, by the IEC 61400-11-2 working group, or in relevant research).	▪ The evidence review and the field measurements indicate that AM is an expected characteristic in wind turbine sound immissions.	Sections 3.5.1, 5.5, 5.6, 6.3.2, Appendix B section 9.2.2
	▪ The evidence review indicates that AM increases adverse impact, that AM can be reliably and practically measured using the IOA metric, that a character penalty scheme is justified by the evidence, and that evidence-based schemes have been proposed.	Sections 3.5.1, 6.3.2, Appendix B section 9.2.2
	▪ The details of application of a suitable scheme in practice have also been considered, but need to be determined in relation to new guidance on the overall approach to assessing compliance with wind turbine noise controls.	Section 6.3.2
	▪ Some refinements to the IOA Reference Method have been proposed, for example it is known that the IEC 61400-11-2 working draft (which addresses measurements of wind turbine sound at receptor locations) currently includes the method, with some modifications.	Sections 3.5.1, 6.3.2, Appendix B section 9.2.2
▪ A review of methods for evaluating tonality characteristics in wind turbine sound should be undertaken, with the aim of establishing the most effective approach (this review should also consider the advice of the IEC 61400-11-2 working group).	▪ It was highlighted in the stakeholder engagement that methods for evaluating tonality have advanced since ETSU-R-97 and these should be reviewed.	Sections 4.2.3, 4.4, 6.4.6, 6.5.1
	▪ The IEC 61400-11-2 working draft (which addresses measurements of wind turbine sound at receptor locations) includes a method that is different to the ETSU-R-97 approach.	Sections 6.4.6, 6.5.1

Recommendation	Rationale and justification	Supporting evidence and information
▪ A review of the approach to compliance determination should be undertaken, to consider: (i) how these could be made less complex while also providing increased confidence in outcomes; (ii) the suitability of establishing a proxy measurement location approach, and (iii) how to address the challenges posed in cumulative situations.	▪ The evidence review and stakeholder engagement highlighted concerns about the difficulties of compliance determination process, which is considered to be complex, and costly, and in some cases the outcomes are not clear or not agreed by relevant parties. ▪ It was also noted in both the evidence review and the stakeholder engagement that cumulative situations increase the complexity of assessments and compliance determinations further, presenting particularly challenging issues. ▪ The potential benefits of using proxy measurement locations nearer to wind turbines were raised in the evidence review and the stakeholder engagement, and are known to be used in some overseas regulations.	Sections 3.3.3, 4.2.3, 4.4, 6.4.1, Appendix B section 9.1.3
▪ Further guidance on assessing and controlling cumulative impacts should be developed, incorporating existing evidence and best practice advice.	▪ It was highlighted in the stakeholder engagement and the evidence review that cumulative assessments and compliance determination are complex and difficult, and further guidance would be valuable.	Sections 3.3.3, 4.2.3, 4.4, 6.4.2, Appendix B section 9.1.3
	▪ The stakeholder engagement suggested that the increase in wind energy development density may have led to more sustained noise impact for situations in which receptors have become 'encircled' by turbines.	Sections 4.2.4, 4.4, 6.4.2
	▪ It was also noted in the stakeholder engagement that further best practice advice has been proposed following the IOA GPG, and this could be incorporated into new guidance.	Sections 4.2.3, 4.2.4, 6.4.2

Recommendation	Rationale and justification	Supporting evidence and information
▪ A review of the approach to measurement data aggregation and analysis should be undertaken, to ensure the methods used are statistically robust, and adequately account for uncertainty.	▪ The evidence review highlighted concerns raised about the potential for the aggregation of measured sound levels to lead to underestimation of noise impact. ▪ It was also noted in the evidence review that the statistical methods recommended in the guidance may not be sufficiently rigorous, and differences of application may introduce uncertainty into assessments that is not considered. ▪ Concerns were also raised in the stakeholder engagement that uncertainty may not be adequately addressed in the current guidance. ▪ Some aspects of sound prediction uncertainty are considered in the guidance, but further consideration and guidance on uncertainty in other parts of the assessment may be needed.	Sections 3.3.3, 6.4.4, Appendix B section 9.1.3 Sections 4.2.3, 6.4.4, Appendix C section 12.2.1 Section 6.4.4
▪ Further guidance on sound and weather measurements should be developed, based on a review of research and available technology.	▪ The evidence review and stakeholder engagement highlighted that sound level meter microphone wind shield specifications, sound level meter self-noise, and weather instrumentation positioning are particular aspects that may require additional guidance. ▪ The IOA GPG explicitly recognises that further research and guidance is needed on wind shielding devices used for measurements. ▪ Research has been undertaken examining the use of various microphone wind shielding devices for wind turbine sound measurements, which should be considered.	Sections 3.3.3, 4.2.3, Appendix C, 12.2.1 Section 6.4.5 Section 6.4.5

Recommendation	Rationale and justification	Supporting evidence and information
▪ A review of evidence on wind turbine sound predictions should be undertaken, with the aim of (1) identifying the most effective methods for predicting sound propagation over (a) bodies of water and (b) concave terrain profiles, and (2) considering whether further evidence on directivity of turbine sound emissions in varying wind conditions indicates that updates may be required to the existing guidance.	▪ The propagation aspects of wind turbine sound predictions (topics 1a and 1b) were highlighted in the stakeholder engagement as requiring further attention. ▪ Research on these topics (1 and 2) has been published since the IOA GPG (which addressed these aspects).	Section 6.4.8, Appendix C section 12.2.1 Section 6.4.8
▪ Consideration should be given to including a clear position statement in guidance confirming the intended policy balance between protection from noise impact, and enabling of renewable energy development (to achieve Net Zero), linked with the wider policies that underpin the government approach to noise management. Such a statement should be supported by a 'what if' scenario study undertaken to consider the potential outcomes of selecting different approaches or controlling values for noise assessment.	▪ The value of a 'policy balance statement' was highlighted in the stakeholder engagement. The main benefit of such a statement would be management of expectations: it would be made clear that some adverse impact from wind turbine noise may be expected, and would not be prevented by the planning system, if the balance of impacts and renewable energy meets with the relevant policies. ▪ With suitable assumptions, effective collaboration, and sensitivity testing of an appropriate range of scenarios, a scenario study could provide a defensible basis for a policy balance statement, and for taking decisions on the various aspects of the assessment approach that require updating.	Sections 4.2.3, 4.2.5, 4.4, 6.1.1
▪ Consideration should be given to including a clear position statement on wind turbine infrasound in guidance (research in this area is known to be ongoing, and such a statement should be reviewed against further evidence when published).	▪ The evidence review indicates that infrasound from wind turbines at typical exposure levels has no direct adverse effects on health. ▪ Some stakeholders suggested that a position statement on infrasound would be helpful for assessors and decision takers to understand the appropriate scope of wind turbine noise assessments.	Section 3.5.1, Appendix B section 9.2.1 Section 4.4, Appendix C section 12.2.1

Recommendation	Rationale and justification	Supporting evidence and information
▪ Consideration should be given to whether specific guidance for smaller wind turbines should be developed.	▪ The stakeholder engagement highlighted that small and single turbine installations are a particular concern in Northern Ireland, and the current guidance does not cover small turbines.	Sections 4.2.3, 6.4.9
▪ Consideration should be given to the range of other suggestions made by stakeholders during the engagement exercise.	▪ A wide range of suggestions for updates were made in the engagement, some of which it has only been possible to briefly touch upon in this study.	Sections 4.2, 4.3, 4.4, Appendix C section 12.2
Development of new or updated guidance should consider the following suggestions to manage the updates and long-term maintenance:		
▪ the formation of a working group comprising representatives of a range of stakeholder organisations to lead the development of guidance	▪ It was highlighted in the stakeholder engagement that a collaborative approach to guidance development could help to speed up the process (an example given of a longer process thought to be associated with a less collaborative approach was the revision to the Ireland Wind Energy Development Guidelines, which it was noted has been ongoing since 2013).	Sections 4.2.5, 4.4
▪ the separation of the 'policy position' (addressing the balance between controlling noise impact and enabling renewable energy development), 'technical guidance' (application of the assessment approach), and 'technical justification' (the supporting evidence) into discrete, linked documents	▪ It was suggested in the stakeholder engagement that separation of these parts would help to ensure that updates can be made to technical guidance and supporting evidence more quickly without the need to address the policy balance. ▪ It was also suggested in the stakeholder engagement that the existing guidance is too discursive, and separating the supporting evidence would improve clarity and brevity, while retaining the justifications for the approach taken.	Sections 4.2.5, 4.4
▪ the introduction of a guidance review programme (suggestions for periodic reviews were in the range 2-5 years)	▪ It was suggested in the stakeholder engagement that this would help to keep technical guidance up to date with developments in the scientific evidence.	Sections 4.2.5, 4.4

7.3 STRENGTHS AND LIMITATIONS

This study has several strengths, but also should be considered in the context of its limitations, both of which are discussed in this section.

Overall, the design of the study has benefitted from the incorporation of multiple workstreams, which allowed a wide range of evidence, views and experience from academia, industry, national government, local authorities and (to a limited extent) wind farm neighbours to be considered. This also enabled a 'triangulation' approach to developing the study conclusions, which considers where the findings from each workstream are consistent with those of the other study components.

7.3.1 EVIDENCE REVIEW

The evidence review has been based on a formal systematic approach, which ensures rigorous literature searching and screening procedures, reducing the risk of overlooking important information. Nonetheless, it is recognised that the QSR methodology followed specifically precludes systematic evaluation of quality or risk of bias in the reviewed publications, which is a limitation of the approach. In the social field surveys that underpin many epidemiological community noise effect research studies, self-selection bias[546] is always a potential risk. However, the second stage of the review has been focussed on black literature, which should inherently provide a level of assurance on the quality of the study designs and publications, as these have already undergone an independent peer-review process. On the other hand, it is also recognised that a focus on black literature can raise the risk of publication bias[547], however, this risk is reduced by the inclusion of grey literature in the first stage of the review. This approach to the evidence review is consistent with the project scope, aims and constraints. The absence of quality and bias risk evaluation of each publication can (and should) be addressed in further review work, which could use the information from this QSR as its foundation. This would be facilitated by the systematic map developed during this project, which can be straightforwardly expanded according to the scope of any further study undertaken.

Epidemiological research into the effects of wind turbine noise is a relatively emergent field of study, when compared with other areas of environmental noise, such as transportation. In particular, this study has identified a lack of research undertaken in the UK, and, while a greater volume of evidence is available from studies undertaken overseas, there is uncertainty in the applicability of these studies to the UK.

Similarly, consideration of existing guidance on managing wind turbine noise, both domestic and overseas, must be informed by the awareness that any supporting scientific evidence could be relatively weak, and in many cases, the main foundation for published guidance may have been primarily formed from professional judgements.

In any field of scientific research, the findings of studies vary and are not definitively consistent. The field of wind turbine acoustics and noise is no exception to this. This review has sought to highlight those aspects for which the evidence is relatively consistent, while also acknowledging areas in which there remains considerable scientific debate or uncertainty. Studies of human responses to

[546] Bias representing the tendency for individuals or sub-groups of study populations sharing certain characteristics to volunteer to participate, resulting in non-random sampling. For example, people who feel negatively impacted by wind turbines, or those who have positive attitudes to wind energy, may be more motivated to respond to a survey addressing wind turbine noise guidance than other people.

[547] Bias representing the tendency to only publish interesting or 'positive' research results; results showing 'no effect' potentially remaining unpublished.

external stressors typically observe considerable variation between individuals, and this is found to be the case with the evidence concerning wind turbine sound exposure. There are multiple, complex elements that may contribute to this uncertainty, including varying study methods and controls, and it must be recognised that responses to sound or noise naturally vary widely, depending on a broad range of personal and contextual factors.

7.3.2 STAKEHOLDER ENGAGEMENT

The stakeholder engagement offered both online and offline response access options, supported by follow-up communications encouraging stakeholders to respond, both of which would be expected to have contributed to response rates. However, it is acknowledged there are several limitations to the engagement survey and responses:

- The response rate for LPAs was relatively low, at 10%. There are several factors that may have contributed to this, including the time of year of the survey (which partly coincided with the school summer holiday period), as well as the larger overall number of LPAs invited to respond, compared with other stakeholder types (204 LPAs comprised ~88% of the invitee sample). The response rate may indicate a potential for bias in responses, for example, LPAs with negative experiences with onshore wind energy developments may have been more motivated to respond than others. On the other hand, (as discussed in section 4.2.2) for Scotland and Northern Ireland, examination of recorded data for onshore wind energy installations indicates that the respondent LPAs tended to represent those geographic areas with a greater density of wind turbine developments. This suggests that, for these devolved administrations, it tended to be LPAs with the most experience of onshore wind energy developments that responded to the survey. This is less clear for respondent LPAs in England, within which onshore wind energy developments tend to be more sparsely distributed, while no LPAs in Wales responded to the survey invitation.
- There was relatively little engagement achieved with stakeholders representing Wales, the possible reasons for which are unclear. Further efforts to engage with stakeholders in Wales may therefore be worthwhile, given the growth in onshore wind generation capacity in Wales, and in view of the evolving Welsh Government guidance and policy landscape.
- The project steering group suggested additional governmental and non-governmental stakeholders for inclusion in the stakeholder sample, which included one civic group. Other civic groups, that may have presented a diversity of public experiences and attitudes towards wind energy, were not included. Therefore, it may be beneficial for future engagement to seek views from a wider range of civic groups.
- As noted in section 4.5, the survey questions asked respondents to identify the updates they considered to be required to the existing guidance, but did not explicitly ask them to identify aspects they felt were already effective – rather, this was implicit in the responses when topics were not selected as requiring updating. However, it is acknowledged that the design of the questions may have encouraged respondents to focus more on negative aspects of the existing guidance than on positive aspects. Nonetheless, some respondents did highlight areas they felt were addressed effectively by the existing guidance in their free text responses. Moreover, including additional parts in the survey could have adversely affected response rates, due to increasing the effort required to respond.

The engagement interviews provided a constructive discussion environment that helped to clarify and expand the responses received from the interviewed stakeholders. The project constraints limited the numbers of stakeholders that could be interviewed. Future such work could partially overcome this limitation by organising workshops with multiple stakeholders, which may also offer the benefit of collaborative synergy and consensus-building. However, it should also be borne in mind that this kind of format can introduce the risk that some stakeholders may be less willing to offer their honest opinions in the presence of other parties.

7.3.3 FIELD MEASUREMENTS

Project constraints limited the scope of the field measurements, both in duration and geographic extent. This means that the results, when considered in isolation, are not generalisable, either to other locations, types of wind turbine installation, or as a typical, best-case or worst-case representation of the conditions at each measurement location.

As noted in section 5.2, the approach taken only provides a snapshot of AM at the sites during the surveys, and not a dataset that could be used to draw wider conclusions about prevalence of AM in general, or to provide definitive evidence on the association of AM with particular turbine designs or ages. Nonetheless, the data is informative when considered alongside the results of other longer-term measurement campaigns (identified in the literature evidence), with which some consistencies have been observed. Furthermore, the data provides insight into the form of AM that may be emitted by wind farm sites in the UK, as well as demonstrating a suitable method for detecting and quantifying AM.

Appendix A

GLOSSARY

8 APPENDIX A: GLOSSARY

This section provides a glossary of technical terms and symbols used in the report. A list of Abbreviations can be found in the main report front matter.

Table A-1: Glossary

Term	Definition or meaning
Ambient sound (level)	Ambient sound is the total sound environment considered at a given location. In the context of a noise assessment, the ambient sound comprises the specific sound of the source under assessment, and the residual sound. The ambient sound level is normally evaluated in terms of the L_{Aeq}.
Amplitude modulation, AM	In the context of wind turbine acoustics, this normally refers to a periodic variation in the sound level of the broadband spectrum of the aerodynamic sound.
Angle of attack, AoA	The angle between a wind turbine blade (or aerofoil) chord line and the relative incoming flow vector (ie, the vectorial combination the incoming wind vector and the blade or aerofoil motion vector). The AoA can be changed by modifying the blade pitch angle, but the AoA is wind speed-dependent (whereas the pitch angle is not). The angle of attack has a direct influence on the turbine sound emission and controls the risk of blade stall occurring.
A-weighting, C-weighting and Z-weighting	Frequency weighting functions that emphasise particular frequencies over others. A-weighting is intended to approximate the perception of loudness by the ear, and was originally developed from the 40 phon equal loudness contour for pure tones derived by Fletcher and Munson. Comparison with the standardised pure tone equal loudness contours in ISO 226:2003 (which are derived from a more recent and larger database of measurements) indicates that A-weighting corresponds more closely with the 60 phon curve. C-weighting is sometimes said to approximate the hearing response to loud sounds, but comparison with the ISO 226:2003 equal loudness contours indicates this is an inaccurate characterisation, especially at low frequencies. Since C-weighting places greater weight on low frequencies than A-weighting, it is sometimes used to evaluate sounds that have a spectrum with a relatively high proportion of low frequency energy. However, in general, it does not provide a more accurate or reliable approximation to perceived loudness than A-weighting. Z-weighting is 0 dB weighting at all frequencies, ie unweighted sound levels.
Background sound (level)	The background sound level is the residual sound evaluated using the L_{AF90} index. The sound represented by the background sound is therefore those elements of the residual sound that persist throughout 90% of the evaluation interval (ie, the 10^{th} percentile of the cumulative distribution of the sound pressure levels measured with Fast time-weighting).

Term	Definition or meaning
Blade stall	An aerodynamic condition that occurs when the boundary layer on a wind turbine blade (or aerofoil) separates from the surface of the blade, which generates turbulence towards the rear of the blade and trailing edge, and a loss of lift force across the blade, leading to reduction in the torque. Blade stall can affect portions of the blade, as its occurrence is dependent on the angle of attack, which generally varies along the length of the blade.
Boundary layer	The 'transition zone' between the free stream in fluid flow and the surface of an object in the flow (eg, an aerofoil) is the boundary layer. In the boundary layer the flow velocity is affected by the object, the surface of which imposes drag forces, which slow the flow velocity, and can create turbulent eddies.
Broadband	A wide range of sound frequencies.
C-weighting	See 'A-weighing and C-weighting'
Decibel, dB	The logarithmic decibel scale is used to quantify sound. The decibel scale compares the magnitude of a sound relative to another (reference) magnitude, and takes the logarithm of the ratio. The human ear can detect a wide range of sound pressures, typically between 2e-5 and 200 Pa, so the logarithmic scale is used to quantify this range using a more manageable set of values.
Disability weight	A scale factor indicating the severity of a health outcome, which ranges from 0 (full health) to 1 (death). Disability weights are used to estimate the equivalent years of (full) healthy life lost in 'burden of disease' studies, such as those undertaken by the WHO, and in health cost-benefit analyses, such as the approach defined in the UK Government Transport Analysis Guidance.
Emission, sound emission	The sound emitted by a source (resulting in immissions at a receptor location).
Free field, free-field	A sound field comprising only waves arriving directly from the source(s), with no incident waves arriving as reflected sound. In practice, the sound field generated over an acoustically reflective (or partially reflective) ground surface is also commonly described as 'free-field'. In that case, the definition extends to allowing incident wave reflections from the ground surface only.
Immission, sound immission	The sound incident at a given receptor location (resulting from the sound emitted by a source).
Impulsivity	A sound characteristic associated with sudden changes in sound level, such as 'banging', 'clattering', 'clicking' etc.
Infrasound and low frequency sound	Infrasound is commonly considered as acoustic vibrations with frequencies <20 Hz, for which the hearing system is increasingly insensitive. 20 Hz is often considered the onset of the 'audible' frequency range, however, sounds below 20 Hz may be audible at sufficiently high levels. Low frequency sound may be considered as overlapping the infrasonic and 'audible' frequency ranges over ~10 Hz to ~200 Hz.

Term	Definition or meaning
Least squares regression	One method of fitting a regression model to data. Least squares involves minimising the sum of the squared 'residuals', which are the differences between the modelled relationship and the observed data. Least squares techniques can be applied to both linear and some nonlinear regression models.
$L_{eq,T}$, $L_{Aeq,T}$, energy time-averaged sound level	A sound level measurement index, which averages all of the sound energy in a period over the measurement time *T*. One useful property of the energy time-averaged sound level is that measurements made over shorter, contiguous intervals can always be accurately and straightforwardly combined to produce the values for longer intervals, while retaining the total sound energy. Due to its energy-averaging, the $L_{eq,T}$ value for a fluctuating sound will vary depending on the duration of the measurement time interval, whereas a continuous sound with negligible fluctuation will produce a constant L_{eq} value that is insensitive to the measurement time *T*. For this reason, the '*T*' is sometimes omitted, which typically implies that the duration is unimportant in the value specified. An example of this is found in predictions of wind turbine sound energy time-averaged levels, which produce an L_{eq} output based on an assumed constant sound power level (per wind speed), which is insensitive to the measurement duration.
Level envelope	The envelope of a signal describes its variation in amplitude over time, and 'encloses' the signal levels.
Linear and non-linear regression	Regression is a process of estimating the expected relationships between variables based on data representing the values of variables. Linear regression is a method of regression analysis that uses a linear function to model the relationship, in the sense that the terms of the model function are linear, ie the function is the sum of products of coefficients with the independent variables. The simplest linear regression model is a straight line (known as an 'affine function'). Polynomial regression is a special case of linear regression, since it is also linear in its combination of coefficients. Non-linear regression uses a model that is based on a function in which the coefficients are not combined linearly; a simple example of a nonlinear regression model is exponential regression, in which terms are raised to the power of a variable. Some simple exponential models can be approximately solved using linear regression, by applying a log-transformation to the function. In general, nonlinear models are fitted to data using iterative numerical procedures.
L_{min}, L_{max}, L_{AFmin}, L_{AFmax}, L_{ASmax}, minimum sound pressure level, maximum sound pressure level	These are special cases of the percentile sound levels, and represent the lower and upper bounding values of the cumulative distribution function of the sound pressure levels measured in a given period.
L_N, L_{AN}, L_{AFN}, N% exceeded sound level, (100-N)th percentile sound level (eg, L_{AF90}, L_{AF50} etc)	The N% exceeded sound level is family of measurement indices that are derived from the cumulative distribution function of the sound pressure level values during the measurement period. In statistical terms, the value at 'N% exceeded' is represented by the (100-N)th percentile of the distribution. Indices in common use include the '90% exceeded' level L_{AF90} (ie, the 10th percentile of the A-weighted, Fast time-weighted sound pressure levels), which is often used to characterise the 'background sound level'.

Term	Definition or meaning
Logistic regression	Logistic regression is a type of 'generalised linear model' (of which linear regression is another type). Logistic regression fits a logistic function to data, and is most commonly used for dependent variables that have binary distributions (eg, pass or fail, annoyed or not annoyed, etc). It can also be used with ordinal (multiple categorical) variables (eg, not / a little / moderately / very / extremely annoyed).
Low frequency sound	See 'infrasound and low frequency sound'.
Masking sound, sound masking	The human perception of a sound is affected by the presence of other audible sounds. Sound can provide masking for other sounds that would otherwise be more clearly perceived. A masked sound may appear less distinct or may even not be detectable at all by a listener when a masking sound is present. In some situations, such as wind farms with residential neighbours, some masking sound (such as wind blowing through local vegetation) may be desirable.
Modulation depth, AM depth	The depth of amplitude modulation in a signal with a periodically varying level is a measure of the range between the highest (peak) and lowest (trough) sound levels. In real signals, the peak and trough levels vary and there is no agreed definition in this context. Typically for wind turbine sound, the modulation depth is taken as the peak-to-trough level difference ΔL (dB) between the L_{pAF} level envelope, or the 'short term' L_{Aeq} integrated over contiguous 50-125 ms periods. As the peak/trough levels will typically vary, the overall 'modulation depth' within an interval is sometimes established via a statistical method, eg arithmetic averaging of the peak-trough level differences. If the signal has greater modulation in certain parts of the frequency spectrum, the signal may first be band-pass filtered to derive a modulation depth in the relevant spectral range. Comparisons of 'modulation depths' must be made with caution, as there is no agreed definition. The sound level parameter used to derive modulation depth must be identical for reliable comparability between different signals.
Modulation frequency	The number of times within a second that the amplitude fluctuates over the observed cycle, ie from maximum to minimum and back to maximum. The period of modulation is the reciprocal of modulation frequency, ie the length of time between two amplitude peaks in a periodic modulation cycle.
Noise	Sound that is subjectively judged to be undesired in a given context.
Octave band, third-octave band	A sound consisting of more than one frequency can be described using a frequency spectrum, which shows the relative magnitude of the energy in the different frequencies within it. The possible range of frequencies is continuous, but can be split up into discrete bands, often an octave or third-octave in width. Each band is referred to by its centre frequency, e.g. (for octave bands) 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz etc. Separation of the spectrum in this way is typically implemented via band-pass filters.

Term	Definition or meaning
p-values (probability values)	In statistical hypothesis testing and regression analysis, it is common for results to be expressed using *p*-values. In a hypothesis test, the *p*-value represents the probability of obtaining the observed result, or a more extreme one, assuming that the null hypothesis is true (ie, that the dependent variable or outcome is not associated with the independent variable investigated). In a regression analysis the *p*-value is often determined in a hypothesis test of the correlations between dependent and independent variables. Traditionally, the *p*-value is used to test the 'statistical significance' of the hypothesis test result. Most commonly, a *p*-value <0.05 is interpreted as indicating that the null hypothesis (no association) can be rejected, and that the result indicates 'statistical significance'. Increasingly, the statistics community has cautioned against the common use of *p*-values as the marker of statistical significance, and the American Statistical Association published a statement in 2016, with a follow-up commentary in 2019, arguing that this approach distorts scientific process and should be abandoned. Nonetheless, this application presently remains common practice, and the overwhelming majority of the studies considered in this report adopt the traditional approach and interpretation of *p*-values as an indicator of the statistical significance of observed results.
Periodic, periodicity	A sound wave with a repeating form can be described as periodic. The level of a sound with periodic amplitude displays a regular fluctuation, although the peaks and troughs in the level may still vary.
Pitch angle	The angle between a wind turbine blade chord line and the rotor plane. The pitch angle can be used to modify the angle of attack, however the pitch angle is not dependent on the wind speed (whereas the angle of attack is wind speed-dependent). For a constant wind speed, increasing the blade pitch angle will reduce the angle of attack, which reduces sound emissions and also reduces the risk of blade stall.
Pitch control	Pitch controlled turbines allow the pitch angle of the blades to be adjusted to modify the angle of attack, achieve optimum power, and maintain the rotation speed of the turbine within its design limits.
Residual sound	Residual sound is the component of the total ambient sound that does not include the specific sound from the source being assessed. The residual sound level is normally evaluated in terms of the L_{Aeq}.
RMS, root-mean-square	Acoustic pressure waves comprise perturbations of air pressure, and the instantaneous pressure values at any given point in space therefore take positive and negative values around the mean, which is the steady local atmospheric pressure. To represent a meaningful amplitude, it is necessary to square the values (to make all values positive), calculate the mean (over some time interval), and take the square root of the result. The acoustic energy (or power, for finite signals) can be described by the mean-square of the pressure amplitude. The square root reduces the mean-square value to linear (amplitude), rather than squared, units.
Signal-to-noise ratio	The level difference between a target sound (the 'signal'), and a masking or contaminating sound (the 'noise'). Typically, this would be determined by the difference in the energy time-averaged sound levels.

Term	Definition or meaning
Sound pressure level, L_p	The sound pressure level is expressed in decibels, and compares the acoustic pressure of a sound to the smallest acoustic pressure normally perceptible by the human ear, which is taken as the reference pressure. It is defined as follows: $$L_p\ (dB)\ =\ 10\ \log_{10}\left(\frac{P}{P_{ref}}\right)^2$$ Where P is the root-mean-square sound pressure (in Pascals, Pa), and P_{ref} is the reference pressure 2e-5 Pa. L_p of 0 dB means the sound pressure is equal to the reference pressure, which is the approximate threshold of normal human hearing. L_p of 140 dB represents the approximate threshold of pain.
Spectrum, spectral content	Sounds are typically made up of acoustic energy present in many frequencies of the audible spectrum. The frequency spectrum describes this signal 'content'.
Stall control	Stall controlled turbines are designed to allow intentional blade stall to occur at and above the maximum rated power, to maintain the rotation speed of the turbine within its design limits.
Trailing edge	The thin edge of a wind turbine blade (or aerofoil), which is rearmost within the incoming flow
TEDCAR-AM, non-TEDCAR-AM	Trailing edge directivity and convective amplification-related AM (TEDCAR-AM) is sometimes described as 'blade swish', and is normally prominent only at relatively close range to turbines. Non-TEDCAR-AM is associated with a potentially wide range of different influencing factors and mechanisms, and can be prominent at longer ranges.
Time-weighted sound level	A sound level measurement index, that applies exponential time weighting when calculating the RMS sound pressure level. The time-weighted sound levels are commonly determined at relatively short intervals (such as 10-125 ms), and are used to determine the percentile, maximum and minimum sound levels over longer periods. The most commonly-used time weightings are Fast (or 'F'), with a weighting of 0.125 s, and Slow (or 'S'), with a weighting of 1 s. The weighting used is added to the sound level index descriptor, eg L_{pF}. Sometimes, the time weighting descriptor is omitted (eg, in ETSU-R-97) – in these cases, it is commonly assumed that Fast time weighting is intended.
Tonality	A sound characteristic associated with audible discrete tones in the frequency spectrum, which may be perceived as 'droning', 'whining', 'whistling', 'humming', 'buzzing' etc.
White / pink noise	White noise is a defined as a broadband random signal that has constant energy density across the frequency spectrum. Pink noise is defined as a broadband random signal that has an energy density that is inversely proportional to the frequency, which also means that it has equal energy in each octave band.

Appendix B

SCOPING REVIEW EVIDENCE SUMMARIES

9 APPENDIX B: SCOPING REVIEW EVIDENCE SUMMARIES

This appendix presents summaries of the reviews of publications corresponding with each topic identified during the evidence review. Further details and a full list of publications can be found in the systematic map.

In this section, referencing to publications included in the review is provided by first author name and date, with full references found in the References section. References to other publications made in commentaries within review summaries are provided as footnotes.

9.1 STAGE 1: IDENTIFICATION OF ISSUES WITH CURRENT GUIDANCE

9.1.1 NOISE LIMITS AND EFFECTS

Reference	Relevant evidence and discussion: noise limits and effects
Black literature	
Cooper (J) et al (2012)	Cooper (J) et al (2012) analysed measurements from 6 wind farms taken at 13 locations (at distances to the nearest turbine in the range 300-3000 m) within the context of examining a range of Australian regulations for wind turbine noise compliance determination. They considered the data to represent relatively uncontaminated measurements (ie, measured values were thought to be generally dictated by the turbine sound emissions rather than other sources). In relation to the ETSU-R-97 assumption, they observed that the difference between wind turbine sound levels measured over 10 minutes as energy time-averaged ($L_{Aeq,10min}$) index and as 10th percentile ($L_{AF90,10min}$) index is (as an average over the range of wind speeds) typically in agreement with the range of 1.5-2.5 dB suggested in ETSU-R-97, tending towards the lower end of this range. There was no quantification or discussion of the degree of AM that may have been present during the measurements.
Hansen (KL) et al (2018)	Hansen (KL) et al (2018) considered procedures for demonstrating compliance with Australian state regulations, some of which are based on ETSU-R-97. They highlighted the 1.5-2.5 dB difference between the L_{Aeq} and L_{AF90} indices assumed in ETSU, arguing that AM is under-represented by the L_{AF90} metric.

Reference	Relevant evidence and discussion: noise limits and effects
Davy et al (2018; 2020)	Davy et al (2018) presented findings from their work on the Australian Government's Independent Scientific Committee on Wind Turbines. In relation to ETSU-R-97, they argued that the formulation of the limits has a relatively weak evidence base, due to the limitations of the research data available at the time. They highlighted the basis for the ETSU-R-97 night-time minimum limit in the 1980 WHO Environmental Health Criteria 12[548] report, noting that the evidence examined concerned a small number of studies addressing effects of exposure to sound from transportation sources. Davy et al (2020) also note the conclusions of the 2016 AM review study[549] as suggestive that the higher night-time limit in ETSU-R-97 does not make sense. The origin of the ETSU-R-97 relative noise limit (background +5 dB) in BS 4142:1990[550] was also raised, and it was pointed out that the ETSU-R-97-defined relative limit in terms of the original metrics employed in the BS 4142 method is equivalent to a margin above background sound level of +6.5 to +7.5 dB. Davy et al (2018) also recommended a new range of noise limits for wind turbine sound based on an analysis of exposure-response relationships taken from the literature. Community Tolerance Level (CTL) curves were identified for each of the studies considered (the 2nd Sweden study, the Netherlands study, the Health Canada study and the Japan study) and averaged together. This composite CTL curve was then converted to the $L_{AF90,10min}$ index used in Australia (and in ETSU-R-97). In this conversion, the assumption of a 2 dB difference between 10th percentile level $L_{AF90,10min}$ and energy time-averaged level $L_{Aeq,10min}$ for wind turbine sound levels was adopted, without reference to specific evidence. However, they also cautioned that the 2 dB value represents wind turbine sound that does not exhibit 'excessive' AM (without defining what was meant by this description). The suggested limit values were taken from the curve at 10% highly annoyed, which produced a value of 35 dB L_{AF90}, (with a standard deviation of 3 dB). The authors concluded that to limit annoyance to 10% HA, wind turbine sound exposure should be limited to a value in the range 32-38 dB $L_{AF90,10min}$, or 34-40 dB $L_{Aeq,10min}$.
Cooper (S) et al (2020)	Cooper (S) et al (2020) noted that revisions have been to WHO guidelines, and also to the BS 4142 standard, observing that ETSU-R-97 has not yet been similarly updated. They also note that the ETSU-R-97 limits do not enable an assessment of noise impact.

548 WHO, 1980. *Environmental Health Criteria 12: Noise*. World Health Organization. [URL]
549 WSP | Parsons Brinckerhoff, 2016. *Wind turbine AM review: Phase 2 report.* 3514482A Issue 3. Department for Business, Energy & Industrial Strategy. [URL]
550 BSi, 1990. *BS 4142:1990 Method for rating industrial noise affecting mixed residential and industrial areas*. British Standards Institution. [URL]

Reference	Relevant evidence and discussion: noise limits and effects
Hansen (C) et al (2020)	Hansen (C) et al (2020) argued that the difference between the 10th percentile index $L_{AF90,10min}$ and the energy-averaged index $L_{Aeq,10min}$ is typically larger than assumed in ETSU-R-97, and proposed a range of 2-3 dB (ie 0.5 dB greater than the ETSU-R-97 range), citing Bowdler et al (2018, discussed further in section 6.1)[551] and Zagubień (2018). They suggested that further research is needed to establish the most appropriate sound measurement index for regulating wind turbine noise and assessing compliance. Additionally, Hansen (C) et al pointed out that the method applied in ETSU-R-97 compliance tests of logarithmically subtracting one percentile sound level value from another is mathematically invalid[552] (in practice this arises when subtracting an $L_{AF90,10min}$ for a 'turbines off' background sound level from the $L_{AF90,10min}$ for a 'with turbines on' total sound level).
Alamir et al (2021)	Alamir et al (2021) again noted that the sleep disturbance threshold value used in ETSU-R-97 to derive a night-time limit value has its origin in the 1980 WHO Environmental Health Criteria 12[553] report. They highlighted that this guidance has been superseded by newer supporting evidence and thresholds presented in later WHO guidelines[554,555,556], suggesting that, on this basis, the ETSU-R-97 night-time limit appears too high to avoid sleep disturbance. The atypicality of having a numerically higher night limit than for the daytime compared with other national wind turbine regulation regimes was noted.
Grey literature	
State of South Australia Environment Protection Authority (2009)	The State of South Australia Environment Protection Authority (2009) guidelines reference ETSU-R-97 in setting more relaxed controls for properties with financial involvement with the development. Limits are set in terms of L_{Aeq}, but the guidelines allow compliance to be established using measurements of L_{AF90}; no adjustment to measured levels to account for an expected L_{Aeq}-L_{AF90} level difference is specified.

[551] Bowdler, D, Cand, M, Hayes, M, Irvine, G, 2018. *Wind turbine noise amplitude modulation penalty considerations*. Acoustics 2018, Cardiff, 23-24 April. Institute of Acoustics. [URL]
[552] This fact is acknowledged in ETSU-R-97, which refers to Nelson (1973) for methods of addressing the issue more rigorously, although no indication is given in ETSU-R-97 of the expected uncertainty associated with not being rigorous with this calculation, and our experience is that practitioners generally do not apply a mathematically rigorous approach: Nelson, P M, 1973. The Combination of Noise from Separate Time Varying Sources. *Applied Acoustics*, 6 (1), 1-21. [URL]
[553] WHO, 1980. *Environmental Health Criteria 12: Noise*. World Health Organization. [URL]
[554] WHO, 1999. *Guidelines for community noise*. World Health Organization. [URL]
[555] WHO Regional Office for Europe, 2009. *Night noise guidelines for Europe*. World Health Organization. [URL]
[556] WHO Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region*. World Health Organization. [URL]

Reference	Relevant evidence and discussion: noise limits and effects
Chiles (2010)	Chiles (2010) outlined the considerations leading to a revised version of the New Zealand standard NZS 6808. The previous 1998 version of the standard[557] was based on ETSU-R-97, and included a lower fixed noise limit equivalent to the upper bound of the ETSU-R-97 daytime minimum limit. Chiles confirmed that the 2010 revision[558] retained the same limit value as it "*protects health and maintains reasonable amenity*", a position taken based on considering advice in the 1999 WHO Guidelines[559].
AECOM (2011)	AECOM (2011) pointed out that, apart from ETSU-R-97, no other UK environmental noise assessment procedures use the 10th percentile level L_{AF90} to set limits on noise impact. They highlighted the insensitivity of the L_{AF90} index to fluctuating sound levels, such as may be exhibited in AM wind turbine sound, and that the associated impact may therefore be underestimated. They noted that wind turbine noise regulations in some other countries are based on the energy time-averaged level L_{Aeq}. AECOM also suggested that addressing the invalidity of logarithmically subtracting percentile levels is only a concern in situations where the variation of the wind turbine sound level is much greater than variation of the background sound level (although no analysis or evidence was presented to support this). AECOM (2011) also noted that wind turbines are often found in low sound level environments, but tend to generate lower sound levels than other common environmental sources, indicating that sound masking could be more important in determining the effects of wind turbine sound. Research results from a listening test in Denmark were also noted, which indicate that noise annoyance is reduced in the presence of natural residual sounds[560]. It was also highlighted that propagation effects can contribute to lower frequency sound character in wind turbine immissions, which are less readily masked by residual sounds.
Bastasch (2011)	In reviewing a range of international assessment criteria Bastasch (2011) highlighted the higher limit for night-time than for daytime imposed in ETSU-R-97, which was noted to be different to the approaches in the other regulatory regimes examined.

[557] Standards New Zealand, 1998. *NZS 6808:1998. Acoustics - The assessment and measurement of sound from wind turbine generators.* [URL]
[558] Standards New Zealand, 2010. *NZS 6808:2010 Acoustics - Wind farm noise*. [URL]
[559] World Health Organization, 1999. *Guidelines for community noise.* [URL]
[560] Legarth, SV, 2007. *Auralization and assessments of annoyance from wind turbines*. Wind Turbine Noise 2007, Lyon, 20-21 September. INCE-Europe.

Reference	Relevant evidence and discussion: noise limits and effects
Bowdler (2012)	Bowdler (2012) reiterated that setting night-time limits with a higher value than for daytime is unusual compared with other countries. Bowdler also highlighted (i) that the 'pass/fail' nature of the manner in which the limits tend to be applied does not describe the impact that may be imparted, and (ii) that their prescriptiveness can result in unbalanced application, in which relatively large developments are more constrained (in terms of noise) than relatively small ones. Bowdler argued that the approach of setting minimum limits in environments with low existing sound levels may enable impacts with greater significance to be disregarded.
Bullmore et al (2013)	Bullmore et al (2013) analysed field data from three sites as well as artificial synthesised wind turbine-like sound stimuli, and concluded that the L_{Aeq}-L_{AF90} level difference range assumed in ETSU-R-97 remains valid even for AM with relatively large modulation depth (see section 6.2.1).
Perkins et al (2013)	Perkins et al (2013) suggested that a UK-specific exposure-response study could be necessary to further understanding of wind turbine noise assessment.
Marshall Day Acoustics (2013)	Marshall Day Acoustics (2013) argued that the periodic nature of wind turbine sound (ie, AM) can make it more easily audible against wind-induced sound, and that differences in wind conditions between source and receptor locations (eg, sheltering) could lead to uncertain effectiveness of masking by wind-induced sound.
Fowler et al (2013)	Fowler et al (2013) reviewed several national and regional (US) wind turbine noise regulations. They noted that a majority use L_{Aeq} or an L_{Aeq}-derived (eg, L_{den}) index as the assessment metric. They also noted that the variation in L_{Aeq} regulations was approximately 20 dB, with the US states typically having higher limits (50-55 dB) than western Europe or the state of South Australia. Some of the national regulations reviewed had varying limits depending on land use type, with some imposing *more* stringent limits in rural areas, with others imposing *less* stringent rural area limits (compared with other residential areas).

Reference	Relevant evidence and discussion: noise limits and effects
Goeme, (2015)	Goeme, (2015) compared the regulations and assessment procedures for France, UK and the Netherlands. The author noted that the 2011 French regs limit wind turbine noise to 35 dB (ambient L_{A50}) or a sound emergence of 5 dB (day) and 3 dB (night), both in terms of L_{A50}, and that an adjustment variable was added to allow limit exceedances of 1 dB for 4-8h, 2 dB for 2-4h or 3 dB for 20mins-2h. The French method classifies the measured ambient levels (L_{A50}) into 'homogeneous classes', which are time periods during which sound levels are consistent (eg, morning rush hours, night…) - these are judged by the assessor according to criteria, and must be justified. In each class, the ambient level is derived as a wind speed binned median value. The French approach includes a defined method for incorporating uncertainties, which includes uncertainty in the measurement distribution, and in each individual measurement itself. These are incorporated into the assessment according to the procedure. It is noted that neither ETSU-R-97 nor the Dutch method deals with uncertainty beyond forming a regression model.
Cox et al (2015)	Cox et al (2015) suggested that the noise impact that may be permitted within the limits established in ETSU-R-97 can adversely affect sleep and health.
Perkins (2015)	Perkins (2015) noted that a sample poll of attendees at a conference held to launch the IOA GPG indicated a "*large majority*" of attendees agreed that the existing ETSU-R-97 noise limits were too high, especially for the night-time. Perkins also suggested that many UK acousticians consider the ETSU-R-97 difference between night-time and daytime lower fixed limits as "*open to question*", and highlighted that some developers design sites to exploit the more relaxed night limit, stating that "*few would argue that this is what the original authors of ETSU-R-97 had intended*".

Reference	Relevant evidence and discussion: noise limits and effects
SLR & Hoare Lea (2015)	SLR & Hoare Lea (2015) reviewed 10 case study applications for wind farms and compared the application documents with the experiences of residents. They reported that about 3/4 of the 390 respondents (themselves making up roughly 17% of all the 2303 invited households) stated either they could not hear the turbines (2/3, or ~260), or if they could hear them, they were indifferent to the sound (~33 households). Around 24% of respondents could hear the turbines and disliked the noise, and about 18% strongly disliked it. They also noted that ~80% of those who could hear the sound heard it outdoors. Less than half of the total respondents reported impact indoors, but when this was reported, descriptions tended to be more negative. For the 15% of respondents that were predicted to be exposed to sound levels ≥40 dB $L_{AF90,10min}$ (at 8 ms^{-1} standardised 10 m height wind speed), all reported being able to hear the sound, with 75% reporting disliking it. By contrast, 29% were predicted to be exposed to 35-40 dB $L_{AF90,10min}$ of whom 54% reported hearing it, with around 79% disliking it. It was noted that above predicted exposure levels of around 38 dB $L_{AF90,10min}$, almost all respondents reported audibility of the sound. An increased dislike of the noise was associated with predicted levels in the 35-40 dB $L_{AF90,10min}$ range and above. In cases where negative impacts were reported despite being predicted to be exposed to levels below 25 to 30 dB $L_{AF90,10min}$, audible characteristics (tones or AM) were identified from the survey responses. Respondents reporting negative impacts from noise tended to also report negative impacts from one or more of the other factors investigated, ie visual impact or shadow flicker. A weak negative correlation between financial involvement in the wind farm and negative responses was observed. It was noted that respondent comments suggested that increased noise compared with baseline conditions was an important factor in people's response judgements. The authors noted the risks of participation bias (which is suggested by the response rate of 17%, and relatively high rates of reported dislike of the sound) and that the results are not generalisable. Key recommendations from the study included: - Guidance should include requirements for description and assessment of experiential impacts such as audibility. - A review of the derivation of noise limits should be undertaken to consider whether an appropriate balance between protection, robustness and simplicity is achieved. The review should include investigating the masking effects of background sound, and the merits of setting relative or absolute limits.

Reference	Relevant evidence and discussion: noise limits and effects
Bullmore et al (2015)	Bullmore et al (2015) considered options for a new acoustic assessment method for wind turbine noise, looking beyond ETSU-R-97. They noted that current (England and Northern Ireland) noise policies rely on 'effect levels', which are defined over a range of increasingly adverse effect. By contrast, it was noted that ETSU-R-97 is effectively a pass/fail approach, albeit with some flexibility in the definition of minimum limits. It was suggested that the alternative could involve greater flexibility to establish a range of impacts. Another aspect raised was the possibility of assessing predicted percentage of time of impacts or exceedances.
Schild et al (2015)	Schild et al (2015) presented a comparative study of US, UK, France, Germany and the New South Wales guidelines. An exercise was undertaken to apply each assessment method to 3 wind farm cases, for which measurement survey data had been acquired, analyse curtailment schemes that would be necessary in each case to meet the limits, and the expected impact on the energy yield. Some questionable decisions on the assumptions were made, such as assuming that the UK guidance would apply a 35 dB $L_{AF90,10min}$ minimum limit for day and night. This means the impact of the UK guidance on the energy yields is pessimistic. The WHO 1999 guidelines were also used, which consistently produced the lowest yield impact (indicating these are relatively relaxed compared with the national guidelines). This is because out of the 5 countries included, only Germany has a daytime limit as high as the 50 dB $L_{Aeq,16h}$ WHO threshold assumed, and all of the countries (including UK) were analysed with a lower night time limit than the 45 dB $L_{Aeq,8h}$ WHO threshold (even though the UK's 43 dB $L_{AF90,10min}$ is broadly equivalent to 45 dB L_{Aeq}, this is disregarded, as the authors selected 35 dB $L_{AF90,10min}$ as the UK night lower limit).
Walsh (2015)	Walsh (2015) contrasted the use in ETSU-R-97 of L_{AF90} to control wind turbine sound with other countries that use L_{Aeq}. Walsh cited evidence from Hayes McKenzie Partnership (2006), indicating that AM content in wind farm sound emissions can sometimes be greater than assumed in ETSU-R-97, and argued on this basis that ‘further consideration’ should be given to the ongoing use of L_{AF90}. Walsh (2015), echoing AECOM (2011), noted that greater low frequency spectral content in wind turbine sound immissions at longer ranges could mean that masking by residual sounds would be less effective. Walsh also noted that locations sheltered due to topography could be subject to less wind-induced sound, which could reduce any beneficial masking effects.

Reference	Relevant evidence and discussion: noise limits and effects
Hansen (CH) et al (2017)	Hansen (CH) et al (2017) highlighted later revisions to WHO guidelines (contrasting this with the ETSU-R-97 limits), and noted the atypicality among noise regulations of imposing higher night-time limits than for daytime. They again raised the issue of setting minimum limits in low sound level environments, and also noted that the ETSU-R-97 relative limit framed in terms of L_{Aeq} is approximately equivalent to a margin above background sound levels of around 7 dB, which they argued suggests a risk of complaints about noise being expected. They suggested that the ETSU-R-97 limits do not address low frequency noise impact, and raised concern with the allowable increase to the limits for financially involved properties (their specific concern with this was not detailed, but is presumed to be based on their assertion that the ETSU-R-97 limits are already too high prior to any considerations of financial involvement).
Parra et al (2018)	Parra et al (2018) reported on the development of a Chilean regulation for wind farms. The regulation uses the ETSU-R-97 measurement approach. Noise limits for rural areas are set at background +10 dB, with an upper limit of 65 dB(A), day or 50 dB(A) night.

Reference	Relevant evidence and discussion: noise limits and effects
Government of Ireland (2019)	The Irish Government produced Draft Revised Wind Energy Development Guidelines (WEDG) for public consultation in 2019. The existing 2006 WEDG[561], contain a relatively brief section on noise, which sets out a regime of noise limits that is based on the ETSU-R-97 approach, but with a less stringent default minimum daytime limit, and a less complicated approach that, in practice, could potentially lead to more relaxed noise protections (compared with ETSU-R-97). The Draft Revised Guidelines on the other hand, while retaining some of the methodologies drawn from ETSU-R-97 and the IOA GPG, proposed the introduction of a new approach to setting limits. This approach aims to ensure that sound levels do not exceed the value 'conditionally' recommended by the WHO in the 2018 ENGER[562] as representing a level above which noise is associated with adverse health effects. This new *maximum* limit is underpinned by a detailed analysis[563], which provides a rationale for the conversion of the value recommended by the WHO into the assessment and measurement metric used in the Draft Revised Guidelines. The resulting maximum limit is equal to the *minimum* limit recommended in ETSU-R-97 for the night-time, whereas the existing 2006 WEDG support the ETSU-R-97 minimum limit. This demonstrates that the Irish Government has considered reducing the allowable levels below the existing ETSU-R-97-based limit, which implies that this may no longer be considered sufficient for noise protection in Ireland, if it does not ensure adherence with the WHO recommendation. However, it must be noted that the validity of converting between different sound level indices can be fraught with uncertainties, and in this case is based on debated assumptions – the consultation for the Draft Revised WEDG received a response from a group of 13 members of the IOA which, among other things, challenged the strength of the supporting evidence and highlighted technical inaccuracies in the analysis used to underpin the development of the proposed new limits[564].

9.1.2 AMPLITUDE MODULATION CONTROL

Reference	Relevant evidence and discussion: amplitude modulation control
Black literature	
Cooper (S) et al (2020)	Cooper (S) et al (2020) highlighted that ETSU-R-97 has not been updated to account for what they describe as 'excessive' AM.

561 Government of Ireland, 2006. *Wind energy development guidelines* [URL]
562 World Health Organization Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region.* [URL]
563 RPS, 2018. *Draft wind energy guidelines wind turbine noise analysis.* Report MGE0713RP0001F01. [URL]
564 Mackay, J, Singleton, J, Reid, M, Cand, M, Mahon, J, McKenzie, A, Keaney, D, Hayes, M, Bowdler, D, Kelly, D, Jiggins, M, Irvine, G, Lester, M, 2020. *Public consultation on the revised wind energy development guidelines: Joint consultation response.* [URL]

Reference	Relevant evidence and discussion: amplitude modulation control
Alamir et al (2021)	Alamir et al (2021) noted that ETSU-R-97 does not consider a penalty for AM, contrasting this with the New Zealand standard, NZS 6808:2010[565] (which includes a rudimentary 'interim' approach of applying a fixed +5 dB penalty for AM, in recognition that more robust objective methods may supersede it in the future).
Grey literature	
Hayes McKenzie Partnership (2006; 2011)	In investigating noise complaints associated with three sites, Hayes McKenzie Partnership (2006) identified that reports of low frequency noise disturbance were attributable to AM, measurements of which indicated a greater magnitude than assumed as typical in ETSU-R-97. They suggested that it may be appropriate to apply a penalty for AM. The same authors later recommended (2011) that the lack of an AM control in ETSU-R-97 is a position that either needs support, or otherwise requires further guidance.
Bowdler (2012)	Bowdler (2012) noted that there is no AM penalty applied in ETSU-R-97, contrasting this with the approach taken for tonality, and for other types of characteristics addressed in BS 4142.
Perkins (2015)	Perkins (2015) commented that, following the introduction of the IOA GPG, AM has been highlighted as an issue requiring further attention.
Walsh (2015)	Reporting to the Northern Ireland Assembly Committee for the Environment's inquiry into wind energy, Walsh (2015) argued that the assumption in ETSU-R-97 that wind turbine sound is relatively steady and characterless has been undermined by later evidence on AM, which calls into question the relevance of using the L_{AF90} metric. Walsh also suggested that the introduction of larger turbines leads to a higher risk of AM occurrence, due to the increased wind shear associated with greater hub heights.
Cox et al (2015)	Cox et al (2015) argued that a planning control for AM is necessary, and recommended that either i) BS 4142:2014[566] should be applied, with a rating limit of 10 dB above background, or ii), if AM is a concern but the overall sound levels are not, a control based on limiting AM occurrence should be applied.

[565] Standards New Zealand, 2010. NZS 6808:2010 Acoustics – wind farm noise. [URL]
[566] BSi, 2014. *BS 4142:2014 Methods for rating and assessing industrial and commercial sound*. British Standards Institution. (Subsequently amended: BSi, 2019. BS 4142:2014+A1:2019 [URL]).

Reference	Relevant evidence and discussion: amplitude modulation control
SLR & Hoare Lea (2015)	SLR & Hoare Lea (2015) reviewed 10 case study applications for wind farms and compared the application documents with the experiences of residents. It was highlighted that in 2/3 of the 10 case studies examined, the likelihood of AM influencing impacts was identified in resident descriptions of sound characteristics, and about 1/3 were clearer in indicating that AM in these cases was more pronounced. It was noted that there is a lack of guidance on AM, and a key recommendation from the study was to develop good practice guidance on AM assessment.
WSP | Parsons Brinckerhoff (2016)	In 2015, the UK government commissioned a research study to review the evidence available on the human response to AM in wind turbine sound, and to consider how this evidence could be used to form a control for AM suitable for use in development planning. The results of the WSP | Parsons Brinckerhoff study were published by BEIS in 2016, the conclusions of which confirmed that a penalty adjustment for AM is appropriate and supported by evidence, and included a recommendation for a form of penalty scheme to assess AM in the event of complaints. Subsequent to the 2016 WSP | Parsons Brinckerhoff study, McKenzie et al (2017)[567] proposed an example of a wording for a UK planning condition applying the penalty scheme advised in the BEIS-published review.
Large et al (2017)	In the context of a case-study example, Large et al (2017) discussed the assumptions made in ETSU-R-97 on the nature of AM inherent in wind turbine sound, noting that this is different in its characteristics to their observations at the site in question. They considered the approaches developed in the UK to characterise and rate the impact of AM to be inferior to their own method, which is based on limiting occurrences of AM exceeding a specified threshold (ie, independent of the absolute sound levels).
Hansen (CH) et al (2017)	Hansen (CH) et al (2017) highlighted the omission of an AM control from ETSU-R-97, noting that a suitable control could either be a penalty adjustment or, as per the suggestion of Large et al (2017), a limit on AM occurrences. They also raised a concern about 'random AM', which they suggested could arise due to the interaction of sound from multiple turbines.

[567] McKenzie, A, Cand, M, Bowdler, D, Jiggins, M, Irvine, G, Reid, M, Perkins, R, Lotinga, M, Hayes, M & Bullmore, A, 2017. A planning condition for wind turbines. *Acoustics Bulletin*, 42 (6), 56-60. [URL]

9.1.3 OTHER ISSUES

Minimum 'set back' distances for noise control

Reference	Relevant evidence and discussion: set back distances for noise control
Black literature	
Davy et al (2020)	Within the context of Australian wind turbines, wind farm siting and neighbouring residences, Davy et al (2020) advised that, while sound levels should be the main factor in considering proximity of turbines to residents, a minimum set back distance should also be imposed. They argued that with current turbine technology (ie, relevant to Australia), this distance should be in the range 1-1.5 km, which they clarified is intended to achieve "*near imperceptible*" sound levels.
Hansen (C) et al (2020)	Hansen (C) et al (2020) noted that some regulations specify a set back distance, but that sound levels at any given distance are highly site-specific, and more research would be needed understand relevant variables.
Grey literature	
Department of the Environment Planning and Environmental Policy Group (2010)	The Northern Ireland Executive Department of the Environment Planning and Environmental Policy Group (2010) produced the guidance document *Best Practice Guidance to Planning Policy Statement 18 'Renewable Energy'*, which advises that, for reasons of potential noise impact, the authority would generally apply a best practice setback distance of the greater of 10×rotor diameter or 500 m. No supporting evidence is cited in the document.

Reference	Relevant evidence and discussion: set back distances for noise control
Marshall Day Acoustics (2013)	Reporting to the Sustainable Energy Authority of Ireland, Marshall Day Acoustics (2013) considered the potential advantages and disadvantages to the use of fixed set back distances for noise control – they observed that: • For regulators, set back distances are easy to assess at planning stage, but there is no facility to address noise complaints within planning conditions (protection against noise impact would be reliant on nuisance legislation) • For neighbouring residents, set back distances are easy to understand, but could enable high sound levels in some cases, there is no incentive for developers to employ quieter or less noisy turbines • For developers, set back distances represent a greatly reduced planning burden but there is the potential for lost power generation capacity The authors recommended that fixed set backs are not used for noise control, as these have the potential to over or under-protect against noise impact.
Walsh (2015)	Reporting to the Northern Ireland Department of the Environment Committee's inquiry into wind energy, Walsh (2015) argued that set back distances are more appropriate for control of visual impact than noise, and reproduced analysis from a 2013 study for the Scottish government by the University of Dundee, which found that a set back approach is not justified by evidence[568].
Hansen (CH) et al (2017)	Hansen (CH) et al (2017) made suggestions for desirable features of wind turbine noise regulations, highlighting a suggestion made by Shepherd et al (2011)[569] for a minimum setback distance of 2 km, and arguing that for large turbines (≥3 MW) the distance should be much larger.

[568] Onyango, V, Illsley, B & Radfar, M, 2013. *Review of the 2km separation distance between areas of search for onshore wind farms and the edge of cities, towns and villages. Final report*. ClimateXChange. [URL]
[569] Shepherd, D, McBride, D, Welch, D, Dirks, KN & Hill, EM, 2011. Evaluating the impact of wind turbine noise on health-related quality of life. *Noise & Health*, 13 (54), 333-339. [URL]

Data aggregation and treatment of uncertainty

Reference	Relevant evidence and discussion: influence of measured sound level data aggregation
Black literature	
Hansen (KL) et al (2018) Hansen (C) et al (2020)	Hansen (KL) et al (2018) and Hansen (C) et al (2020) highlighted that the use of regression models to aggregate data means that measured levels would be below the curve-fitted value for a substantial proportion of the time. They noted that this implies wind turbine sound would (for these periods) be more noticeable than expected. Hansen (KL) et al (2018) argued that to address this in a more conservative way, it would be preferable to use an alternative approach such as taking a lower-weighted statistical estimate of the 'typical' background sound value[570], or by not using relative limits at all (thus avoiding the need for aggregation of measured background sound data).
Grey literature	
Bowdler (2012)	Bowdler (2012) suggested that people base their perception of 'intrusive noise' on the periods when other (ambient or background) sounds are quieter. As such, Bowdler proposed that the derivation of a 'prevailing' background level should be based on a low-weighted estimate (rather than using the value of a regression model line), giving the example of the mean minus one standard deviation.

[570] In the original article, Hansen et al suggest the 90th percentile of the $L_{AF90,10min}$, however, (given that this would be a high-weighted estimate) we have confirmed via personal communication with the lead author that this is actually a previously undetected error: the proposal is intended to be the 10th percentile of the $L_{AF90,10min}$, which would be a low-weighted estimate.

Reference	Relevant evidence and discussion: influence of measured sound level data aggregation
Greenough et al (2013)	Greenough et al (2013) questioned the validity of the ETSU-R-97 approach taken to deriving prevailing background curves from measured data. They pointed out that the measured data may not meet the assumptions underlying a valid linear[571] least squares regression analysis, yet this approach is generally applied in relation to ETSU-R-97 assessments[572]. They also raised the concern that (in their experience) practitioners assess the goodness of fit of derived regression models for background sound levels solely by examining the coefficient of determination (the r^2 value), pointing out some of the drawbacks of reliance on this statistic (NB: the IOA GPG SGN 2 published later in 2014 cautions against selecting a regression model based solely on the highest r^2 value, advising that professional judgement is required[573]). Greenough et al highlighted examples for which the common approach could potentially produce illogical results, and how different applications of the guidance could lead to a range of outcomes, suggesting that this methodological variance is a source of uncertainty unaccounted for in assessments. They proposed several options for statistical techniques that they argued could provide more robust data aggregation, addressing the problems examined.
Hansen (CH) et al (2017)	Hansen (CH) et al (2017) preceded their later black literature articles (referenced above) with similar views on the subject, but also proposed using a value one or two standard deviations below the 'average' to establish a suitably low-weighted typical background level for assessments of relative impact.

[571] Here, 'linear' is used in the strict statistical sense of the manner in which regression model equation terms are combined, and does not refer to the 'straightness' of the line produced by a model fit; in this sense, least squares regression models defined using a simple polynomial equation (of any order) are considered linear regression models, as the terms are linear combinations. This strict definition is distinct from the terminology used in the IOA GPG (which uses 'linear' to mean a 'straight line' model – ie, an 'affine linear' function –, which can also be considered as a polynomial equation of order 1). Linear least squares regression is also sometimes called 'ordinary' least squares regression.
[572] Linear least squares regression (using simple polynomial equation models of order 1-4) is the only statistical aggregation procedure for measured background sound level data recognised in the IOA GPG, which was published later in the same year as the 2013 article by Greenough et al. A more flexible approach was available under the ETSU-R-97 guidance, which prescribes only the use of the 'least squares' method, which technically would allow a wide range of different regression models to be potentially applicable, both linear and non-linear (in the strict statistical sense of linearity of regression equation terms). It is also noted that neither ETSU-R-97 nor the IOA GPG (including SGN 5) are prescriptive on the specific type of 'best fit curve' to be applied to wind turbine sound levels measured for compliance testing purposes – in the case of the IOA GPG, it's unclear whether this omission is an oversight or intentional flexibility in application (whereas the ETSU-R-97 guidance clearly intended for greater flexibility in the data aggregation than afforded by the later IOA GPG prescriptive approach).
[573] IOA GPG SGN 2: *Data processing & derivation of ETSU-R-97 background curves*. [URL]

Measurement instrumentation

Reference	Relevant evidence and discussion: measurement instrumentation
Grey literature	
Perkins et al (2013) Perkins (2014) Perkins (2015)	In discussing the introduction of the IOA GPG, Perkins et al (2013) and Perkins (2014; 2015) acknowledged that further research and definitive guidance may be necessary to establish suitable designs of microphone wind shield to limit wind noise contamination of measurements.
Hansen (CH) et al (2017)	Hansen (CH) et al (2017) echoed the point that the IOA GPG is not definitive on suitable wind shield designs, and additionally, raised the concern that there is no guidance on addressing the potential influence of the instrumentation self-noise on measured levels, which they argued could lead to overestimated background sound levels in quiet environments.

Wind shear effects

Reference	Relevant evidence and discussion: wind shear effects
Grey literature	
Bowdler et al (2009)	Bowdler et al (2009) presented proposed refinements of the ETSU-R-97 assessment approach, to address three points of debate arising from its application: 1. The mismatch between background sound measured with 10 m height measured wind speeds and the predicted sound immissions derived from sound power referenced to standardised 10 m height wind speeds. It was recommended that the 10 m height measured wind speeds should not normally be used, and instead wind speed should be measured at greater heights (such as hub height), and standardised to 10 m using the standard ground roughness and log wind shear curve. 2. Predictions of wind turbine sound should be made using ISO 9613-2, with specific input parameters designed to avoid overestimation of attenuation due to ground effects, air absorption and obstacle attenuation. 3. That there was no robust evidence to support the suggestion that infrasound and groundborne vibration from wind turbines adversely affect wind farm neighbours (The recommendations on wind shear and predictions were later carried through into the IOA GPG.)
McLaughlin (2012)	McLaughlin (2012) considered wind shear prior to the IOA GPG, arguing that wind shear was generally misunderstood in noise assessments. The author explained the wind shear issues affecting the comparison of sound immissions and background sound levels as functions of wind speeds referenced to 10 m. Use of site measured wind shear exponents to adjust the turbine sound levels to wind speed at site 10 m height was warned against, because this would result in uncertainty in the predicted immissions (depending on wind shear) – it was argued that it is better that the uncertainty is embedded into the background sound data, as this already includes uncertainty due to other influences.
Bowdler (2013)	Bowdler (2013) reviewed the guidance introduced in the IOA GPG, noting that the approach to standardising wind speed measurements to 10 m height averages the effects of wind shear. Bowdler also highlighted that criticisms of this approach, made on the basis that it systematically provides lower protection to receptors from noise impact, have been based on further mistaken conflations of wind speed referencing systems.

Reference	Relevant evidence and discussion: wind shear effects
Coulon (2014)	Coulon (2014) reviewed the approaches to measuring and deriving wind speeds in planning, sound power testing, and compliance testing phases of assessment under ETSU-R-97 and the IOA GPG. The author suggested that it could be less confusing and more transparent to abandon 10 m height wind speed standardisation and instead reference everything (baseline data and turbine sound immissions) to hub height wind speeds.
Bullmore et al (2015)	Bullmore et al (2015) highlighted that the IOA GPG approach to standardising wind speeds to 10 m height effectively 'averages' the wind shear conditions present during survey measurements, raising a question over the representativeness for given periods within measured baseline data.
Hansen (CH) et al (2017)	Hansen (CH) et al (2017) noted that the ETSU-R-97 approach may not adequately address situations with high wind shear, in which the assumption of a correlation between background sound levels and hub height wind speeds may not be reliable. They also reviewed the IOA GPG approach, arguing that the approach of standardising wind speeds to 10 m height produces 'large errors' compared with actual 10 m height wind speeds, as atmospheric effects are disregarded in the standardisation.
Summers et al (2021)	Summers et al (2021) reported on reviews of 16 planning application noise assessments in Scotland. They noted that the majority of assessments reviewed followed the IOA GPG. They highlighted increasingly complex cumulative issues arising at planning caused by densification of wind farms, including wind shear issues raised by cumulative sites with shared receptors and background sound level data, but with differing turbine heights (leading to varying 10 m-height wind speed standardisation). They also highlighted a case in which the wind speed measurement heights during the baseline sound monitoring survey did not meet the recommendations in the IOA GPG in relation to the proposed turbine height, but this had been retrospectively addressed by further wind data acquisition and analysis for greater heights. The authors suggested that further guidance would be beneficial to address these issues.

Compliance assessments and cumulative impacts

Reference	Relevant evidence and discussion: compliance assessments and cumulative impacts
Grey literature	
Summers et al (2017)	Summers et al (2017) reported on reviews of 20 planning application noise assessments in Scotland. The majority were found to follow the IOA GPG. They highlighted 2 case studies to illustrate potential for difficulties in application – these both concerned cumulative assessments, which followed the GPG. They also noted that quality and consistency of assessments has improved following GPG.
Sutherland (2014) Garnett et al (2015)	Sutherland (2014) and Garnett et al (2015) reported issues with demonstrating compliance with the ETSU-R-97 35 dB(A) simplified limit. They highlighted that the sensitivity of making logarithmic subtractions when wind turbine sound measurements are close to background levels reduces confidence in the calculations, and is a problem for robust compliance assessment, especially for the 35 dB simplified limit. They argued that this may lead to situations in which non-compliance is identified at wind conditions that do not relate to any disturbance (ie, at higher wind speeds when background sounds are higher), whereas at lower wind speeds (with increased turbine audibility above background) compliance is achieved, according to the method. They also highlighted the difficulties in getting reliable hub height wind speeds for small developments (to which the simplified limit may apply) where met mast installations may not be practicable. They proposed possible solutions as - taking proxy location measurements nearer the turbine (alongside any complaint locations), or; - using a 10 m mast as a wind speed control measurement alongside turbine power curve derivation, calibrating the 10 m data to the valid power curve data to enable the wind shear to be taken into account in deriving hub height wind speeds for speeds outside the valid range.
Bullmore et al (2015)	Bullmore et al (2015) highlighted the increasing likelihood of multiple wind farm developments in an area, and the difficulty of allocation of noise limits – if one development is allocated the whole (potential) headroom, that may negate any further development. It was also noted that the pass/fail application of ETSU-R-97 limits ensures there is no flexibility in the allocation – this was contrasted against other environmental impacts, which it was asserted are not treated in a similar way.

Reference	Relevant evidence and discussion: compliance assessments and cumulative impacts
Mackay et al (2016)	Mackay et al (2016) highlighted advantages and disadvantages of determining compliance using proxy measurement locations in four different configurations of varying complexity. They queried whether the uncertainties involved in using proxy locations would be expected to be any worse than the uncertainties in using locations with poor signal-noise-ratio. They pointed out that one disadvantage of using a proxy compliance location near to the wind farm site is that the derived sound characteristic penalties cannot easily be used to determine the applicable penalty at a receptor. They suggested that future work could examine how to use proxy locations to extrapolate sound levels for compliance determination.

Turbine technology

Reference	Relevant evidence and discussion: compliance assessments and cumulative impacts
Grey literature	
Bullmore et al (2015)	Bullmore et al (2015) highlighted the changes in turbine design since ETSU-R-97: turbines are larger, which leads to increased separation distance from receptors (implying lower frequency immissions), and they are pitch regulated, variable speed, rather than fixed speed, sometimes stall regulated. It was noted that control systems have advanced, enabling greater flexibility in operation while meeting noise limits, and this may mean that impacts can now be maximised within the limits, where they would not have been previously.

9.2 STAGE 2: REVIEW OF PRIORITISED THEMES

9.2.1 NOISE LIMITS AND EFFECTS

Noise limits

Reference	Relevant evidence and discussion: Noise limits
Black literature	
Hansen (KL) et al (2018)	See Stage 1 evidence review summary in section 9.1.1. Hansen (KL) et al (2018) also suggested that a more reasonable approach to controlling the impact of wind farms could be to specify maximum proportions of time that the immissions could exceed the specified noise limits at different times of the day.
Cooper (S) et al (2020)	See Stage 1 evidence review summary in section 9.1.1. Cooper (S) et al (2020) also summarised regulations in Australia and New Zealand, noting the minimum noise limits, which range from 35-40 dB $L_{Aeq,10min}$, and relative limits of background $L_{AF90,10min}$ + 5 dB.
Davy et al (2020)	See Stage 1 evidence review summary in section 9.1.1. Davy et al (2020) summarised the analysis undertaken in the authors' previous article (Davy, Burgemeister, & Hillman, 2018) in which they derived a set of levels they proposed as corresponding to approximately 10% HA, given as 34-40 dB $L_{Aeq,10min}$, with a mean value of 37 dB $L_{Aeq,10min}$. They noted that this is equivalent to the value extracted from the WHO 2018 ENGER chart at the intersection of the exposure-response curves for noise annoyance taken from the Japan study and the combined Sweden and Netherlands study at 10% HA. Their recommendation for devising suitable limits for wind turbine sound is that the approach should ensure no more than 10% of people would be highly annoyed. They advised that in addition to limiting sound exposure (which they stated is the ‘primary determinant’ of how close turbines can be allowed to be to dwellings), there should also be a minimum setback distance; no supporting evidence was provided for this view, but the authors noted that they consider such setbacks are necessary to ensure sound is attenuated to ‘near imperceptible’ levels.

Reference	Relevant evidence and discussion: Noise limits
Alamir et al (2021)	Alamir et al (2021) provided a summary review of international guidelines on wind turbine noise limits. According to their review, the majority of the countries and territories reviewed (comprising northwest Europe, north America, and Australasia) set limits in terms of the energy time-averaged sound level, L_{Aeq} (or the period-weighted annual average L_{Aeq}-based 'EU noise directive' descriptors used by Norway and the Netherlands). Other exceptions include the UK, New Zealand (which applies NZS 6808:2010), and the Australian state of Victoria (also applying NZS 6808:2010), all of which set limits in terms of $L_{AF90,10min}$. Although Alamir et al suggested that the state of South Australia also imposes limits in terms of $L_{AF90,10min}$, this is not the case in the 2009 EPA Guidelines: the minimum noise limits are defined in terms of $L_{Aeq,10min}$, but for the purpose of compliance testing it is acceptable to report $L_{AF90,10min}$ without making an adjustment for the expected difference between the indices.

Effects of noise

In this section, any references to numerical sound levels should be assumed to be implicitly referring to **outdoor A-weighted energy time-averaged levels** ($L_{Aeq,outdoors}$), unless otherwise specified.

Evidence summaries

Reference	Relevant evidence and discussion: effects of noise
Black literature: evidence reviews	
Onakpoya et al (2015)	Onakpoya et al (2015) reported a systematic review and meta-analysis of observational cross-sectional studies published 2004-2014. Included studies covered turbine power ratings ranging from 150 kW to over 2 MW, and sample sizes ranged from 62 to 754 participants. Exposure indicators comprised either energy time-averaged levels (commonly determined using modelling of estimated worst-case levels, with some studies conducting limited verification measurements) or distance to turbines, interpreted as an assumed proxy indicator for levels of sound exposure. The exposure indicators were used to determine 'high' and 'low' exposure categories (determined as >40 dB L_{Aeq} and <40 dB L_{Aeq} respectively[574]), or 'near' and 'far' proximity categories (taken as the proximity divisions in the corresponding original studies). A quantitative meta-analysis showed a statistically significant increase in the odds ratio of being annoyed by wind turbine noise for the 'high' exposure (>40 dB L_{Aeq}) or the 'near' proximity, and a significant increase in the odds ratio of reporting (subjective) sleep disturbance in some form. It was also noted that the evidence in the included studies suggests that sleep disturbance is correlated with noise annoyance. A narrative analysis of effects on subjective quality of life (QoL) suggested a possible association with turbine proximity. Noted personal and contextual factors with the apparent potential for associations with adverse noise effects included: visual impacts, economic benefits from wind energy, residual sound environments, and attitude to wind turbines. However, the evidence across the studies was not found to be consistent on these aspects.
Saveedra et al (2015)	Saveedra et al (2015) presented a narrative literature review (described as a 'systematic review', but there is no description of the search or screening methods applied, or a survey of the resulting literature, all of which are expected in a systematic review). They noted the reviewed studies' conclusions that there is no evidence that wind turbine sound exposure has direct adverse health 'consequences', but highlighted the evidence for associations with noise annoyance. Saveedra et al also noted the apparent connection between visual impacts and noise annoyance, as well as the link between noise annoyance and potential (subjective) sleep disturbance.

[574] There was no reported attempt to ensure the reported levels of sound exposure were determined using consistent methodologies between different studies included in the meta-analysis.

Reference	Relevant evidence and discussion: effects of noise
Harrison (2015)	Harrison (2015) presented a narrative literature review examining potential biological mechanisms that might conceivably account for the range of health symptoms associated with the hypothetical disorder 'wind turbine syndrome'. The evidence considered is focussed on a specific pathological condition known as 'superior (semicircular) canal dehiscence syndrome' (SCDS), which can enable acoustic activation of the vestibular system at levels around 20-30 dB lower than expected in adult humans without SCDS. Harrison et al considered how common the occurrence of SCDS is, presenting evidence indicating rates of around 1-5% in adults, but higher in young children (which may be related to immature ear canal development). Combining this evidence with expected levels of acoustic stimulation from wind turbine sound, the author concluded that, although there is a biological pathway to vestibular effects associated with SCDS, the sound levels required for vestibular activation appear to be too high compared with wind turbine sound levels to support this as a plausible biological explanation for the reported symptoms. It was acknowledged there remain knowledge gaps and it was suggested that subjects reporting vestibular symptoms in relation to wind turbine sound exposure should be scanned for possible SCDS, to help separate possible biological and psychological causes of symptom reporting.
Basner et al (2015)	Basner et al (2015) reviewed peer-reviewed articles on the effects of wind turbine sound exposure published between 2011-13. They noted that no evidence was found indicating direct effects of exposure on sleep quality. However, they also highlighted that wind turbine sound is associated with noise annoyance, and evidence suggests that annoyance may in turn be a potential pathway to (subjective) sleep disturbance or 'psychological distress'. It was noted that recognising the sound as generated by wind turbines, and other attitudinal and personality factors have also been related to reported noise annoyance. It was also noted that swishing modulation sounds have been associated experimentally with increased annoyance.
Kageyama (2016)	Kageyama (2016) considered the WHO 1999 GCN[575], and the 2009 NNGE[576] against later evidence, noting that wind turbine sound levels exceeding 40 dB L_{Aeq} have been associated with effects on (subjective) sleep disturbance. However, in some cases this was shown to be the case only for subjects who are particularly sensitive to environmental stressors, or to changes in their physiological state. It was noted that some researchers suggest symptoms reported in relation to wind turbine sound exposure are similar to other psychosomatic complaints linked with 'functional somatic syndromes'[577].

[575] World Health Organization, 1999. *Guidelines for community noise.* [URL]
[576] WHO Regional Office for Europe, 2009. *Night noise guidelines for Europe*. World Health Organization. [URL]
[577] ie, chronic diagnoses characterised by symptoms with no identifiable organic cause [URL]

Reference	Relevant evidence and discussion: effects of noise
Guski et al (2017)	Guski et al (2017) undertook a systematic review to inform the development of the 2018 WHO ENGER[578] addressing noise annoyance. The review screened identified publications up to the end of 2014, resulting in two included publications covering four original studies (the Japan study, and the pooled results of the two Sweden studies and the Netherlands study). A meta-analysis of correlation between levels of sound exposure and annoyance produced a significant correlation with a 'moderate'[579] quality of evidence. However, when the authors attempted to directly compare the exposure-response relationships for the % highly annoyed (%HA) at a given day-evening-night level (L_{den}, the values for which Guski et al took directly from the corresponding publications), the evidence was found to be inconsistent and graded as low quality. Guski et al stated that the evidence showed wind turbine levels of sound exposure are related to noise annoyance, including at levels <40 dB L_{den}.
Rand et al (2017)	Rand et al (2017) presented a narrative literature review focussed on the North American wind energy industry. They noted the association between wind turbine sound and noise annoyance, and the link between annoyance and (subjective) sleep disturbance, but acknowledged the results of the Health Canada study, which found that direct exposure is not associated with objective sleep quality indicators (actigraphy). They also noted that research concludes that wind turbine sound is not directly related to any other adverse health effects, but that nocebo effects have been proposed as an explanation for reported symptoms. They acknowledged that some evidence relates noise annoyance to proximity to turbines, but noted that distance is just one factor influencing how sound propagates, and there is no consensus on 'set back' distances for wind turbine sound. They also highlighted the apparently heightened annoyance response to wind turbine noise compared with other common environmental sound sources, and that some evidence suggests this is related to AM characteristics. They noted that noise annoyance may be strongly influenced by personal and contextual factors, especially visual impacts from turbines. The authors reviewed noise effects thresholds, including the WHO 1999 GCN[580] and 2009 NNGE[581], noting that for wind turbine noise these tend to be in the range 40-45 dB L_{Aeq}.

[578] World Health Organization Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region.* [URL]
[579] Rated according to the GRADE system employed by the WHO Regional Office for Europe [URL]
[580] World Health Organization, 1999. *Guidelines for community noise.* [URL]
[581] WHO Regional Office for Europe, 2009. *Night noise guidelines for Europe*. World Health Organization. [URL]

Reference	Relevant evidence and discussion: effects of noise
Micic et al (2018)	Micic et al (2018) presented a narrative literature review addressing associations between wind turbine sound exposure and sleep disturbance. They reviewed five observational studies that employed subjective sleep quality indicators. In the first Sweden study, 16% of respondents exposed to modelled worst-case sound levels >35 dB L_{Aeq} reported some sleep disturbance, compared with none in categories <35 dB L_{Aeq}. In the second Sweden study, no direct association between exposure and self-reported sleep disturbance was found. In the Netherlands study, a significant increase in the odds ratio for reported sleep disturbance was found for respondents in the modelled worst-case exposure category >45 dB L_{Aeq} when compared with those in the <30 dB L_{Aeq} category. Micic et al concluded that a direct association could not be consistently established based on this evidence. They noted the link between noise annoyance and (subjective) sleep disturbance, as well as the association of annoyance with noise sensitivity. They also reviewed two studies employing objective sleep quality indicators (the Health Canada study, which employed actigraphy, and a small-scale longitudinal study in Ontario, Canada, which employed PSG), both of which found no evidence of direct effects on sleep from wind turbine sound exposure. Micic et al highlighted that subjective and objective sleep quality indicators are not necessarily closely correlated, and pointed out limitations of these studies, including the relatively poor specificity of actigraphy, and the low indoor sound levels in the PSG study. It was concluded that there is a lack of robust and consistent evidence on the effects of wind turbine sound exposure on sleep quality, and further research is necessary using objective sleep measures to clarify any potential effects.
Basner et al (2018)	Basner et al (2018) undertook a systematic review to inform the development of the 2018 WHO ENGER[582] addressing effects on sleep. The review screened identified publications up to 1 December 2015, resulting in eight included publications covering six studies, of which one included objective sleep quality indicators, with the rest addressing self-reported sleep disturbance. It was noted that in the Netherlands study, the apparent significant increase in subjective sleep disturbance for exposure at sound levels >40 dB L_{Aeq} was non-significant when analysed using structural modelling, which indicated that noise annoyance better predicted the reported sleep disturbance. Basner et al highlighted the results of the first Poland study, which found a significant increase in the proportion of respondents reporting sleep disturbance for 40-45 dB L_{Aeq} exposure compared with 35-40 dB L_{Aeq}, and the Japan study, which found a significant increase in the odds ratio for reported 'insomnia' among respondents who also self-reported as being noise-sensitive, and were exposed to estimated levels of 41-45 dB $L_{Aeq,2200\text{-}0600}$, compared with those in the ≤35 dB $L_{Aeq,2200\text{-}0600}$ category. On the other hand, the review authors noted that the Health Canada study found no significant association between levels of wind turbine sound exposure and subjective or objective indicators of sleep quality. Basner et al conducted a meta-analysis of five of the studies, which yielded a non-significant pooled odds ratio for subjective sleep disturbance. The quality of the evidence was rated as 'very low'[583].

[582] World Health Organization Regional Office for Europe, 2018. *Environmental noise guidelines for the European Region.* [URL]
[583] Rated according to the GRADE system employed by the WHO Regional Office for Europe [URL]

Reference	Relevant evidence and discussion: effects of noise
Clark et al (2018) van Kempen et al (2018)	Clark et al (2018) and van Kempen et al (2018) undertook systematic reviews to inform the development of the 2018 WHO ENGER addressing effects on QoL, wellbeing and mental health, and on cardiovascular and metabolic effects, respectively. Both reviews concluded that the quality of evidence identified concerning wind turbine sound exposure was 'very low'[584], noting inconsistent and non-significant results, and high risks of bias. No exposure-response relationships were reported.
Tonin (2018)	Tonin (2018) presented a narrative literature review focussed on wind turbine infrasound, including hypotheses for potential explanations for reported health symptoms and emerging research evidence. The range of hypotheses discussed included 'vibroacoustic disease', a specific 'wind turbine syndrome', and suggestions that exposure to infrasound below perception thresholds may impart stimulation of inner ear components not directly associated with auditory sensations, or vestibular activation, which may be linked with 'motion sickness' symptoms. Tonin noted that, from those reviewed, the only observational study to examine infrasound was the Health Canada study, which employed year-long measurements to demonstrate that wind turbine infrasound could sometimes be detected up to 10 km, but was often below residual levels; infrasound levels measured near the turbine base were around a perception threshold corresponding to the most sensitive 1% of people. Tonin reported the results from the author's own experimental study, which used controlled infrasound exposure based on a real wind turbine signal. It was found that exposure to either real or sham infrasound had no influence on the reporting of health symptoms by participants. However, the expectation of effects connected with the participants' attitudes prior to the experiment did have a significant effect, which supports a nocebo explanation for reported health symptoms associated with wind turbine infrasound. Tonin also reviewed an earlier experimental study that used lower levels of infrasound exposure (Tonin asserted these levels were too low, such that the experimental comparison for exposure groups would have been sham/sham rather than real/sham), but arrived at similar conclusions; symptom reporting could be explained by nocebo effects rather than infrasound exposure.
van Kamp et al (2018) (continued below)	Van Kamp et al (2018) reported a narrative literature that employed a methodology with similar characteristics to a QSR. They reviewed 10 previous evidence reviews up to February 2017 and 24 publications describing original studies 2015-17. They included a review of evidence on the potential for audibility and effects of low frequency wind turbine sound and infrasound.

[584] Rated according to the GRADE system employed by the WHO Regional Office for Europe [URL]

Reference	Relevant evidence and discussion: effects of noise
van Kamp et al (2018) (cont.)	The review of previous evidence reviews noted that the strongest association with wind turbine sound exposure is found for noise annoyance, and, while an association with sleep disturbance is plausible, a direct effect remains uncertain, due to lack of consistency. It was highlighted that wind turbine noise tends to be more annoying than with other environmental sound sources, and evidence from both observational and experimental studies indicates this is related to the AM characteristic. van Kamp et al discussed the personal and contextual factors investigated, noting that visual impacts, financial involvement, noise sensitivity and perceptions of intrusion have been found to influence annoyance, and that some evidence indicates that noise annoyance may be greater in rural than in urban or suburban areas (though this is not consistent). The authors found that the evidence suggests an indirect relationship between subjective sleep disturbance and levels of sound exposure, with noise annoyance as a mediating path. It was concluded that there is no robust evidence from the reviews for any other adverse effects on health. The review of original studies highlighted the outcomes of the Health Canada study, which found a significant association between level of sound exposure and noise annoyance, and the influence on annoyance of several personal and contextual factors, including visual impacts, economic benefits, and increasing length of time living near wind turbines (which was linked with greater annoyance). The study found no significant effect on subjective or objective (actigraphy) measures of sleep quality for exposure at estimated (worst-case annual average) levels up to 46 dB L_{Aeq}, but it was noted that respondents who felt compelled to close windows at night in order to sleep because of wind turbine sound reported greater noise annoyance. It was also noted that the study found no significant associations between exposure and other health outcomes or QoL. The review of a study combining observational results from Germany, Switzerland and the USA found that noise annoyance and stress was correlated with perceptions of fairness during the wind energy development planning process. An observational study in the UK was reviewed, which found that noise annoyance among respondents in suburban areas appeared to be lower than had been observed in the mainly rural studies from Sweden, the Netherlands, Poland and Canada. The results of the Japan study concerning sleep disturbance were noted, which found a significant increase in the likelihood of ‘insomnia’ among respondents describing themselves as noise sensitive. Van Kamp et al noted from an observational study in Denmark that, after controlling for exposure to non-wind turbine sound sources and agricultural odour, an initially significant association between wind turbine proximity and reporting of idiopathic symptoms became negligible.

Reference	Relevant evidence and discussion: effects of noise
van Kamp et al (2018) (cont.)	Several experimental studies were reviewed, and it was noted that a significant influence of positive or negative media messaging on health symptom reporting has been observed. Other results also highlight that expectancy of negative effects of wind turbine infrasound exposure is associated with symptom reporting, but actual controlled exposure to infrasound is not. The review of evidence on low frequency sound and infrasound noted that emission levels from wind turbines are as low or lower than other common environmental sources such as road traffic. The authors also highlighted the typically close correlation between A-weighted and C-weighted wind turbine sound levels, which indicates there is no additional benefit to specific controls on C-weighted levels. The review noted the results of a study indicating activation of outer hair cells at sub-audible infrasound levels, and that wind turbine infrasound at ≥45 dB(A) could reach this threshold, but highlighted that there remains no explanation why similar levels emitted by other sources are not associated with equivalent reports of health symptoms. The authors identified that the symptoms proposed to be connected with exposure to inaudible infrasound are already described in the manual of health disorders as associated with generalised anxiety disorder, and noted that anxiety could be brought about by negative feelings about new or planned wind farms. It was concluded that there is little scientific evidence to support any new or unique health effects associated with wind turbine infrasound or low frequency sound. Reported symptoms linked with wind turbine infrasound could be explained by stress. Suggestions of wind turbine syndrome and vibroacoustic disease are not supported. See also Evidence review corrections entry below.
Carlile et al (2018)	Carlile et al (2018) presented a narrative literature review as part of their work on the Australian Government's Independent Scientific Committee on Wind Turbines (see section 3.3.1). They highlighted an experimental study using fMRI[585] to analyse brain activity during exposure to slightly sub-threshold (-2 dB) infrasound exposure, which showed evidence of in some parts of the brain associated with stress, and anxiety-related disorders. The authors also noted experimental work that detected outer hair cell activation at infrasound levels below audibility thresholds. On this basis, the authors suggested there is a case for further research into potential effects of wind turbine infrasound.

[585] Functional magnetic resonance imaging

Reference	Relevant evidence and discussion: effects of noise
Caddick, ZA et al (2018)	Caddick, ZA et al (2018) reported a narrative literature review of the conditions considered necessary for sleep, including the sound environment. They noted the results of three observational studies, including the Health Canada study, a small-scale longitudinal study in Ontario, Canada, and a study in Maine, USA. Both the Canadian studies used objective indicators of sleep quality along with subjective measures, while the USA study recorded self-reported sleep disturbance only. The authors considered this evidence to suggest that quieter environments are better for sleep, but more research is needed to determine sound characteristics (level and frequency) that is detrimental to sleep outcomes. It's also clear that the authors considered 'continuous noise' as a suitable description to represent the characteristics of wind turbine sound, which indicates they did not consider any time-varying aspects of wind turbine sound, such as intermittency or amplitude modulation. They considered 'intermittent noise' separately, which was exemplified as slamming doors, passing trains, aircraft flyovers or traffic noise.
Simos, J et al (2019) (continued below)	Simos, J et al (2019) presented a narrative literature review addressing the possible health effects associated with a range of environmental impacts of wind turbines, including noise. Their review included consideration of the Netherlands study, the pooled results of the Netherlands study with the two Sweden studies, the Japan study, and the Health Canada study, along with smaller-scale studies, including one in Denmark (that investigated the influence of co-exposure to environmental stressors other than noise), and one in Ontario, Canada (a longitudinal study using objective measures of sleep quality). They also reviewed several experimental studies, which investigated AM, audio-visual interactions, and the relevance of recognising wind turbine sound in noise annoyance responses. Simos et al noted that wind turbine sound is associated with noise annoyance, particularly for levels greater than 35 dB(A), and that wind turbine noise annoyance appears to be exaggerated compared with other sources; some evidence reviewed suggests this is related to the AM characteristic. They highlighted that noise annoyance may also be influenced by visual impacts, individual attitudes, informational messaging, ambient sound environments, and the time of day. They also noted that there are inconsistencies in the evidence on sleep disturbance.

Reference	Relevant evidence and discussion: effects of noise
Simos, J et al (2019) (cont.)	Simos et al highlighted experimental evidence indicating that wind turbine sound can be relatively easily detected within road traffic sound, suggesting that road traffic sound is a poor sound masker for wind turbine sound. It was also noted that recognition of sound as coming from wind turbines can increase noise annoyance. Audio-visual results reviewed indicate that visual impacts may be more influential on noise annoyance responses at lower sound immission levels than at higher levels. The review authors concluded that there is no evidence to support an association between wind turbine sound and other reported health complaints of residents. See also Evidence review corrections entry below.
Freiberg et al (2019) (continued below)	Freiberg et al (2019) reported a systematic 'scoping review' that also included critical appraisal of study quality and risks of bias (the authors noted that this appraisal is an extension to the scoping review methodology, but included it due to their stated view that the subject matter is controversial). The authors retained 84 publications for synthesis following the screening process, including 64 from peer-reviewed literature. They noted that the number of publications identified rises sharply after 2010. Freiberg et al used the critical appraisal of quality and bias risk to categorise studies as 'higher quality' or 'lower quality'. They noted that the lower quality studies tend to produce higher estimates and greater significance of associations for both noise annoyance and sleep disturbance with wind turbine sound exposure, when compared with higher quality studies. They suggested that in some cases this could be explained by selection bias[586] present in lower quality studies. They noted that noise annoyance prevalence rates among wind farm neighbours in higher quality studies spans a wide range, from 4-45% (compared with 6-100% in lower quality studies). They also highlighted that the majority of lower quality studies addressing sleep effects found significant associations with wind turbine sound, which were not found in higher quality studies.

[586] Bias introduced by participant sampling that is insufficiently randomised, which can result in a sample unrepresentative of the target population, and 'self-selection' of participants more likely to respond in a particular way (for example, people who feel more annoyed by wind turbine noise than others in the same population).

Reference	Relevant evidence and discussion: effects of noise
Freiberg et al (2019) (cont.)	From their review of experimental studies, the authors noted that: • Some sound masking by residual sounds has been observed, as long as the wind turbine sound is below 50 dB(A), and lower than the residual sound • Some studies find that AM characteristics in wind turbine sound, such as modulation depth and modulation frequency, may influence noise annoyance • Some studies find wind turbine noise to elicit greater annoyance than road traffic noise • Studies employing audio-visual stimuli exposure demonstrate the interdependence of noise- and visual-related annoyance responses to wind turbines • Nocebo effects relating to wind turbine infrasound have been demonstrated, and it has also been shown that positive information about wind turbines and explanation of the nocebo effect itself can help to overcome this In relation to the potential influence of individual attitudes and expectation, the authors noted that: • Studies have demonstrated links between positively- or negatively-framed information about wind turbine health effects with rates of symptom reporting, indicating a psychogenic effect. Moreover, it has been observed that negative health implications and poorer QoL have been found in communities of wind farm opponents than in communities supportive of wind energy developments • Analysis in Australia found that rates of complaints about wind turbine noise and associated health problems increased alongside an increasing focus on health issues among civic groups opposed to wind farm developments The review authors identified that research gaps remain concerning the 'complex pathways of annoyance' acting as a mediator for other health effects and acted upon by numerous personal and contextual factors; investigation of visual impacts of wind turbines; interactions between wind turbine stressors (noise, visual impacts etc); 'clinically apparent' health outcomes; and observational studies on low-frequency and infrasound from wind turbines, noting that future research needs to incorporate thorough, high-quality, prospective (longitudinal) study designs. See also Evidence review corrections entry below.

Reference	Relevant evidence and discussion: effects of noise
Hansen (C) et al (2020) (continued below)	Hansen (C) et al (2020) presented a narrative literature review intended to give a general overview of current research findings and future research directions across all aspects of wind turbine acoustics. In relation to emerging evidence on noise limits, they referred to a study that analysed community annoyance exposure-response relationships for wind turbine noise from the Sweden, Netherlands, Japan and Health Canada studies. By combining these relationships, the study authors suggested that securing a maximum of 10% 'highly annoyed' people according to the derived relationship would entail imposing an upper limit on wind turbine sound of 37 dB L_{Aeq}. However, Hansen (C) et al also observed that the exposure-response relationships derived in the various studies are difficult to compare, due to different methods used to establish the exposure estimates. They highlighted the results of an attempt to normalise the exposure estimates from different studies, which indicated that noise annoyance outdoors increases substantially for levels above 35 dB $L_{Aeq,1h}$. The review authors noted results from another study of wind turbine sound exposure-response relationships, which observed that noise annoyance associated with wind turbine sound increases more rapidly and at lower levels than common transportation sound sources. They also noted review findings that AM appears to increase noise annoyance associated with wind turbine sound. Hansen (C) et al highlighted results from two observational studies (the third Poland study and the UK study), both of which found that the noise annoyance associated with levels of wind turbine sound exposure was in turn associated with (subjective) sleep disturbance (ie, no direct association with sound levels was observed). Results from the Danish nationwide study were noted, which (using very large sample sizes enabled by the Danish national health register database alongside sound exposure modelling for over 7000 wind turbines across Denmark, incorporating wind condition simulations over a 31-year period) identified a significant association between long-term average outdoor night-time wind turbine sound levels ≥42 dB $L_{Aeq,2200\text{-}0700}$ (5-year average) and redemption of antidepressant prescriptions, when compared with exposure to <24 dB $L_{Aeq,2200\text{-}0700}$. Among an elderly subset of the sample, a significant association was found for sleep medication redemption among elderly people (but not for antidepressants). The study authors noted that replication of the results would be desirable to confirm the findings. Hansen (C) et al also reviewed experimental studies, one of which indicates that the residual sound environment has an effect on annoyance ratings attributed to wind turbine sound.

Reference	Relevant evidence and discussion: effects of noise
Hansen (C) et al (2020) (cont.)	Regarding the effects of infrasound, the review authors noted experimental results that indicate that participants are unable to discern between real or sham infrasound exposures. Hansen (C) et al critiqued the tests, suggesting that future studies should include longer exposures, people who consider themselves sensitive to infrasound, and field recordings of wind turbine infrasound (rather than the synthesised signals designed to mimic wind turbine infrasound as used in the tests). However, they also noted initial results from a separate pilot study that used real wind turbine infrasound recordings alongside synthetic signals, in which the participants could not identify the infrasound during exposure to levels representing typical wind turbine immissions.
Davy et al (2020)	See Stage 1 evidence review summary in section 9.1.1. Davy et al (2020) also referred to their other previous article (Carlile, Davy, Hillman, & Burgemeister, 2018), and highlighted that, while research has not identified robust evidence supporting specific effects from wind turbine infrasound or low frequency sound, their review suggested there is a case to support the notion that there is physiological transduction, neural excitation and encoding by the nervous system of infrasound and low frequency sound even at moderate sound levels, although whether there are resulting effects of these mechanisms remains unknown. Davy et al (2020) noted that since there is no robust evidence for health effects of wind turbine infrasound, they cannot recommend any specific infrasound limits, although they advised that further research is needed. The authors noted that evidence on sleep, health and quality of life is inconsistent. They also confirmed their support for the conclusions of the Australian NHMRC that there is no consistent evidence that wind farms cause adverse health effects in humans. They also highlighted the results of experimental studies showing that AM increases annoyance ratings of wind turbine sound, and the depth of modulation is weakly associated with the increased annoyance.
Clark et al (2020)	Clark et al (2020) reported a systematic review covering the effects of common transportation sound sources and wind turbines on a range of physiological and psychological health outcomes. The search covered studies published between the corresponding WHO 2017-18 systematic review search end dates (in 2015) up to March 2019. For effects on cancer or dementia (which were not covered in the WHO reviews), the search covered studies from January 2014. They included one publication from the Health Canada study addressing QoL, which was appraised[587] as very low quality evidence indicating no effect. They also included one publication from the Danish nationwide study addressing adverse birth outcomes, which was appraised as moderate quality evidence indicating no effect.

[587] Rated using the same GRADE system as employed in the WHO 2017-18 systematic reviews

Reference	Relevant evidence and discussion: effects of noise
van Kamp et al (2020) (continued below)	Van Kamp et al (2020) presented a scoping review that also included some appraisal of study quality (either directly using a simple scoring system, or indirectly by study type selection). The search covered studies published between the corresponding WHO 2017-18 systematic review search end dates (in 2014-15) and June 2019 (with specific papers from December 2019 added). They retained 18 publications concerning wind turbine sound that met the screening criteria, 14 of which address annoyance or sleep disturbance effects. The review authors noted that the number of large-scale studies of medium to good quality[588] addressing wind turbine sound has increased since the WHO reviews. They concluded that an updated meta-analysis of the new evidence on annoyance and sleep disturbance associated with wind turbine sound is warranted. They also reviewed the results from the Danish nationwide study, noting that • there was no significant association found between wind turbine sound exposure and: ○ antihypertensive medication redemption ○ incidence of stroke ○ increased risk of diabetes

[588] According to application of PRISMA criteria for risks of bias [URL]

Reference	Relevant evidence and discussion: effects of noise
van Kamp et al (2020) (cont.)	Among the supplementary materials, further details of review summaries from the wind turbine studies were recorded: • In the Health Canada study, multiple logistic regression models of high annoyance (%HA) indicated a relatively weak association with levels of sound exposure (Nagelkerke pseudo-R^2 of 9%). The odds ratio for high annoyance with sound level (at 5 dB intervals of worst-case modelled L_{Aeq}) was significant at 2.38. The Health Canada study also found no significant effect of wind turbine sound exposure on the objective or subjective sleep indicators employed. • In a small study in Norway, a larger increase in annoyance was attributed to wind turbine sound compared with road traffic noise than was found in the combined Netherlands and Sweden studies. Further analysis suggested that once personal and contextual factors were controlled for, including visual perceptions and attitudes to wind energy, the difference was similar to that observed in the combined Netherlands and Sweden studies. • In the Poland studies, significant associations were found between annoyance (%A) and level of sound exposure, with general attitude being a primary factor influencing annoyance. • In the Japan study, it was found that self-reported 'insomnia' was significantly more prevalent in areas with levels of night-time wind turbine sound exposure >40 dB compared with <35 dB ($L_{Aeq,2200\text{-}0600}$). • In the Finland study, a significant association was found between level of sound exposure and both outdoor annoyance (%A) and subjective sleep disturbance. Odds ratios were 1.41 for outdoor annoyance (%A) and 1.38 for sleep disturbance by wind turbine noise, based on 5 dB intervals starting from 25-30 dB up to 40-45 dB L_{Aeq}. • In the China study, annoyance (%HA) and subjective sleep disturbance were investigated, finding significant associations for both with sound level. Levels of sound exposure were rather higher than observed in other studies. See also Evidence review corrections entry below.

Reference	Relevant evidence and discussion: effects of noise
Liebich et al (2020)	Liebich et al (2020) reported a systematic review and meta-analysis of studies addressing the effects of wind turbine sound on sleep, published from 2000 until April 2020. The review included six observational studies (including the Health Canada study along with five small-scale studies, three in Canada, one in the US and one in Iran) and three experimental studies (which all stem from the University of Gothenburg WiTNES project in Sweden). Three of the observational studies employed subjective sleep quality indicators, while three used objective measures alongside self-reported sleep disturbance. The three experimental studies used both objective and subjective sleep quality indicators. Five studies using objective measures were included in the meta-analysis, which found no significant effect of wind turbine sound exposure on any of the key sleep quality indicators. The narrative review and synthesis highlighted that: • Some evidence for effects on particular sleep stages was found in the WiTNES study (%N3 sleep, %REM and latency to REM). • Subjective sleep quality indicators in the form of validated questionnaires or sleep diaries suggest that the former support a potential effect while the latter are inconsistent. The authors concluded that the results of the review and meta-analysis did not support the notion that wind turbine sound exposure impacts on objective indicators of sleep quality, but does appear to impact some subjective sleep indicators, which suggests that wind turbine sound can contribute to subjective sleep disturbance.
Mucci et al (2020)	Mucci et al (2020) presented a systematic review of publications from 2010 to November 2020, addressing the effects of a range of sound sources in terms of 'psychological distress', a term that is qualified by the description of "*psychological disorders, in particular annoyance and sleep disorders*". The review included six original articles addressing effects of wind turbine sound exposure, and the WHO Systematic Review for annoyance (Guski, Schreckenberg, & Schuemer, 2017). The review authors concluded that wind turbines 'cause' annoyance (although the cross-sectional design of all of the studies reviewed that investigated annoyance would technically preclude causal inferences), visual impacts are more pronounced in rural areas than more densely populated areas, and financial involvement can reduce reported annoyance. See also Evidence review corrections entry below.

Reference	Relevant evidence and discussion: effects of noise
Lubner et al (2020)	Lubner et al (2020) reported a narrative literature review of evidence concerning effects from exposure to infrasonic or electromagnetic waves. One study concerning wind turbine infrasound was reviewed, which suggests that outer hair cell activation could occur in the inner ear at levels below the normal infrasound audibility thresholds, and it is speculated that this may have some previously unknown effect on the audiovestibular system.
Tham et al (2020)	Tham et al (2020) presented a scoping review of evidence on a wide range of renewable technologies and associated potential impacts, including noise. They reviewed seven wind turbine studies since 2015, including the Heath Canada study, the Japan study, a small study in Norway, two small longitudinal studies investigating sleep quality in Ontario, Canada, and a Portuguese study examining residents' choices over implementing sound insulation measures to their homes in relation to wind turbine sound exposure. In summary, the review authors noted that the findings from the studies reviewed do not highlight contradictory evidence to that found in previous systematic reviews. They also noted that the more recent research suggests stronger adverse effects as being associated with negative attitudes towards wind turbines.
van Kamp et al (2021) (continued below)	Van Kamp et al (2021) reported an update to their earlier narrative literature review (van Kamp & van den Berg, 2018) to cover publications from 2017 to June 2020, and to add some earlier publications (from 2016) missed in the previous review. The evidence synthesis was described as 'scoping' but an assessment of quality of evidence using a 'short and user-friendly' protocol was undertaken. 24 publications were included in the review, comprising 10 reviews and 14 original studies.

Reference	Relevant evidence and discussion: effects of noise
van Kamp et al (2021) (cont.)	In reviewing evidence reviews in the period 2017-20, the review authors noted that the WHO 2017 Systematic Review had concluded that the evidence reviewed was low quality and generalised exposure-effect relationships for annoyance or sleep disturbance were not justified. The conclusions of Freiberg et al (2019) were highlighted, namely that lower quality studies tend to produce larger estimates of annoyance and sleep disturbance effects compared with higher quality ones. The review authors also noted the conclusions of Simos et al (2019), ie that reported health symptoms apart from annoyance can probably be explained by nocebo effects, and those of Micic et al (2018), which suggested two plausible potential pathways for sleep disturbance, but did not provide evidence. In reviewing original observational studies 2017-20 (with 3 studies from 2016 also added) the authors noted: • a small study in Norway, which indicated wind turbine sound is ~17-18 dB more annoying than road traffic sound • the third Poland study found significant associations between noise annoyance and i) wind turbine sound and ii) distance to turbines. The %HA increased significantly for worst-case exposure levels ≥35 dB L_{Aeq}. Confounders included 'residential satisfaction', visual perception, demographics, and individual attitude to wind turbines. • the Finland study found a significant association between wind turbine sound levels and noise annoyance (%A) outdoors, but not indoors. The study also identified a weak (but significant) association between sound levels and subjective sleep disturbance (although the study article notes the sleep disturbance question specifically drew respondents' attention to wind turbines as a possible cause). • the China study identified significant associations between sound levels and both noise annoyance and sleep disturbance – the range of exposure levels in the study was rather higher than in other studies, and %HA rates were correspondingly high, ranging from 40% to 75%. • the Health Canada study derived an 'aggregate annoyance' measure to take into account multiple factors affecting responses, including sound level, visual impacts, visibility of warning lights, vibrations and shadow flicker, which explained 58-69% of the variability in total annoyance. The aggregate annoyance was significantly associated with distance to turbines. • a small study in Portugal concluded that residents in the vicinity of one wind farm took decisions to install sound insulation to their dwellings on the basis of sound levels and not on noise annoyance

Reference	Relevant evidence and discussion: effects of noise
van Kamp et al (2021) (cont.)	• the US DoE study found that wind turbine sound level was the most robust predictor of audibility, but a weak (significant) predictor of noise annoyance, which was better explained by visual perception and receipt of economic benefits • a study led by German researchers combined the US DoE study results with two studies in Germany and one in Switzerland, and established a noise-annoyance-stress composite response indicator, which was correlated with negative perceptions about fairness in the planning process for wind farms • the same German research group presented results from one of the Germany studies that employed a longitudinal design. It was found that wind turbine sound was an important indicator of annoyance and subjective stress. However, they also found that symptoms were more influenced by road traffic sound than by wind turbine sound. • a small study in Canada used a case control design, measuring objective (PSG) and subjective sleep indicators, finding no statistically significant difference between the exposed and control groups • the Danish nationwide study found a significant association between long term averaged night-time wind turbine sound levels ≥42 dB $L_{Aeq,2200\text{-}0700}$ and redemption of sleep medication among the ≥65 years age group. • the Japan study found that self-reported 'insomnia' was significantly more prevalent in areas with night-time wind turbine levels of sound exposure >40 dB $L_{Aeq,2200\text{-}0600}$ compared with <35 dB(A) among respondents self-described as noise sensitive. • the Danish nurse cohort study found "*suggestive evidence*" of an association between wind turbine sound exposure and atrial fibrillation, based on a significant hazard ratio for long term wind turbine sound levels ≥20 dB(A) compared with <20 dB(A). They cautioned against overinterpretation however, due to the low exposure levels. The influence of personal and contextual factors identified in the studies was discussed, noting these include noise sensitivity, general anxiety or worry, perception of fairness in the planning process, local community involvement and participation, beliefs in ‘wind turbine syndrome’ or ‘vibroacoustic disease’ related to wind turbine sound or infrasound emissions, economic involvement and benefit, as well as some evidence on contributions from sex and educational level. The results of experimental studies were highlighted, which identified that noise annoyance ratings are affected by AM character, and that visual and acoustical impacts interact with attitudinal factors in determining annoyance.

Reference	Relevant evidence and discussion: effects of noise
van Kamp et al (2021) (cont.)	The review authors also highlighted an experimental study in Finland, which exposed a sample of symptomatic respondents (intentionally selected as self-declaring infrasound-sensitive from a much larger sample of 1351 used in an observational study) to wind turbine sound and infrasound recordings made at houses said to be uninhabited because the occupants had vacated due to wind turbine noise (1.5 km from nearest turbine). The results showed that people reporting symptoms did not exhibit an increased sensitivity for infrasound; annoyance was instead related to total sound level and the AM in the sound, but not to the presence of infrasound. Infrasound or annoyance had no association with heart rate or heart rate variability, nor with skin conductance (as objective measures of stress). The review authors concluded that the quantity and quality of studies investigating associations between wind turbine sound exposure and health effects has increased since 2017, and that the WHO 2017-18 Systematic Review conclusions on the strength of evidence are no longer valid; the number, size and quality of studies has increased sufficiently to justify undertaking a new systematic review and meta-analysis. Their findings from the review also included the following: • A robust association with annoyance has been demonstrated: %HA increases with sound level, and the combination of noise and visual impacts explains a large portion of the annoyance responses. Annoyance is also increased by audible AM, an effect which some evidence suggests can also interact with the visual impact. Wind turbine noise annoyance is greater than for other common environmental sound sources at equivalent exposure levels. • Evidence on other health effects associated with wind turbine sound exposure, including sleep disturbance or insomnia, mental health or cognition, cardiovascular health and metabolic effects, is inconsistent or absent. Noise annoyance is sometimes associated with other health symptoms, but study designs preclude conclusions about the causality in the relationship. • Any adverse health effects from low frequency sound or infrasound are highly unlikely at typical wind turbine sound levels. Low-frequency sound is part of the sound emitted by wind turbines and has the same kind of effects that normal sounds have; some people will find it annoying, which may have some consequent effects on sleep and chronic annoyance that could potentially lead to other health outcomes. This is also the case for sound emitted by other common environmental sources, including aircraft, road traffic, or railways. • There are several other important factors beyond sound exposure that strongly influence noise annoyance responses, and managing the impact of wind turbine sound could also entail addressing these factors, which include communities' sense of participation in development planning, procedural justice and perception of fairness in the balance of costs and benefits of developments See also Evidence review corrections entry below.

Reference	Relevant evidence and discussion: effects of noise
Alamir et al (2021)	Alamir et al (2021) presented a narrative literature review that followed a systematic search process. The stated purpose of the review was to summarise the available evidence regarding current wind turbine noise assessment guidelines, and to make comparisons between wind turbine sound and road traffic sound. In comparing wind turbine and road traffic sound, the authors noted that wind turbine sound tends to have greater impact at night (whereas road traffic tends to be daytime) and affect predominantly rural areas (whereas road traffic mostly affects urban areas). It was highlighted that expectations of the local acoustic environment may differ between residents of each of these areas, which could affect responses to the sound. They also noted that wind turbine sound has a periodic AM characteristic with a modulation frequency ~0.5 to 2 Hz (which can be faster than is typical for road traffic), and that wind turbine sound tends to have greater low frequency content than road traffic, which is consequently less-effectively attenuated by building envelopes. On the other hand, they noted that wind turbine sound immission levels are typically lower than road traffic. Alamir et al suggested that the apparently higher annoyance responses to wind turbine sound compared with road traffic sound (at the same exposure levels) are likely partly due to these differences in acoustical characteristics. In reviewing noise limits identified in existing regulations, Alamir et al noted that these have tended to be based on those applied to other types of sound source. They reviewed the basis for the ETSU-R-97, highlighting that this appears to have been superseded (see Stage 1 review summaries in section 9.1.1). They observed that the range of variation between equivalent limits imposed in different national and state regulations (in Europe, Australasia, and the US) is large, at around 25 dB, and a range of different sound level quantification indices are employed. In relation to future development of noise regulations for wind turbine sound, Alamir et al note the approaches taken by researchers in Italy, which derived a proposed limit for wind turbine sound by using road traffic and wind turbine sound exposure-response relationships for noise annoyance from the literature, to transpose the Italian road traffic noise limits to the equivalent wind turbine sound level. The limit they arrived at by this process for wind turbine sound was 43 dB L_{Aeq}, based on the Italian road traffic noise limits of 70 dB L_{Aeq} (daytime or evening) and 60 dB L_{Aeq} (night-time). They also noted the approach taken by Davy et al (2018) (see Stage 1 review summaries in section 9.1.1). The authors observed that there is very little research evidence explicitly investigating the variability and intermittency of wind turbine sound, and advised that this should be addressed in future work. See also Evidence review corrections entry below.

Reference	Relevant evidence and discussion: effects of noise
Black literature: original studies	
Wilson et al (2016)	Wilson et al (2016) reported a case-study of a small-scale UK wind farm. Semi-structured interviews were conducted with 58 stakeholders (including 52 randomly selected local residents within 3 km). Of the 52 residents, 18 (35%) objected to the proposals during the application stage in 2002. In 2013, 5 years after installation, 15 (29%) considered themselves to be still 'strongly against' the turbines. No sound level or character data were collected as part of the study. Interviewed residents frequently mentioned noise as an issue: 30% reported being either irritated by the noise or that it kept them awake at night; on the other hand, 70% of respondents indicated they had habituated to the sound. When the study area was divided into annular segments, 100% of respondents within 1 km mentioned noise frequently, compared with 16% for locations >1 km. It was noted however that no official complaints have been made to the council about possible noise nuisance. One respondent suggested this lack of taking action could be explained by concerns about possible impact on property values. Compared with previous studies looking at acceptance models over time, this case-study indicated lower (but still observable) recovery of positive acceptance post-installation.
Hessler et al (2017) (continued below)	Hessler et al (2017) presented a discursive, opinion-based article in which the four authors presented personal views on the 'impasse' in the debate around possible health effects caused by wind turbine low frequency sound or infrasound. It was noted the authors agree that wind farms should be designed to not exceed a limit of around 40 dB(A), with lower limits down to 35 dB(A) applicable in areas with lower ambient sound levels, and potentially higher limits up to 45 dB(A) in higher ambient sound level areas. One author concluded that there is no evidence that wind turbine infrasound affects health, and some indications that it does not, but audible wind turbine noise can cause annoyance and stress, leading to poorer sleep quality, effects which can be heightened in those who oppose wind energy developments, whose "*hostility can be heightened by the actions of objector groups*".

Reference	Relevant evidence and discussion: effects of noise
Hessler et al (2017) (cont.)	Another author speculated on two 'possible overlooked' pathways by which wind turbine sound or infrasound might be sensed by people at very low sound levels: the first being some as yet undiscovered non-cochlear pathway, and the other being some mechanism linked to the turbine power generation of turbines, rather than overall levels of sound exposure. It was suggested that this latter mechanism might be connected with blade flex causing greater blade-tower interaction with increasing power output. A third author speculated on a specific type of signal that may be similar to or contained within wind turbine sounds, that produces a 'thump' that could be mistaken for infrasound. With their collective conclusions, the authors noted that, based on analysis of a 'typical' 3 MW turbine spectrum, the low frequency sound levels are very unlikely to exceed suggested limits for other low frequency sound sources. It is also highlighted that the difference between dB(C) and dB(A) levels (commonly used to identify and characterise sounds that may be associated with a low frequency noise problem), is relatively small for wind turbine sound, and does not increase with distance (when considering the influence of a typical quiet ambient sound environment). On this basis it was concluded that wind turbines are not a 'classic' problematic source of low frequency noise. The authors also concluded that their shared view is that no specific infrasound or low frequency noise criteria are necessary to control wind turbine noise impact, over and above limiting A-weighted levels. They caveated this conclusion with the recommendation that further work should investigate the ‘possible overlooked’ pathways identified.

Reference	Relevant evidence and discussion: effects of noise
Barry et al (2017) Michaud et al (2018) (responding)	Barry et al (2017) conducted a reanalysis of the Health Canada study dataset, substituting proximity to turbines for level of sound exposure as the predictor variable. Regression models were developed to investigate noise annoyance, sleep disturbance and QoL. The authors claimed that their reanalysis showed that distance *was* significantly associated with increased noise annoyance and poorer QoL scores (by contrast, the results of the Health Canada study, using exposure sound level as the predictor, did not find a significant association with either outcome). In response to Barry et al (2017), the Health Canada study researchers (Michaud, Guay, Marro, & Than, 2018) contested the conclusions of the reanalysis on two primary, related grounds: i) they identified that the approach to the regression modelling was inconsistent with the type of model being applied; consequently, this made interpretation of the model results problematic; ii) on that basis, the findings claimed by Barry et al (2017) were incorrect because they had wrongly interpreted the models using distance, and demonstrated this with an example. Michaud et al (2018) concluded with a rebuttal of the conclusions reached by Barry et al (2017), however they also acknowledged that they have subsequently investigated (and found significant associations between) distance to turbines and an 'aggregated annoyance' rating towards multiple features of turbines (including sound level) using the Health Canada data.
Poulsen et al (2018)	Poulsen et al (2018) reported a large-scale 'big data'-based observational study using a case crossover design: the Danish national health register was used to obtain data corresponding to all Danish adults exposed to sound levels generated by ~7000 onshore wind turbines across Denmark that were estimated to be >30 dB $L_{Aeq,1h}$ for at least two days during the years 1982-2013 (the total sample size was >700,000 people). Exposure estimation was conducted by hourly modelling of time-averaged sound levels using simulated meteorological conditions. The nightly-averaged external levels were then used as the exposure indicator. Indoor low frequency sound levels were also estimated, using building envelope attenuation spectra derived from averaged measurements for typical Danish housing stock (which included windows open and closed conditions). The health register data was used to identify diagnosis cases of heart attack or stroke. The authors observed that the resulting exposure-effect relationships (odds ratios) were non-significant at the 95% level. However, it was also highlighted that the analysis indicated a (weak) potential trend could be present in the data due to persistent (but non-significant) positive odds ratios across the sensitivity analyses, which adjusted for potential confounders. The study acknowledged that this observation could also simply be due to chance, and reproduction would be necessary to confirm any potential association.

Reference	Relevant evidence and discussion: effects of noise
Taylor et al (2019)	Taylor et al (2019) presented a review based on a ‘Science and Technology Studies’ (STS) approach, employing rhetorical analysis to examine how the different arguments in the wind energy debate compete for legitimacy and to convince people of their veracity in 'trials of strength'. The search included publications up to 31 December 2017, with the earliest included from 2004. From reviewing 118 publications, the authors established three possible explanations for the cause of reports of ill health among people living near wind turbines: (i) exposure to wind turbine infrasound directly causes adverse physiological health effects; (ii) exposure to wind turbine sound is associated with annoyance, sleep disturbance and poorer quality of life, and annoyance also acts as a mediator to other adverse effects; (iii) psychogenic factors, such as the visual perception of turbines, or expectations of negative health impacts, mediate between wind turbine sound exposure and adverse health outcomes. The authors put forward various arguments to illustrate the different sides of the debate, and drew links between the political ambitions and motivations of those involved, and the corresponding rhetorical positions, as well as the emphasis on different aspects of 'the science'. It was noted that there is very little evidence of adverse effects from wind turbine infrasound exposure, and the arguments used to advance this position include (i) the typically below-threshold exposure and (ii) the similarity between levels of wind turbine infrasound and other common sources. On the other hand, some of the reviewed studies argue that the precautionary principle should be applied, on the basis that ‘absence of evidence is not evidence of absence’. The review authors pointed out that, although there is widespread support for links between wind turbine sound and noise annoyance, annoyance itself is not consistently defined, and has been interpreted differently by various researchers. Moreover, regulators often do not consider annoyance as a health outcome, but see it instead as a potential mediator or an irritation. It was noted that case study evidence is often dismissed as unreliable, but that some authors argue that the weight of many case studies together forms an important part of evidence. The authors highlighted that case-control and cohort studies are costly and time-consuming, and consequently cross-sectional studies are usually employed, which cannot demonstrate causality.
Bahsi et al (2019)	Bahsi et al (2019) reported a local interview questionnaire study of 126 respondents in one area in Turkey. It was noted that, although participants were randomly selected, the geographic sampling was not randomised, with specific villages intentionally targeted. It is also noted that 65% of the respondents were male, while 32% were 'housewives', and 34% were pensioners. ~32% of respondents lived within 1 km of a wind farm, with 44% stating they could hear the turbines, while 62% stated they were not disturbed by noise from the turbines. Most of the respondents were supportive of wind farms in general, and of the installation of more turbines.

Reference	Relevant evidence and discussion: effects of noise
Mills et al (2019)	Mills et al (2019) reported a repeated post-construction survey of 520 landowners around wind farm sites in Michigan. The aim was to examine how perceptions related to the benefits and impacts of wind farms changed over time, and how these might be related to feelings about justice in the planning process, or financial compensation. Their analysis indicated that, for those who felt there was an unjust planning process for wind farms, or those who had not been compensated financially, there was an association between worsening perception of noise impacts over time – the association with feeling the process was unjust was marginally significant, while the association with no compensation was significant and stronger.
Brudermann et al (2019)	Brudermann et al (2019) surveyed 137 summertime visitors to locations in the Austrian Alps in the vicinity of operational wind farms. Acceptance rates of the wind farms in the locality were relatively high. Respondents completed a questionnaire with Likert-scale statement items, some of which concerned annoyance due to potential adverse impacts such as noise and visual perception. It was found that the annoyance items were the main predictor for non-acceptance, while perceived benefits were the main predictor for acceptance. The authors concluded that policy makers need to concentrate on promoting the benefits of wind energy, while operators need to take annoyance concerns seriously, in order to promote public acceptance of future developments.

Reference	Relevant evidence and discussion: effects of noise
Johansson et al (2019) (continued below)	Johansson et al (2019) reported results from an experimental study that exposed 34 participants to ‘target’ wind turbine sounds simultaneously with residual potential masking sounds. The target sounds included a ‘large’ and ‘medium’ size horizontal axis turbine and a ‘small’ vertical axis turbine, while the range of residual sounds comprised wind-vegetation interaction in a forest, urban street pedestrian and vehicle sounds, and motorway traffic. The sounds were presented over headphones, with the residual sounds at a relatively high fixed presentation level of 60 dB(A), which was determined by the participants themselves as being perceived as ‘natural’. A ‘magnitude production’ procedure was employed, in which participants adjusted the sound level of the target sounds to match a given annoyance value on a rating scale. A psychoacoustic loudness metric was also used to quantify the sounds. Two stages to the test were conducted: i) the target sounds in isolation, and ii) the target sounds with the masking residual sounds. The study found that: • in the target sound only test, the authors compared the derived annoyance with a range of international guidelines on limiting wind turbine sound levels typically to the range 35-45 dB L_{Aeq}, and noted that the corresponding annoyance ratings in the test were 'weak' for the average individual, but 'strong' for the ~10% most annoyed individuals. They also noted that the differences in responses for the different turbine sizes is small at these levels, on the basis of which they suggested there is no need to have different guidelines for smaller or larger turbines, or to revise guidelines to take account of changing sound characteristics of turbines (associated with changes in size). • in the masking test, the signal-noise-ratio of the target sounds was positively correlated with the annoyance scale. At the lowest SNRs, the spread of annoyance results across the different residual sounds and across the different turbine sizes was greater, with observed differences reducing as the SNR increased. This indicates that, as the target sound becomes more prominent within the total ambient sound, differences in responses to different target and residual sound types could become less pronounced. Furthermore, at the lower annoyance ratings (‘very weak’ / ‘just noticeable’), the wind-vegetation sound was the poorest masker, while with increasing annoyance ratings (‘weak’ / ‘moderate’), the results for wind-vegetation and motorway sounds became very similar; urban street residual sounds were consistently the best at masking for the medium and large turbine sizes. The authors noted that the differences in the apparent performance of the residual sounds to influence annoyance was found to be significant. It was also noted that the psychoacoustic loudness metric did not provide a better prediction of annoyance than the A-weighted sound level.

Reference	Relevant evidence and discussion: effects of noise
Johansson et al (2019) (cont.)	It was highlighted that, in comparison with previous work by the authors[589] examining detection thresholds for wind turbine sound in partial masking sound, the annoyance onset masking thresholds seem to roughly coincide with observed detection masking thresholds (masking in the presence of natural residual sounds comprising wind-vegetation interaction or sea waves. This suggests that thresholds of annoyance may be close to perception thresholds.
Kim et al (2019)	Kim et al (2019) interviewed 20 people in Korea known to have opposed local wind farms. It was reported that respondents felt noise had disrupted their memories of the place prior to the wind farm construction, making it into a more mechanical or industrial type of area. They used descriptive words to describe disruptive aspects of the noise, some of which imply audible amplitude modulation.
Keith et al (2019)	Keith et al (2019) reported a field measurement exercise that formed part of the Health Canada study. The measurements characterised the building envelope attenuation afforded by dwellings representing Canadian housing stock. Measurements were taken with both windows open and closed. The measurements were used alongside calculated outdoor wind turbine sound level spectra to estimate indoor levels of wind turbine sound, and compared with a range of standardised hearing thresholds (for different age groups and levels of hearing acuity) to estimate indoor audibility of wind turbine sounds in the absence of any potential masking by residual sound. The results showed that the building envelope attenuation (free-field outdoor to indoor level differences) for wind turbine sound spectra at the 11 receptor dwellings with windows open (100-150 mm opening gap) averaged to 14 dB for dB(A) levels and 10 dB for dB(C) levels (with standard deviations of 2.5 dB and 3.4 dB respectively). The corresponding results for windows closed (façades constructed with timber or brick veneer on timber frame with drywall lining, double glazing to 5-20% bedroom wall area) were 26 dB for dB(A) levels and 15 dB for dB(C) levels (with standard deviations of 3.1 dB and 3.9 dB respectively). Third-octave spectral values were also reported for the range 16-5000 Hz. The calculations of audibility of wind turbine sound (in the absence of masking sound) indicated that, at an outdoor level of 35 dB L_{Aeq}, wind turbine sound would be expected to be audible for almost all adults ≤60 years old, whether outdoors, or indoors with windows open.

[589] Bolin, K, Nilsson, ME & Khan, S, 2010. The potential of natural sounds to mask wind turbine noise. *Acta Acustica united with Acustica*, 96 (1), 131-137. [URL]

Reference	Relevant evidence and discussion: effects of noise
Dutilleux et al (2020)	Dutilleux et al (2020) reported an experimental study that exposed 32 participants to recorded wind turbine sounds mixed together with recorded residual sound (distant road traffic interspersed with bird calls in a 'semi-rural' environment). The aim was to investigate associations between annoyance ratings or audibility of wind turbine sound and the total sound level or the 'sound emergence' (a relative impact concept defined in ISO 1996-1[590]). The study found that annoyance ratings were more strongly associated with the total sound level than with sound emergence. Audibility was influenced by the sound emergence, by the total sound level, and by the individual wind turbine sound sample (one of which was noted as including some blade swish AM, the prominence of which was not quantified). Nearly 1 in 3 participants could detect the least prominent wind turbine sound sample at a signal-to-noise ratio of -10 dB relative to the residual sound level, rising to nearly 70% for the most prominent turbine sample, which contained the audible blade swish. At -5 dB SNR, the minimum audibility rate was ~40%, rising to around 90%. Audibility consistently increased with the total (combined) sound level. The results of the tests indicate that wind turbine sound is relatively easily detected against the type of residual sound used, and that blade swish increases the detectability. For the SNR of -10 dB, sound emergence is almost zero, and for more negative SNRs, sound emergence would asymptotically approach zero. The relatively high audibility rates for sound emergence at the near-zero value suggests that sound emergence is a poor and insensitive proxy for sound audibility.
Zagubień et al (2020)	Zagubień et al (2020) undertook sound and infrasound measurements at a primary school situated ~500 m from 2MW wind turbines on a 25-turbine wind farm. The measurement locations were also ~150-200 m from a main road, and the road traffic could have influenced the measured data, but it was noted that the measured infrasound levels were well below expected audibility thresholds. They presented a simplistic analysis of pupil reading, writing and 'learning' scores over time, which indicates that the school has below-average achievement in these metrics compared with other nearby schools of a similar size. There is no reported exploration of any other possible reasons for differing educational outcomes, nor is there examination or evidence presented concerning when the wind farm became operational and whether that time coincided with any detectable change in learning outcomes. There is no statistical analysis to determine whether the differences in scores are meaningful within the range of educational outcomes.

[590] ISO, 2016. *ISO 1996-1:2016 Acoustics – Description, measurement and assessment of environmental noise – Part 1: Basic quantities and assessment procedures.* International Organization for Standardization. [URL]

Reference	Relevant evidence and discussion: effects of noise
Peri et al (2021)	Peri et al (2021) reported a study that employed GIS analysis to investigate the balance between risk of noise and shadow flicker impacts against energy potential yield for hypothetical siting within a region of Israel, to determine an optimal setback distance. The consideration of sound levels was based on an arbitrary sound level criterion of 35 dB(A). It was noted that greater setback distances could reduce potential noise annoyance among neighbouring residences, but that such constraints influence the total area available for wind energy and decrease the number of permits, while also potentially pushing wind turbine developments into areas of ecologically sensitive land, further away from dwellings. The results are not generalisable to other localities, but do indicate the kind of high-level policy impact assessment study that might be used inform thresholds for adverse effects that are balanced against energy yield implications.
Chaban et al (2021)	Chaban et al (2021) reported an experimental study that examined the effect of infrasound exposure on discarded atrial tissue samples that were stimulated in controlled lab conditions to simulate the muscle contractions of a beating human heart. The infrasound exposure was a 16 Hz sinusoid signal, with exposure levels of 100, 110 and 120 dB(Z) each for 1 hour. There were six sample pairs used, with each pair comprising a control and a test sample. It is noted that the samples were from elderly patients undergoing heart surgery for a range of cardiac pathology reasons. The results showed that for exposure levels 110 and 120 dB(Z), there was a reduction in the measured contraction force for the test vs control. There was no consistent change in contraction durations. The authors noted that the human body provides little attenuation for infrasound, and body cavity resonances may even emphasise it. The authors suggested that a limit on wind turbine infrasound long-term exposure should be set at 80 dB(Z), but no evidence is given to support that specific value as a threshold with reference to the experimental evidence; the value appears to be selected based on an arbitrary 20 dB margin below the lowest 100 dB(Z) used in the authors' experiment. Furthermore, there is no consideration of the relevance of the infrasonic frequency used in the tests to the frequency range of wind turbine infrasound.

Reference	Relevant evidence and discussion: effects of noise
Merino-Martinez et al (2021)	Merino-Martinez et al (2021) reported an experimental study investigating the effects of a range of blade trailing edge modifications on the sound emission, and the associated ratings of (short-term) annoyance. The estimated reductions in overall sound levels at long range receptor locations (simulated at 400 m and 600 m) were ~2-3 dB for all the measures, with third-octave band reductions up to 9 dB. However, the authors noted that the angle of attack used in the scaling up to full size was assumed to be 0º, and cautioned that a greater angle would likely reduce the sound attenuation performance of the modifications. The study presented 16 participants with the corresponding sounds for each variant and the baseline case. The participants rated their judgement of noise annoyance, and it was shown that the ratings were significantly lower for all measures except the metal foam insert. Analysis showed that the reduction in annoyance was well explained by the reduction in the overall sound level (which addressed 77% of the variance), compared with analysis based on psychoacoustic measures loudness, tonality and sharpness. The study also showed a good agreement between the psychoacoustic annoyance model and the ratings of annoyance, indicating that this could be a good prediction tool to use to rate different measures, although the authors cautioned that this might not be generalisable to other sound sources or experiments.

Reference	Relevant evidence and discussion: effects of noise
Turunen, Tiittanen et al (2021) and Turunen et al (2021)	Turunen, Tiittanen et al (2021) presented an observational study with 1351 respondents in four 'wind power areas' identified by consultation with local authorities and civic organisations as being known to contain people reporting health symptoms they associated with wind turbine infrasound. The questionnaire intent was not masked due to the objective of understanding whether respondents associated their symptoms with wind turbine infrasound, which was noted by the authors as impeding generalisability of the results. The authors highlighted that a third of the (self-reporting) symptomatic respondents rated their symptoms as severe, and the symptom spectrum was very broad, covering several organ systems. Many of the symptomatic respondents self-reported as being annoyed by audible wind turbine sound, and also associated their symptoms with vibration or electromagnetic fields from wind turbines. It was concluded that diminished health status, feeling annoyed about wind turbines, and perceiving wind turbines as a health risk were more common among the symptomatic respondents. Turunen et al (2021) also presented a broader investigation of self-reported health issues not necessarily associated with infrasound. The numbers of respondents in the study varied for each health outcome in the range 925-1093, although the overall number of participants is reported as 1411, which was reduced following data cleaning to a total sample of 1180 in the statistical modelling. The prevalence of self-reported symptoms, diseases and medication use was recorded and separated into distance categories. The results of the study showed that annoyance and self-reported sleep disturbance attributed to wind turbine noise were strongly associated with distance to turbines, while the prevalence of all other self-reported health factors examined was approximately the same for all distance categories. The authors concluded that there was no consistent evidence for associations between distance to wind turbines and self-reported health problems beyond annoyance and sleep disturbance.

Reference	Relevant evidence and discussion: effects of noise
Michaud et al (2021)	Michaud et al (2021) presented an investigation using data from a sub-sample of the Health Canada observational study. The sleep quality of 343 participants was monitored over a week period using objective indicators (actigraphy). Corresponding estimates of the levels of sound exposure were determined using wind turbine SCADA data, and synchronised with the sleep monitoring in 10-minute intervals. The exposure estimates were analysed in three ways: i) 9h average night level $L_{Aeq,2200\text{-}0700}$, ii) the 10-min level $L_{Aeq,10min}$, and iii) the level difference between each 10-min level and the night average $\Delta L_{Aeq(10min\text{-}9h)}$. Estimated outdoor exposure levels ranged up to 45 dB (for both $L_{Aeq,9h}$ and $L_{Aeq,10min}$), with average values of 33 dB $L_{Aeq,9h}$ (standard deviation 6.4 dB) and 31 dB $L_{Aeq,10min}$ (standard deviation 10 dB). The analysis found that neither of the absolute exposure indicators exhibited a significant association with the measured actigraphy outcomes. However, a significant association was found between the relative indicator $\Delta L_{Aeq(10min\text{-}9h)}$ and both awakenings and motility. The authors emphasised that the magnitude of the effects was relatively small: for each +5 dB variation in 10-minute L_{Aeq} from the nightly average level, the awakenings were found to increase by 42 seconds per night, while motility increased by 60 seconds. The authors described these magnitudes of change as 'negligible' and unlikely to have any consequential impact on measurable sleep quality. This was taken as support for the previous conclusion drawn from the wider Health Canada study dataset, which found no evidence that wind turbine sound impacted on sleep outcomes. They also noted further analysis comparing adjacent 10-minute periods, which found no evidence for a significant association between actigraphy-measured sleep indicators and the relative sound level metric. The authors highlighted that there is no research evidence on the effects of wind sound itself on sleep quality, which could be an important factor in studies of the effects of wind turbine sound on sleep.
Qu et al (2021) (continued below)	Qu et al (2021) reported an observational study conducted around three sites in the UK. The participant sample included 359 respondents living in suburban areas within 500-2000 m of turbines at 3 sites, each with 1 or 2 wind turbines per site. The intention of the study was to survey suburban respondents, rather than those in rural areas. The main ('focussed') questionnaire included targeted questions about wind turbine sound characteristics, annoyance, personal attitude and financial involvement, while questionnaire variant that had the study intent masked by removing any detailed questions about wind turbine noise was completed by a sub-sample of 97 respondents. The response outcomes measured included noise annoyance, (subjective) sleep disturbance, and a range of other psychological and physiological health symptoms. The levels of sound exposure were modelled for worst-case conditions (8ms^{-1} downwind), which indicated respondents were exposed to levels in the range 25-55 dB L_{Aeq}.

Reference	Relevant evidence and discussion: effects of noise
Qu et al (2021) (cont.)	16% of the respondents noticed the wind turbine sound, while 11% felt some annoyance about it. Of the 16% who noticed the sound, 41% were 'not at all annoyed' by it. The vast majority (90%) of the respondents who reported feeling some noise annoyance by wind turbine sound lived within 900 m of a turbine. Less than 3% of respondents living more than 900 m from a turbine felt any annoyance about wind turbine noise. In the highest exposure category (>40 dB L_{Aeq}), less than half of the respondents noticed wind turbine sound and less than one third felt annoyed by wind turbine noise (although this was the category with the smallest number of respondents, ~15% of the total sample). Swishing and whooshing were the most common sound characteristics indicated by respondents (to the focussed questionnaire). Respondents to the focussed questionnaire were also more likely to feel annoyed by noise if they could see a turbine from inside their home and garden. In comparing their results with earlier studies in predominantly rural areas, the authors noted that wind turbine sound appears to be less noticeable and less annoying to suburban residents. The authors speculated this could be related to the presence of other environmental sounds, either through masking of wind turbine sound, or by comparison with other potential common noise nuisances associated with urban areas, or otherwise it could be related to more positive attitudes to wind energy, which they noted was evident in the study from participant comments. Exposure to wind turbine sound was not directly associated with self-reported sleep disturbance. However, the noise annoyance was found to influence the probability of responses indicating reduced sleep quality. Within the masked questionnaire sub-sample, wind turbine sound exposure exhibited a significant association with the self-reported prevalence of nausea and a weak (non-significant) association with the prevalence of headaches or ear discomfort. These results were not replicated in the main sample of focussed questionnaire respondents; the study found that in this respect there were significant differences between the results from the (main sample) focussed questionnaire and the (sub-sample) masked questionnaire. The authors speculated that this may be because the majority of respondents to the focussed questionnaire indicated they did not think wind turbine noise was harmful to health. This observation demonstrates that the effectiveness of study masking (or lack of) can have a significant influence on the results. Other influences on self-reported health symptoms were also observed to include respondent sex, age and attitude to wind energy development.

Reference	Relevant evidence and discussion: effects of noise
Ascone et al (2021)	Ascone et al (2021) presented results from a randomised-controlled singled-blinded repeated measures observational pilot study that exposed 38 subjects in their own bedrooms to sham or real infrasound over 28 nights (23 subjects had the real exposure and 15 had the placebo). The measured response outcomes included self-reported symptoms (psychiatric symptoms, such as depression or anxiety, perceived stress or subjective sleep disturbance indicators), cognition tests and brain MRI scans. The real exposure comprised a sinusoid of 80-90 dB at 6 Hz for 8 hours during each subject's sleep period. The authors noted that, although this is a level well below audibility threshold, it is ~25 dB higher than might be expected for exposure at a wind farm neighbour. The findings showed no significant effects on the self-reported symptoms or the cognition tests, although a 'trend level' (non-significant) observation was made that perception of 'weakness in parts of the body' was higher in the real exposure group than in the placebo. The brain scans indicated that the exposure group exhibited some decline in brain areas associated with somatomotor and specific cognitive functions (‘working memory’ and ‘higher auditory processing’, comprising speech or speech intelligibility, linguistic processing and reading). The authors concluded that the results suggest that inaudible 6 Hz infrasound exposure does not affect human behaviour, health or general cognitive functions, and future research should further examine bodily sensations, and focus on tasks specifically addressing verbal working memory and linguistic processing.
Lechat et al (2021) (continued below)	Lechat et al (2021) reported an experimental pilot study investigating effects on objective sleep indicators including ‘K-complex’ occurrences. The 21 participants were monitored over 1 night of sleep using PSG to monitor sleep quality. The analysis of K-complex occurrences was automated using a validated machine learning algorithm, while the other indicators were manually scored. During stage N2 and N3 sleep, participants were exposed to 20-second samples of a range of recorded sounds, including wind farm sound at long range (3 km) with and without very low frequency AM (in the 40-50 Hz third octave bands), and a wind farm at short range (700 m) exhibiting a 'blade swish' type of AM (predominating the 315-800 Hz bands), as well as road traffic sound at short (100 m) and long (700 m) ranges. These samples were interspersed with 20-second samples of a quiet steady residual sound at a lower level (the sound characteristics of which were not reported, but can be inferred from the report of the partner study undertaken concurrently[591]).

[591] Liebich, T, Lack, L, Micic, G, Hansen, K, Zajamšek, B, Dunbar, C, Lechat, B, Scott, H, Lovato, N, Decup, F, Nguyen, D & Catcheside, P, 2021. The effect of wind turbine noise on polysomnographically measured and self-reported sleep latency in wind turbine noise naïve participants. *Sleep*, 45 (1), zsab283. [URL]

Reference	Relevant evidence and discussion: effects of noise
Lechat et al (2021) (cont.)	It was found that at sound levels ≥39 dB L_{Aeq}, significant changes were observed in the measured sleep structure indicators, ie K-complex, arousal and awakening occurrences, compared with the quiet steady sound of 23 dB L_{Aeq}. There was no evidence that the type of sound influenced the observed effects, although the authors advised caution in interpreting the results due to the small number of sound presentations. It was noted that controlling for hearing acuity and noise sensitivity showed observable differences in the groups; better hearing acuity was associated with greater odds of K-complex occurrences, while greater noise sensitivity was associated with lesser odds of K-complex occurrences. The authors concluded that long-term effects on sleep related K-complex occurrence are uncertain and further research is needed.
Chiu et al (2021) (continued below)	Chiu et al (2021) reported an experimental interventional field study, investigating the effects of low frequency sound exposure on 'heart rate variability'. 29 participants were recruited for the study, although not all 29 participated in all parts of the experiment. The study design comprised two parts: (i) simultaneous monitoring of A-weighted low frequency sound levels (in the third-octave range 20-200 Hz) and participant heart rates for 2-hour periods during the day, repeated over 2 days, twice in 2 months, one month in summer and one in winter (ie 16 hours total measurement time); (ii) continuous 48-hour monitoring of A-weighted low frequency sound levels at 7 households, once in summer and repeated again in winter, intended to establish whether resident sound levels were similar to those measured during the experiment. The simultaneous sound and heart rate monitoring was undertaken at two sites, one outdoors in very close proximity (20 m) to a wind turbine, and one indoors situated approximately 500 m from the nearest turbine. 24 participants took part in the summer, reducing to 19 in winter; of which 14 took part in both seasons.

Reference	Relevant evidence and discussion: effects of noise
Chiu et al (2021) (cont.)	Measurements were made of A-weighted energy time-averaged sound levels in third-octave bands in the range 20-200 Hz. The levels were evaluated in 5-minute intervals from raw data. No analysis was presented of measured spectra to indicate what low frequency sound content the measured levels represent. The measurements were taken in an area with relatively dense vegetation, near to a beach, and with an elevated highway running through the middle. No measurements were reported of residual sounds (in the absence of turbine operation) to establish what proportion of the measured levels was contributed to by the wind turbines, and what may have been from other sources. The authors stated they were confident that the measured levels were from wind turbines, based on some data 'cleaning' procedures: it is noted that 'regular patterns' comprising 'waves with an amplitude of 1-2 dB' were observed in the data, although no examples of this were presented; it was also noted that the 'regular patterns moved gradually up or down with wind speed'; finally, it was stated that the raw data was examined visually for sudden peaks, defined using a criterion of '10 dB change' in L_{Aeq}, to identify periods for exclusion – this method resulted in exclusions of less than 1% of the data. There was no indication that sound recordings, or any other form of analysis was used to identify and exclude extraneous sound from the measurements. The measurements made at the indoor site were closer to the highway than to the wind turbines. It was noted that no exclusions were applied to the indoor measurements, and that other sources contributed to the measured levels. Further measurements and analysis revealed that one likely contributing factor was ongoing conversations being held within the indoor test environment – this suggests that there was no attempt or instruction to limit extraneous sounds generated by talking etc during the measurements, which indicates that the measured levels may not represent any external sources, but could be representative only of sounds generated within the test environment. This is supported by the observation that the sound levels were sometimes higher at the indoor location (compared with the outdoor). Similarly, there was no reported checking or filtering of the measurements made at households to exclude data that did not represent levels of wind turbine sound. (Inspection of the outdoor measured data suggest there is no consistent relationship between sound levels and distance to turbines. Considering the distances between households and the nearby highway against the measured levels indicates there may be a stronger relationship with distance to the road, which suggests that the measurements may have been contaminated with road traffic sound.) By using a statistical model, the authors concluded that their results show low frequency sound exposure is associated with heart rate variability (HRV), and extrapolated from this to suggest that the effect is from wind turbine low frequency sound, which therefore has an adverse effect on health. Two indicators were used to measure HRV, one of which the modelling showed had a significant association with measured L_{Aeq}, while the other was not significantly associated. The authors also noted their own previous work showing that poorer air quality is associated with changes in heart rate variability, and noted that air quality was not measured or controlled for in the experiment. (Given that the outdoor location was closer and more exposed to the highway than the indoor location, this suggests that there is an uncontrolled factor that could potentially have explained or influenced the results that has not been investigated.)

Evidence review corrections

During the review, a small number of technical inaccuracies or errors were detected in the evidence reviews considered. In some cases, these are likely to have arisen due to the reviewers' tendencies to exclude errata from the search protocols. The issues identified do not fundamentally undermine the conclusions made in the reviews. The issues are summarised below, and should be considered in any future review work based on the same publications:

Reference	Issues identified
van Kamp et al (2018)	van Kamp et al (2018) stated that "*Most environmental sounds with a level of 40 dBA will approximately have the same loudness for human hearing because the A-weighting (that is implied by the A in dBA) is based on the loudness curve of 40 phon (which equals 40 dB at 1000 Hz)*". The notion that the A-weighting curve follows the 40 phon equal loudness contour has been shown to be inaccurate when compared with contemporary equal loudness curves – for example, Yokoyama et al (2015)[592] highlighted this in a study of wind turbine sound loudness perception: "*Another problem of the A-weighted SPL often pointed out when discussing its applicability to a wide range of sound levels is that the A-weighting function was originally proposed as an inverse characteristic of the 40-phon curve of the equal-loudness contours proposed by Fletcher and Munson; therefore, it is unsuitable when assessing intermediate- or high-level sounds. However, when comparing the inverse A-weighting curve to the revised equal-loudness contours specified in ISO 226:2003, it fits around the 60-phon curve. This finding means that the A-weighting curve is not necessarily a frequency weighting function for relatively soft sounds.*"

[592] Yokoyama, S, Sakamoto, S, Tsujimura, S, Kobayashi, T & Tachibana, H, 2015. Loudness experiment on general environmental noises considering low-frequency components down to infrasound. *Acoustical Science and Technology*, 36 (1), 24-30. [URL]

Reference	Issues identified
Freiberg et al (2019) (continued below)	Freiberg et al (2019) noted results from the Health Canada study on sleep effects: "*One cross-sectional study declared that wind turbine noise was not statistically significantly associated with biophysiological variables of sleep (p > 0.05), except with wake after sleep onset*". This statement was based on the original 2016[593] publication, but did not take account of the corrigendum published in 2018[594], which corrected errors detected in the analysis, and had the effect of modifying the observed results, although the overall conclusions were unaltered. The corrigendum notes that: "*Following the reanalysis the most notable secondary observations can be summarized as follows: 1) annoyance toward blinking lights on wind turbines (aircraft warning signals) was no longer found to be related to awakening bouts, however the association with reduced total sleep time remained; 2) annoyance toward vibrations/rattle perceived to be associated with wind turbine operations was found to be related to higher total sleep time in the reanalysis; 3) participants' history of exposure to WTN* [wind turbine noise]*, assessed as "years hearing WTN" was inversely related to awakening bouts; 4) WTN was marginally related to sleep efficiency (p = 0.0519), however there was no consistent pattern revealed in the pairwise tests; 5) caffeine consumption was no longer found to be associated with any of the actigraphy measures; and 6) the correlations between actigraphy outcomes and self-reported sleep measured using the Pittsburgh Sleep Quality Index (PSQI) were more widespread and stronger than previously reported…There is no impact on any of the self-reported outcomes and the overall conclusion of the original paper does not change.*" In other words, following the corrected analysis, the association with 'wake after sleep onset' was deemed by Michaud et al (2018)[594] to be statistically non-significant, but instead an association with 'sleep efficiency' was found to be *nearly* statistically significant ($0.05<p<0.06$). Referencing errors made by Freiberg et al (2019) were also detected, which mixed up the various Health Canada study publications.

[593] Michaud, DS, Feder, K, Keith, SE, Voicescu, SA, Marro, L, Than, J, Guay, M, Denning, A, Murray, BJ, Weiss, SK, Villeneuve, PJ, van den Berg, F & Bower, T, 2016. Effects of wind turbine noise on self-reported and objective measures of sleep. *Sleep*, 39 (1), 97-109. [URL]
[594] Michaud, DS, Feder, K, Keith, SE, Voicescu, SA, Marro, L, Than, J, Guay, M, Denning, A, Murray, BJ, Weiss, SK, Villeneuve, PJ, van den Berg, F & Bower, T, 2016. Corrigendum: Effects of wind turbine noise on self-reported and objective measures of sleep. *Sleep*, 41 (5), zsy037. [URL]

Reference	Issues identified
Freiberg et al (2019) (cont.)	Freiberg et al (2019) also stated that "*Two experimental studies illustrated that wind turbine noise was rated to be more annoying than road traffic noise*", citing van Renterghem et al (2013)[595] as one of the studies. However, reference to the original publication shows that this is an inaccurate representation. In analysing their results, van Renterghem et al actually found that: "*In general, the participants do not rate (pure) wind turbine noise as more annoying than e.g. highway noise at the same (low) equivalent noise level. The samples containing local road traffic noise were rated as significantly more annoying than the others* [ie, including the wind turbine sound]*. The two SNRs considered for the local road samples cannot be considered different even at the 1%-significance level in the multiple comparison tests. Since the annoyance rating is higher than in the case of unmixed wind turbine noise, it can be concluded that local road traffic noise (at close distance) is perceived as more annoying than wind turbine noise at the same equivalent indoor noise level.*"
Simos et al (2019) (continued below)	In considering the results of van Renterghem et al (2013)[595], Simos et al (2019) stated that "*During the first phase of the test, participants were not informed about the objective of the study and it was found that a similar level of noise coming from a wind turbine combined with road traffic elicited significantly more distress than noise coming only from a wind turbine.*". This statement could lead to misinterpretation of the results of the original study, which investigated two different types of road traffic sound (alongside wind turbine sound): (i) distant highway traffic, and (ii) nearby local road traffic. The results as reported in the original study showed that "*The samples containing local road traffic noise were rated as significantly more annoying than the others*" – ie, the combined 'wind turbine + nearby local road traffic' sound was found to be more annoying than either the 'wind turbine only' or the 'wind turbine + distant highway traffic' sound. Regarding the same study, Simos et al (2019) also stated that "*In a second phase, participants were asked to identify the contribution of the wind turbine within a noise constellation including road traffic. It was found that they were able to do this as long as the noise level was lower than 23 dB(A).*", which, again, could be misinterpreted – what the original study found was that "*Noise from a single wind turbine, submersed in highway noise, can easily be detected once it is known and the detection limit is as low as -23 dBA*.". In other words, the 23 dB refers to a negative signal-noise-ratio of wind turbine sound to highway traffic sound at which the wind turbine sound could be detected, rather than the overall sound level, as implied by Simos et al (2019).

[595] van Renterghem, T, Bockstael, A, de Weirt, V & Botteldooren, D, 2013. Annoyance, detection and recognition of wind turbine noise. *Science of the Total Environment*, 456-457, 333-345. [URL]

Reference	Issues identified
Simos et al (2019) (cont.)	In considering results from the Health Canada study[596], Simos et al (2019) stated that "*Michaud et al. showed that among 1,238 individuals living between 0.25 and 11.22 km of wind farms, tolerance to wind farm noise was between 11 and 26 dB lower compared to road transportation noise.*". This statement is inaccurate, in that the originally published analysis found the quoted level range as corresponding with several different types of transportation sound source, ie not only road traffic – the original study article stated that: "*With the CTL calculated, direct comparisons can be made to other noise sources…This can be interpreted to mean that, on average, communities are about 11 dB less tolerant of WTN than of aircraft noise, 16 dB less tolerant of WTN than of road traffic noise, 14 dB less tolerant of WTN than of rail noise accompanied with high vibrations, and 26 dB less tolerant of WTN than of rail noise without vibrations.*" The statement made by Simos et al (2019) also overlooked an erratum published 7 months after the original article, which identified and corrected an error in the analysis. The erratum noted that the relevant values and corresponding charts had showed the wind turbine sound exposure-response curve was 0.8 dB too high, with the effect that the range of values quoted would be ~1 dB higher, ie the wind turbine sound exposure-response curve was found to be ~12 to ~27 dB lower relative to the equivalent curves for transportation sources, with a difference of around ~17 dB corresponding with road traffic sound. With reference to the Health Canada web page summarising the results of the study[597], Simos et al (2019) stated that "*the Health Canada study found a significant association between self-declared annoyance and measured noise levels produced by the wind turbines, as well as vibrations, light flickering, the so-called stroboscopic effect, and visual prominence. The increase in annoyance was particularly high when the noise induced by the turbines exceeded 35 dB(A).*". However, the cited web page actually states only that "a *statistically significant increase in annoyance was found when WTN levels exceeded 35 dBA.*". For the same citation, Simos et al (2019) also stated that "*it was found that annoyance began to decrease after a distance of 550 metres in one area, but only after a distance of 1 to 2 km in another setting. No explanation could be found for these discrepancies.*", which implies that the observed difference between the regions was investigated, but the investigation found no explanation. However, the Health Canada web page actually notes that "*Community annoyance was observed to drop at distances between 1-2km in ON, compared to PEI* [Prince Edward Island] *where almost all of the participants who were highly annoyed by WTN lived within 550m of a wind turbine. Investigating the reasons for provincial differences is outside the scope of the current study.*".

[596] Michaud, DS, Keith, SE, Feder, K, Voicescu, SA, Marro, L, Than, J, Guay, M, Bower, T, Denning, A, Lavigne, E, Whelan, C, Janssen, SA, Leroux, T & van den Berg, F, 2016. Personal and situational variables associated with wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1455-1466. [URL]
[597] Health Canada, 2014. *Wind turbine noise and health study: Summary of results*. [URL]

Reference	Issues identified
van Kamp et al (2020)	Referencing errors were identified in van Kamp et al (2020), which mistakenly cited Michaud et al (2018)[598] when referring to results from the Danish nationwide study[599].
Mucci et al (2020)	Mucci et al (2020) reviewed Guski et al (2017) and stated that "*Guski has described the association between exposure to various environmental noises and annoyance. He found that the relationship between noise levels and annoyance is stronger for noise generated by aircraft and railway than for road traffic and wind turbines.*". This statement could be misinterpreted as suggesting that annoyance was found to be greater at equivalent levels for aircraft and railway sound than for road traffic and wind turbine sound. However, the exposure-response relationships developed from regression analyses examined by Guski et al indicate that (as expected from previous studies and meta-analyses), transportation sounds are judged in descending order of annoyance at equivalent sound levels as: (i) aircraft, (ii) road, (iii) railway, while wind turbines appear to elicit a greater degree of annoyance at the same exposure levels than any of these transportation sound sources. Mucci et al were actually referring to the 'quality of evidence' ratings assigned to each source type (which were given as 'moderate' quality for aircraft and railway studies, and 'low' or 'very low' for road and wind turbine studies), which is potentially unclear from the statement.
Alamir et al (2021)	In discussing results from the Health Canada study[600], Alamir et al (2021) stated that: "*Expectations of allowable limits and penalties depend on a balance between the need for sustainable development and community amenity. For example, ETSU-R-97 presented higher limits for night-time situations, perhaps reflecting outdoor-to-indoor noise reduction when most people would be expected to be indoors. However, Michaud et al. proposed lower limits at night, as people could be more annoyed during the evening and night, when background SPLs are usually lower and nearby residents would usually be wanting to relax and sleep.*". However, the original Health Canada study publication did not present any proposed 'limits', nor any other regulatory or policy recommendations, stating only that "*The prevalence of WTN annoyance was higher outdoors, during the summer, and during evening and night-time hours.*".

[598] Michaud, DS, Feder, K, Voicescu, SA, Marro, L, Than, J, Guay, M, Lavigne, E, Denning, A, Murray, BJ, Weiss, SK & Villeneuve, P, 2018. Clarifications on the design and interpretation of conclusions from Health Canada's study on wind turbine noise and health. *Acoustics Australia*, 46, 99-110. [URL]
[599] Poulsen, AH, Raaschou-Nielsen, O, Peña, A, Hahmann, AN, Nordsborg, RB, Ketzel, M, Brandt, J & Sørensen, M, 2018. Long-term exposure to wind turbine noise and redemption of antihypertensive medication: A nationwide cohort study. *Environment International*, 121 (1), 207-215. [URL]
[600] Michaud, DS, Feder, K, Keith, SE, Voicescu, SA, Marro, L, Than, J, Guay, M, Denning, A, McGuire, D, Bower, T, Lavigne, E, Murray, BJ, Weiss, SK & van den Berg, F, 2016. Exposure to wind turbine noise: Perceptual responses and reported health effects. *Journal of the Acoustical Society of America*, 139 (3), 1443-1454. [URL]

Reference	Issues identified
van Kamp et al (2021)	In reviewing results from the Danish nurse cohort study[601], van Kamp et al (2021) stated that: "*Bräuner et al concluded on "suggestive evidence" of an association between long-term exposure to WT* [wind turbine] *sound and atrial fibrillation (AF) amongst female nurses…A non-significant increased risk (95% CI* [confidence interval]*: 1.05–1.61) of AF was found amongst nurses exposed to long-term (11-year running mean) indoor WT sound levels ≥ 20 dBA at night compared to nurses exposed to levels <20 dBA.*" and later that "*The so-called Danish Nurse cohort study reports, as worded by the authors, "suggestive evidence" for an association between long-term exposure to WT sound and atrial fibrillation (AF) amongst female nurses, possibly because of (chronic) annoyance. However, the association is non-significant.*" However, the original publication states that: "*When assessing the effects of the 11-year rolling mean night exposure to WTN (L_n), we found a 30% statistically significant increased risk of AF (95% CI: 1.05–1.61) comparing ≥ to <20 dB(A) exposure, and similar effects for evening (L_e) (HR* [hazard ratio]*: 1.25; 95% CI: 1.01–1.54) and day (L_d) (HR: 1.24; 95% CI: 1.00–1.53) exposure, as well as for overall 24-h un-weighted mean (L_{24}) (HR: 1.27; 95% CI: 1.03–1.57). The overall associations between the overall weighted 24-hr exposure, L_{den} WTN and AF was not significant when comparing women exposed to levels of noise ≥20 dB(A) to those exposed to levels <20 dB(A), with adjusted hazard ratios (HRs) and 95% confidence intervals (CIs) of 1.01 (0.85–1.19), 1.05 (0.89–1.23) and 1.10 (0.93–1.30), for the 11-year, 5-year and 1-year rolling mean preceding diagnosis, respectively.*". The original study authors concluded that "*We found suggestive evidence of an association between long-term exposure to WTN and AF amongst in women above age 44. This should be interpreted with caution as levels of WTN exposure were low and direct auditory effects leading to AF are not expected.*". In other words, the study authors identified an association between atrial fibrillation and wind turbine sound exposure (for the 11-year mean L_{day}, $L_{evening}$, L_{night} and $L_{Aeq,24h}$ indices) that they considered to be statistically significant, but any potential association with the day-evening-night period-weighted sound level index (L_{den}) was found to be non-significant, and caution was advised in interpretation of the findings, due to the study limitations. Van Kamp et al (2021) suggested the L_{night} result was non-significant, which could only be correct if they disagreed with the statistical analysis, which was not discussed.

[601] Bräuner, EV, Jørgensen, JT, Duun-Henriksen, AK, Backalarz, C, Laursen, JE, Pedersen, TH, Simonsen, MK & Andersen, ZJ, 2019. Long-term wind turbine noise exposure and the risk of incident atrial fibrillation in the Danish Nurse cohort. *Environment International*, 130, 104915. [URL]

9.2.2 AMPLITUDE MODULATION

Causal mechanisms, contributing factors, and prediction

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Black literature	
Oerlemans (2015) (continued below)	Oerlemans (2015) reported a simulation study aimed at identifying a potential cause of increased ('other') AM, which also formed part of the RUK 2013 study[602]. The author recapped an earlier simulation and measurement study examining 'blade swish' AM ('normal' AM)[603], which found that this phenomenon is caused by the trailing edge sound directivity combined with convective amplification of the moving source (ie TEDCAR-AM), which leads to 'swish amplitudes' of 2-6 dB (modulation of the A-weighted sound pressure level) in all directions within 1-2 rotor diameters, and up to 5 dB in crosswind directions over much longer ranges (eg 10 rotor diameters, disregarding any residual sound). The investigation of 'other' AM was aimed at the potential influence of wind shear on the blade angle of attack (AoA) and how an increased AoA leads to thickening or separation of the boundary layer on the suction side of the blade, which can lead to local blade stall. It was noted that local blade stall may be caused by other factors not investigated, including topography, atmospheric turbulence, turbine wake effects, wind yaw or wind veer. The simulation was based on assumptions about the behaviour of the blade sound emission during local stall, which were in turn based on aerofoil studies. It was assumed that during stall, a broadband increase of 10 dB would occur, along with a downward shift in the spectral peak by a factor of 2. The calculation scenarios covered wind shear profiles corresponding to various atmospheric stability conditions, with shear exponents of 0.0 (unstable), 0.3 (stable) and 0.6 (very stable) - these were compared with averaged conditions in a UK flat site of 0.2 (daytime) and 0.4 (night-time).

[602] Oerlemans, S, 2013. Work package A1: An explanation for enhanced amplitude modulation of wind turbine noise. *Wind turbine amplitude modulation: Research to improve understanding as to its cause and effect*. RenewableUK. [URL]
[603] Oerlemans, S, 2009. Prediction of wind turbine noise and validation against experiment. *International Journal of Aeroacoustics*, 8 (6), 555-584. [URL]

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Oerlemans (2015) (cont.)	The simulation results indicated that local stall leads to increased AM in the upwind and downwind directions, although the modulation depths in the A-weighted levels predicted by the model were relatively small (~3 dB), even for the highest wind shear exponent. It was noted that this increase in AM did not occur in the simulation during high wind shear unless local blade stall occurred. The author concluded that local blade stall is a plausible explanation for 'other' AM, but noted that verification of the simulation in experiments would be necessary to confirm this.
Makarewicz et al (2015)	Makarewicz et al (2015) presented a theoretical study examining the influence of blade pitch and wind shear across the rotor diameter on stall-induced AM. It was shown how a turbine operator could alter blade pitch to keep stall-induced AM within a predetermined modulation depth.
Sedaghatizadeh et al (2017)	Sedaghatizadeh et al (2017) investigated the potential causes of 'enhanced' AM based on analysis of the directivity of the swish mechanism (TEDCAR-AM) and that of inflow turbulence and partial or transient blade stall (non-TEDCAR-AM). It was considered that transient blade stall can be caused by changes in the angle of attack due to inflow turbulence, which can be exacerbated by topography or turbine wake effects, or due to high wind shear. The authors noted that while TEDCAR-AM radiates mainly in an arc centred around a line parallel with the blade chord, the inflow turbulence and stall sound radiates mainly normal to the blade chord. It was also noted that while TEDCAR-AM is predominantly in the upper frequency range, and so is attenuated more readily over distance, the inflow turbulence and stall sound contains lower frequency energy, and so is propagated to longer ranges. On this basis, it is suggested that the direction (and distance) of receptors relative to the turbine rotor plane may determine what 'kind' of AM could be perceived. Four case study sites were considered (including one in the UK), with reference to available wind data and noise complaints records. It was demonstrated that at most of the sites, the majority of complaints pertained to wind directions that corresponded more closely with the inflow turbulence/transient blade stall (non-TEDCAR-AM) directivity (downwind or upwind) than with the trailing edge (TEDCAR-AM) directivity (crosswind). The notable exception seemed to be the UK site, for which most of the complaints occurred for crosswind directions. The authors argued that this is explained by the receptors being relatively close, so any AM perceived is probably mainly TEDCAR-AM.

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Fernandez et al (2017)	Fernandez et al (2017) reported a combined experimental and simulation study that used an analytical-numerical model validated for predicting the interior sound generated during excitation by explosions nearby (representing sonic booms of passing supersonic aircraft) to estimate indoor levels of AM wind turbine sound. Predictions made for an open window case showed that the open window created a Helmholtz resonance effect, leading to an amplification of the sound at the resonance frequency, which for the test case room dimensions was in the infrasonic range. The results also showed that the predictions with the window open exhibited lower indoor levels, and a resonance that was observed with the closed building envelope case at 63 Hz was attenuated in the open window case.
Yauwenas et al (2017)	Yauwenas et al (2017) reported a combined experimental and simulation study investigating the contribution from blade-passage mechanisms to blade-tower interaction sound. A CFD model was developed and validated using measurements on a scale model test rig, which was operated in an ‘unloaded’ condition (by setting the angle of attack to 0°). The simulations showed that the pressure field acting on the tower is the dominant source of acoustic energy within the blade-passage component of the blade-tower interaction sound generation mechanism. It was also shown that the source spectrum of the acoustic energy is concentrated on the blade-pass frequency and its harmonics.

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Barlas et al (2017)	Barlas et al (2017) presented a numerical model simulation study employing a combination of techniques to take account of both the source and complex flow field propagation effects. It was noted that the trailing edge sound dominates the mid-range frequencies 200-800 Hz, while inflow turbulence sound dominates the low frequencies <130 Hz. From the time-averaged results, it was noted that turbine wake effects can enhance the propagation of the sound in the far-field downwind of the turbine. From the time-dependent results (with AM quantified using the IOA AM metric), it was highlighted that the propagation effects (turbulence and the downstream wake effect) enhanced the AM in the upwind and downwind directions. In the upwind direction, it was observed that this was due to the variation in shadow zones created by refraction and the varying position of each blade. In the downwind direction, the enhanced AM was shown to be due to the propagation model, which included the turbulence and wake effects. The difference in the modulation depths between the modelled downwind AM levels with and without the propagation effects was ~1-1.5 dB, and tended to increase with increasing distance downstream. It was also shown that reflective ground conditions increase downwind AM and reduce upwind AM, compared with soft ground conditions. A complex interaction was also shown between the AM depth and the wind speed, wind shear, ground characteristics and wake behaviour.

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Barlas et al (2018) (continued below)	In a further simulation study, Barlas et al (2018) used a numerical model to simulate the effects of different atmospheric conditions expected over the daily cycle on wind turbine sound levels and AM. The authors noted several atmospheric factors that could influence sound propagation during the daily cycle: • During a sunny day with slow winds, a convective boundary layer is observed, which has low wind shear, negative temperature shear, and increased turbulence. The increased turbulence leads to higher sound emissions from turbines, but the wake recovery is shorter, and less downward refraction of sound waves is expected. • During stable conditions, wind shear is exaggerated, and temperature is inverted (positive shear), both of which lead to stronger downward refraction. The reduced turbulence means the turbine sound emission is lower, but the downward refraction combined with longer wake recovery (and increased wake-interaction and 'ducting' of sound along the wake) mean that increased sound levels can be expected at far-field receptors. • It was also noted that enhanced AM has been observed at night under high wind shear and low turbulence conditions. Four snapshots during the daily cycle were used to predict sound levels and AM: early morning (05:00), early afternoon (13:00), evening (19:00), and early night (23:00). A low-level jet was included in the early morning model; it was noted that, along with the apparent temperature inversion, these conditions imply 'severe' downward refraction, and the low turbulence intensity results in long wake 'deficit' regions (ie, facilitating wake 'ducting'). The simulations suggested that: • For overall A-weighted sound levels, the levels modelled downwind were predicted to be lower during the early afternoon than during the evening, night and early morning, and this divergence increased with distance, due to the downward refraction effects • Conversely, while the predicted upwind levels showed more rapid attenuation compared with downwind, the daytime upwind levels tended to be higher with increasing distance than the other periods of the daily cycle, due to the increased downward refraction on the downwind side during these periods

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Barlas et al (2018) (cont.)	• For AM depths (quantified using the IOA AM metric), the predicted modulation depths downwind increased with distance up to a peak value, which varied depending on the time of day: ○ The evening peak was highest at ~9.5 dB depth, occurring at around 1400 m, before dropping steadily at longer distance. ○ The early morning and night peaks were similar depth ~8 dB, and occurred at similar distances of 1200-1300 m. After a plateau ~4 dB depth, both time periods also showed a secondary peak of ~5-6 dB depth occurring around 2700-2900 m. ○ The early afternoon showed the smallest peak at 6 dB depth, which dropped slightly to a varying depth between 5 and 6 dB. • The modelled filtered time signals showed that the low frequency levels at close range (2 rotor diameters) were increased in the early afternoon relative to the night, due to the increased turbulence elevating the inflow turbulence sound. At mid-frequencies the trailing edge sound was similar for both early afternoon and night. By contrast, at long range (15 rotor diameters) the inflow turbulence sound level for both periods was similar, but at night-time the peak-trough variation was larger than in the early afternoon. Similarly, at long range, the peak-trough variation in the trailing edge sound was predicted to be larger for night.
Klein et al (2018)	Klein et al (2018) presented a numerical simulation study using coupled models to investigate blade-tower interaction sound. A large (5 MW, 90 m hub height) wind turbine was modelled. The modelling indicates that the horizontal directivity pattern of blade-tower interaction sound is oval-shaped, which is due to the larger contribution of the tower to the sound signature than the blade. The modelled spectra suggest that for large turbines, the influence of blade-tower interaction sound is restricted to the infrasonic region.

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Cotté (2018)	Cotté (2018) reported a simulation study aimed at validating an analytical-numerical model of the source generation coupled with the sound propagation. The modelled AM depths in the downwind direction tended to be relatively small, while larger depths were shown in the crosswind and upwind directions, albeit with lower overall sound levels. Shadow zone effects were noted in the upwind direction, leading to relatively large AM depths associated with a receptor entering and leaving the shadow within a single blade rotation, and large fluctuations in AM depth with distance. Comparison with a stationary point source model indicated the extent of the upwind shadow zone may be overestimated by assuming a point source approximation, and the author highlighted that the AM cannot be accurately predicted using a stationary point source model (even when approximating the variation in sound level with blade position).
Heimann et al (2018)	Heimann et al (2018) presented a simulation study that used a numerical model to investigate the effects of atmospheric turbulence and the turbine wake on sound propagation. The model included four different meteorological conditions intended to represent different times of day, as might occur in summer for a 'mid-latitude' location on grassland. The conditions included a stable atmosphere at night, and also the introduction of a low-level jet around the hub height in the early morning. The model was 3D, but considered static turbine rotor angles individually - the authors noted that this limits the model to only roughly describing the time-dependent sound levels. Nonetheless, a discussion on an approximation for AM is based on results that show the 'excess sound level', defined as the difference between the maximum sound level during one rotor rotation, and the average over all the rotor angles. It was noted that, when compared with the midday scenario, there are greater magnitudes of this indicator during the night, early morning and evening and at shorter ranges downwind of the turbine during these times. However, the results also indicate unrealistically large values during the evening scenario, which the authors speculated may be an artefact of the model.
Cotté (2019)	Cotté (2019) presented a simulation study that developed further on earlier work (Cotté, 2018), and compared two ‘extended source’ models for source generation coupled with propagation using parabolic equation methods with analytical solutions. The advantage of one of the methods was shown to be improved computationall efficiency. The results for predictions of AM were similar to the previous study (Cotté, 2018).

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Makarewicz et al (2019)	Makarewicz et al (2019) described a theoretical study examining the potential influence of a ‘low-level jet’ (formed by 'thermal stratification of the atmosphere') on the propagation of sound and AM from a turbine. It was shown that low-level jets above the turbine rotor may cause refraction of the sound downward, resulting in zones with higher and lower sound levels.
Zajamsek et al (2019)	Zajamsek et al (2019) presented further development of earlier work investigating the mechanisms and characters associated with blade-tower interaction sound (Yauwenas, Zajamsek, Reizes, Timchenko, & Doolan, 2017). Whereas the previous study reported by Yauwenas et al (2017) investigated an ‘unloaded’ condition (0° angle of attack), Zajamsek et al (2019) examined loaded operation. The study used the same scale model and validated CFD simulations to investigate the aerodynamics and flow field around the test rig and in the computational model. It was demonstrated that, (for the model turbine,) the pressure field change on the tower during the blade passby passage is the main source, and produces an impulsive acoustic pressure wave. The results were not generalised towards any implications for full size commercial wind turbine sound emissions, beyond noting that any mitigation for blade-tower interaction sound would be most effective being targeted at the tower aerodynamics.
Hansen (C) et al (2020)	Hansen (C) et al (2020) presented a broad overview of the state of the art in wind turbine acoustical research, with recommendations for future research directions and priorities. Regarding AM causal factors, they noted some evidence of a connection between AM occurrences and meteorological conditions.

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Bolin et al (2020)	Bolin et al (2020) reanalysed measurement data reported in an earlier field study by Conrady et al (2020). Bolin et al (2020) reconsidered the theoretical analysis of Makarewicz et al (2019), which identified shadow zones in the immissions due to refractive effects, and applied it to predictions of AM. They made use of a 2D ray tracing model, together with recorded meteorological forecast data for the site to incorporate a wind shear profile relevant to the measurement periods. The aim of the study was to investigate the influence of 'shading' of the turbine rotor on sound immissions and AM. The rotor shading was based on the proportion of the rotor span disc that would make up the received immissions, investigated under the principle of reciprocity (propagation rays were calculated from the receiver to the rotor disc rather than vice versa). The modelling showed the refraction of the sound rays caused by the wind speed profile, which could cause sound emissions from parts of the rotor disc to be reduced in level (shaded), while other parts are not (illuminated). The predictions of rotor shading produced by the model were used to reanalyse the measured sound data by separating it into different rotor shading categories, which indicated that: • statistically significant differences were found between the distributions of both sound levels (L_{Aeq}) and AM depths for the shaded and unshaded conditions: during partial shading of the rotor, measured sound levels tended to be slightly lower, while AM depths tended to be greater • The greatest AM depths during partial shading occurred for shading of around ~30-50%, and the probability of AM occurrence was greatest for shading of ~40-60% The authors concluded that the analysis suggests an influence of wind shear on AM could be the refraction-induced 'shading' of the rotor disc at specific receiver locations.

Reference	Relevant evidence and discussion: amplitude modulation causal mechanisms, contributing factors, and prediction
Yauwenas et al (2021)	Yauwenas et al (2021) presented further development of the previous work reported by Yauwenas et al (2017) and by Zajamsek et al (2019). The same experimental model and numerical simulation techniques described in the earlier studies was employed, with the simulations used to investigate the directivity patterns of the blade-tower interaction sound. The validated simulations indicated that the horizontal directivity pattern of blade-tower interaction sound from a turbine could be oval-shaped, depending on the relative contributions of the blade and tower; the blade component has a dipole directivity, which was previously assumed to dominate, whereas the study results suggested the tower component, which has a monopole directivity, tends to dominate. The authors also speculated that, although blade-tower-interaction sound is expected to be focussed on the blade passing frequency, the harmonics may be in the audible low frequency range.

wsp

Detection, measurement, prevalence, and distribution

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
Black literature	
Kendrick et al (2016)	Kendrick et al (2016) reported a simulation study that tested two of the candidate AM measurement methods proposed by the AMWG (2015). These comprised the Japan study method 1, and the frequency domain method 2. The hybrid method 3 later adopted by the AMWG in their final report (IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group, 2016) was not tested. The study added artificially simulated microphone wind turbulence noise to synthetic AM stimuli. The AM metrics were applied to the resulting audio signals, which demonstrated that, for windshields of 100 mm diameter, the ability of the Japan study metric to accurately measure AM depth could be impaired at wind speeds rising above ~2ms^{-1}, while the band-limiting used in the modulation frequency domain method was found to be slightly more resistant to contamination at low wind speeds. However, for large modulation depths, the error above 2 ms^{-1} observed for the modulation frequency domain method rapidly became large, and larger than the error in the Japan study metric for high wind speeds. It was also shown that a machine learning algorithm trained to detect and remove periods of wind-affected data could be used to reduce the error, at the cost of a reduction in the available data. The authors acknowledged that the simulation is valid for the selection of a minimal sized wind shield (100 mm), and noted that the error would be expected to be lower when using a larger or more effective wind shield.
Lenchine (2016)	Lenchine (2016) presented a method for estimating AM magnitude by applying the cross-correlation function to a sound level time-series and a cosine function with an assumed modulation frequency. It was noted that the modulation frequency of the target signal must be accurately known to obtain accurate estimates of the modulation depth using this method, and an iterative procedure was proposed in order to obtain the correct frequency. A noted advantage of the approach was the potential for reasonable estimates of AM in situations with low signal-noise-ratio. Using test signals, and comparing with another AM metric, as well as a wavelet-based technique also developed by the author, the cross-correlation approach was shown to produce estimates of the AM depth magnitude within 0.02-0.24 dB of the design depth down to -20 dB SNR, whereas both the comparison metrics showed larger errors at -10 and -20 dB SNR. Using a measured wind turbine sound, broadly comparable results were obtained for each approach.

wsp

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
Zagubień (2018)	Zagubień (2018) presented some short-term measurements of time-varying sound pressure levels at various wind turbine installations in Poland. AM was not explicitly quantified, and the analysis appears to have been based on comparing the sound pressure level maxima with a criterion of L_{Aeq} + 2, based on an assumption that this is the limit of perception.
Hansen (KL) et al (2018)	See Stage 1 evidence review summary in section 9.1.1, and Stage 2 evidence review summary on noise effects in section 9.2.1. Hansen (KL) et al (2018) also argued that AM is under-represented by use of the L_{AF90} measurement index.
Okada et al (2019)	Okada et al (2019) reported an experimental field study investigating the magnitude of AM emitted around a range of horizontal directions from a 1.5 MW upwind rotor turbine (hub height 65 m and rotor diameter 70 m). Measurements were made at relatively close range (distances of 50 m and 40 m) for the directional test, and distances of 80-200 m in a single direction. Turbine operational and wind data were synchronised with the measurements. A modified version of the Japan study D_{AM} method for quantifying AM was used, which was verified against the original method. The measured AM at 40-50 m was in the range 1-5 dB using the modified D_{AM} method (which, according to the regression relationships developed by Fukushima et al (2017)[604], might be expected to be in the range ~1-7 dB using the IOA metric). A direction-dependent relationship for AM depth was established from the close-range measurements, which indicates that the close-range AM depth was greatest over an arc +/-60° relative to the upwind direction. However, the direction-dependence derived from the measurements was relatively slight with variation in the range 2-3 dB D_{AM}. The distance-dependence of the AM depth over the 80-200 m range also indicated that the AM depth remained relatively constant at 2-3 dB D_{AM}. It was also shown that the AM measurements could be used to estimate the rotation speed of the rotor with reasonably high accuracy.

[604] Fukushima, A & Tachibana, H, 2017. *Comparison of the IOA method and Japanese F-S method for quantitative assessment of amplitude modulation of wind turbine noise – A study based on the field measurement results in Japan*. Wind Turbine Noise 2017, Rotterdam, 2-5 May. INCE-Europe.

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
Hansen (KL) et al (2019)	Hansen (KL) et al (2019) reported a field measurement study investigating tonal AM from a wind farm subject to complaints about 'thumping' and 'rumbling'. The measurements were taken over 2 months at several locations between 1.3 and 8.8 km from the turbines, including both outdoor and indoor measurements. AM was quantified using a modified version of the IOA metric, which was adapted to enable quantification of the low frequency, tonal AM character. An optimisation analysis was undertaken to select parametric settings to make the modified metric more sensitive to AM. A detection and adjustment process was also applied to the calculated modulation depth to account for the expected audibility of low frequency tones. An analysis of the prevalence of AM depths at the different locations and under various wind conditions and wind farm power output was undertaken. The diurnal distribution analysis showed that measurable AM occurrences were more frequent during the night and early morning than during the daytime hours. However, all the analysis pertains solely to the 50 Hz tonal AM under investigation.
Thorsson et al (2019) (continued below)	Thorsson et al (2019) reported field measurements of single turbines and analysis aimed at identifying sound characteristics to enable synthesis of turbine sound for use in experimental lab tests. Four measurements sites were used. All the measurements were made at dwelling locations, and in predominantly downwind directions. A method was devised to calculate the AM depths in third-octave bands based on Fourier analysis of the signal magnitude. The method applied enables a 'coherency' check on the phase relationships between the signals in each third octave band, to determine whether the modulation is within (arbitrarily) defined phase limits. Bands with phases outside the defined limits are considered likely due to signal contamination, and it was shown that this tended to occur at the lower and higher ends of the frequency spectrum. The output from the process is the AM depth in the overall A-weighted signal, which was determined according to a definition given by Lee et al, (2011)[605].

[605] Lee, S, Kim, K, Choi, W & Lee, S, 2011. Annoyance caused by amplitude modulation of wind turbine noise. *Noise Control Engineering Journal*, 59 (1), 38-46. [URL]

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
Thorsson et al (2019) (cont.)	The distribution of the AM depth according to these methods indicated that the majority of the AM occurring at the four sites was in the range 4-7 dB depth. From time domain signal inspection and analysis of the AM data in third-octave bands, it was inferred that the different spectral AM characteristics observed in each location were due to the different turbine types. However, no meteorological or topographical data were examined to consider alternative or complementary explanations for the differences.
Jennings et al (2019)	Jennings et al (2019) reported an observational study investigating the application and relevance of the IOA AM metric for detecting and evaluating AM impact at a wind farm site in Ireland. The aim of the study was to examine whether occurrences of AM reported by wind farm neighbours could be quantitatively confirmed using the IOA method. Sound measurements took place over 20 days at a residence 480 m from the nearest turbine on the wind farm. Meteorological conditions were taken from the nearest meteorological measurement station (the authors note that SCADA data was available but is confidential). No details on the turbines were reported. A comparison of subjective analysis by the authors and the resident noise diary information with AM depth values obtained using the IOA metric indicated that the IOA method confirmed the aural assessments for five out of the seven periods focussed on; for two periods the aural evaluation suggested the presence of AM, but the metric returned a zero rating. This was thought to be due to the presence of extraneous sounds (wind-vegetation interaction and aircraft). It was noted that the highest AM depths occurred during crosswind conditions. The authors also analysed a 12-hour period in more detail, noting that the AM magnitudes returned by the low and high frequency bandpass ranges used in the IOA metric were similar, but the low frequency range had 10s periods of valid AM that fell just short of the required threshold of 30× 10s periods (5 minutes) per 10 minutes, whereas the high frequency range consistently passed the validity test. The subjective descriptions for this period comprised 'swishing', indicating the high frequency range is more likely to be the appropriate band for assessment (ie, the metric appeared to be getting this correct). However, the authors pointed out that this kind of situation may arise, with the metric returning 'no AM' ratings when there could be, for example, short periods of intermittent AM. They suggested that, in such cases, a finer resolution of threshold may be appropriate, such as 15× 10s periods (2.5 minutes) per 5 minutes. They also suggested that further research should establish whether shorter periods of AM occurrences (ie, shorter than the ‘5 in 10 minutes’ stipulated in the IOA method) are associated with disturbance. The authors concluded that the IOA metric is a reliable method for confirming AM as evaluated subjectively, but recommended that assessments consider occurrences falling near to but just short of the 50% in 10-minute criterion.

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
Hansen (C) et al (2020)	Hansen (C) et al (2020) presented a broad overview of the state of the art in wind turbine acoustical research, with recommendations for future research directions and priorities. Regarding AM measurement, they suggested that evidence concerning diurnal distribution of AM is inconsistent. They also highlighted the IOA review of AM measurement approaches (IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group, 2015), but noted a lack of a comprehensive validation exercise.
Conrady et al (2020) (continued below)	Conrady et al (2020) reported a field study that analysed long-term measurements taken over 9 months at a site in Sweden, located around 1 km from the nearest turbine of a 22-turbine wind farm. Simultaneous meteorological measurements were taken at relatively low heights (up to 5 m), including wind speed and direction data, and turbine rotational speeds were provided by the wind farm operator. Although not stated in the article, a later related article (Bolin, Conrady, Karasalo, & Sjöblom, 2020) confirms that snow was on the ground for most of the measurement period, due the site location in northern Sweden. The AM detection and quantification method comprised a modulation frequency-domain approach, which takes the peak value of the modulation spectrum within fixed limits corresponding with the typical turbine blade pass frequencies, based on measurements of the sound pressure level at 125 ms intervals. The measurement data were separated into two AM categories depending on the magnitude of the 'AM factor' (corresponding with high or low AM depths). The ‘AM factor’ was defined by the decibel level of the modulation spectrum peak at the modulation frequency.

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
Conrady et al (2020) (cont.)	The analysis showed that: • AM at both magnitude categories tended to increase with increasing atmospheric stability (although the authors noted that this result should be treated with caution, as the stability was estimated based on the low-height meteorological data only) • AM prevalence tended to be greater during the winter months, which the authors indicated is likely due to greater atmospheric stability during these periods • AM was more prevalent during downwind and one crosswind direction, compared with upwind or the other crosswind direction (although more data was collected in the downwind and crosswind direction that led to greater AM prevalence), and wind direction was noted as having the greatest influence on AM out of the factors investigated • AM tended to be more prevalent during the evening, night and early morning than during the day, which was relatively consistent for all months; the authors attributed this mainly to the atmospheric stability conditions • AM tended to increase with increasing wind shear, as measured between the mast and the turbine hub
Wszolek et al (2020)	Wszolek et al (2020) reported field measurements taken to investigate the differences between measurements made at 4 m height and on a board at the ground surface. Measurements were taken at ~122 m around one turbine on a 6-turbine wind farm. Single-layer wind screens were used. An indication of AM in the measurements was taken from the standard deviation in the A-weighted sound pressure level at 125 ms intervals. Although the authors suggested that the results indicate no constant relationships between the measurements at the two heights, the overall A-weighted values, the standard deviation in the 125 ms A-weighted levels, and the spectral levels >100 Hz are relatively consistent between the two heights (ie, the differences are relatively small). Below 100 Hz, the spectral levels indicate that the 4 m height measurements were affected by wind (which is consistent with the type of wind screen employed).

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
Nguyen, Hansen (KL), Lechat et al (2021) Nguyen, Hansen (KL), Catcheside et al (2021) (continued below)	Nguyen, Hansen (KL), Lechat et al (2021) presented the development of an AI-based AM detection algorithm, which was shown to be a reliable approach to AM classification of audio signals. The AI algorithm developed employed a 'random forest' machine learning method, based on decision trees comprising multiple features of the signals to arrive at a majority 'verdict' on the classification. The authors compared the algorithm with existing methods, including the IOA metric, the Japan study metric and another metric used by researchers in Sweden. It was concluded that the AI algorithm outperforms the other methods for detection. (However, inspection of the descriptions indicates these may not have been faithfully implemented, so the results of the inter-metric comparisons may not be completely accurate.) Nguyen, Hansen (KL), Catcheside et al (2021) used the AI-based AM detection algorithm in a field measurement study quantifying AM outdoors and indoors over 1 year at 3 locations situated 1-3.5 km from turbines at 3 wind farms in South Australia. It was noted that, in Australia, distances to turbines are typically at least 1 km, so sound and AM is more low frequency in character. Outdoor measurements were taken in free-field conditions, while the indoor measurements were taken in the bedroom corners. The AM detection algorithm was used to identify 10-second periods with AM, and a measure of AM was calculated as the L_{A5}-L_{A95} for the identified periods (it is not stated whether any bandpass filtering was applied). It is noted that the AM detected was intermittent, with <20% of consecutive 10-second periods spanning more than 1 hour. The median AM depths across the 3 sites were in the range 2.1-2.6 dB, with a skew towards low depths in the distribution. The spectral modulation analysis indicated the modulation depths tended to be greater in the low frequency 63-250 Hz octave bands than in the mid frequency 500-1000 Hz bands, indicating a low frequency AM character. It was suggested that this could be due to variations in propagation conditions, and in residual sounds at measurement locations. The analysis indicated that detected AM occurrences tended to be less frequent indoors than outdoors, but the AM depths indoors tended to be as high or around 1 dB higher than those outdoors.

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
Nguyen, Hansen (KL), Lechat et al (2021) Nguyen, Hansen (KL), Catcheside et al (2021) (cont.)	Diurnal variation in the AM prevalence showed occurrences were more common in the night/early morning period 0000-0400 hours, and evening period 2000-2300 hours. Seasonal variation in AM prevalence was relatively slight, but an analysis of hourly prevalence by month revealed that the prevalence was consistently related to the daytime length; during the shorter days in the autumn and winter, the observed AM prevalence increased. It was noted that the diurnal and seasonal variation is probably explained by favourable conditions for sound propagation during the night (refraction caused by wind shear and temperature inversions associated with stable atmospheric conditions). Analysis of the influence of wind speed variation showed that prevalence of AM occurrences was greatest at low-height wind speeds of 0-4 m/s, and dropped rapidly at wind speeds above 5 m/s. Analysis of the influence of wind direction showed that upwind conditions were associated with lowest AM prevalence, and cross- or downwind directions had similar prevalence rates. No analysis of AM depths by wind direction was reported.
Cooper (S) (2021)	Cooper (S) (2021) presented a discursive article primarily focussed on the semantic distinction between the common use of the term 'AM', and its specific, historic, use in relation to radio wave signal transmission. The author argued that, in the case of the common usage of AM in relation to wind turbine sound, since the signal being modulated (ie, the carrier) is not generally a sinusoid, this should technically be described as 'modulation of the amplitude' rather than 'amplitude modulation'. However, the author also notes other fields (such as audiology) that use the term 'amplitude modulation' to describe modulation of a broadband sound (which is consistent with its common usage in wind turbine acoustics). The motivation behind the author's proposition to use differing terminology for broadband AM is based on the presence at some sites of low frequency tonal AM, which would be more consistent with the AM definition used in radio wave signal transmission. It was noted with reference to site data from Australia that AM indoors can have greater modulation depth than outdoors. The author also proposed a method of quantifying AM by calculating the L_1-L_{90} of the signal. No validation exercise is reported, nor is any analysis of sensitivity or specificity of the proposed approach.

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
Grey literature	
IOA NWG (WTN) AMWG (2015)	The Institute of Acoustics Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group (2015) presented a narrative literature review and 'preliminary' conclusions on candidate methods for detecting and quantifying AM in wind turbine sound. 'Over 30' publications were reviewed, from the perspective of developing a suitably robust metric. The review was intended to address general AM in wind turbine sound, defined as "*periodic fluctuations in the level of broadband noise from a wind turbine (or wind turbines), the frequency of the fluctuations being the blade passing frequency of the turbine rotor, as observed outdoors at residential distances in free-field conditions*". The review identified three basic approaches to quantifying AM, grouped as modulation frequency domain, time domain or hybrid (combined) methods. Within these groups, 11 methods were reviewed, along with an indicator based on a psychoacoustic model and another standardised metric for quantifying impulsivity. The review concluded that: • time domain-based methods of quantifying AM were identified as being susceptible to the influence of extraneous sounds, which could lead to low specificity (ie, high rates of false positives). To improve specificity required removal of periods affected by extraneous sounds, which would be difficult to automate for application to large datasets. It was recognised, however, that time domain methods are potentially more intuitive. • modulation frequency domain methods were recognised as addressing some of these issues, by enabling filtering of modulation frequencies unlikely to be related to the wind turbine sound. However, it was also recognised that averaging is required to obtain useful results, and the approach may neglect some features of AM that could be potentially important in determining perception and responses. The AMWG proposed three candidate methods for consultation, which included (i) the Japan study time domain method, (ii) a modulation frequency domain method based on the RenewableUK approach[606], but using a band-limited A-weighted level time-series (which increased the AM depth values), and (iii) a hybrid approach that would extend the modulation frequency domain analysis by isolating the relevant peaks of the modulation spectrum, and then inverse-transforming these back to the time domain to evaluate the modulation depth using the L_{05}-L_{95} approach.

[606] White, P, 2013. Work package B1: The measurement and definition of amplitude modulations; Bullmore, A & Cand, M, 2013. Work package F: Collation of work package reports and final reporting. *Wind turbine amplitude modulation: Research to improve understanding as to its cause and effect*. RenewableUK. [URL]

Reference	Relevant evidence and discussion: amplitude modulation detection, measurement, prevalence, and distribution
IOA NWG (WTN) AMWG (2016)	In their final report, the IOA NWG (WTN) AMWG (2016) reported the method developed and endorsed by the IOA for quantifying AM following a consultation period prompted by the earlier discussion document (IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group, 2015). The final Reference Method as developed comprises a 'hybrid' approach combining a modulation frequency domain technique to identify the parts of the signal believed to correspond with wind turbine AM, isolate these, and then switch back to the time domain for analysis of the modulation depth. An 'indicative method' comprising the Japan study method was also described, which was advised as potentially useful for short-term attended surveys (to provide an indication of AM). However, limitations with this approach were acknowledged, ie its susceptibility to influence from extraneous sounds. The indicative method is to be considered as "*secondary to the reference method and in no circumstances as a substitute for it when the level of AM is being assessed against a specific criterion or limit (such as might be specified in a planning condition)*" There was no systematic field measurement validation process for the endorsed methods reported, although calculated comparisons with AM values determined from experimental exposure-response studies were presented.

Effects, controls, and mitigation

Reference	Relevant evidence and discussion: amplitude modulation effects, controls, and mitigation
Black literature	
Basner et al (2015) Rand et al (2017) van Kamp et al (2018) Freiberg et al (2019) Hansen (C) et al (2020) Davy et al (2020) van Kamp et al (2021) Alamir et al (2021)	See Stage 2 evidence review summary on noise effects in section 9.2.1. These review studies have highlighted that, based on evidence from observational or experimental studies, the presence of AM in wind turbine sound appears to aggravate noise annoyance responses, and equivalent degrees of annoyance response are associated with wind turbine sound levels that are lower than other common environmental sources of sound, such as transportation. Davy et al (2020), Hansen (C) et al (2020) and Alamir et al (2021) also discussed the need for a penalty to address the impact of AM; Davy et al (2020) proposed that the study scheme proposed in 2016 BEIS-published review of response to AM (WSP | Parsons Brinckerhoff, 2016) should be trialled in Australia, while Alamir et al (2021) outlined various approaches found in the literature, and Hansen (C) et al (2020) highlighted that research in this area is ongoing, noting also that any penalty might need to be a function of the sound level.
Johansson et al (2019)	See Stage 2 evidence review summary on noise effects in section 9.2.1. The experiment conducted by Johansson et al (2019) exposed participants to sounds from three different sizes of turbine (small, medium, and large), which had correspondingly different modulation frequencies (3 Hz, 1 Hz and 0.6 Hz respectively). The annoyance rating procedure indicated that, when just-noticeable (at low signal-noise-ratios relative to residual sounds) and at low levels of annoyance, the turbines were detectable and disturbing in correspondence with their size, suggesting a relationship between the modulation frequency and perception or response. As the SNR increased, the differences between the turbine sounds reduced, indicating that as the sounds become more noticeable (and annoying), the differences in the AM characteristics became less important than the levels (relative to residual sound).

Reference	Relevant evidence and discussion: amplitude modulation effects, controls, and mitigation
Nguyen et al (2020)	Nguyen et al (2020) presented an experimental study investigating how convincing different methods of synthesising AM wind turbine sound are for listening tests. A range of methods for synthesising signals representing AM wind turbine sound were tested with 8 expert participants, and it was shown that increasing complexity of synthesis did not necessarily translate into greater indistinguishability of the synthesised signals from real recordings. The study was focussed entirely on low frequency tonal AM (at 47 Hz), and no broadband AM signals were tested. While this was not noted as a study limitation, it limits generalisability to the wind turbine AM sounds more commonly reported in the literature, which have modulation focussed in broader and higher frequency bands. It was found that the most important factor was ensuring similarity of the signal spectrum with the recording spectrum, and more refined control of temporal AM parameters (such as random fluctuations in AM peaks, and use of Gaussian pulse rather than sinusoid envelopes) did not lead to a consistent increase in perceived realism for the tonal AM signals tested.
van Kamp et al (2021)	In reviewing experimental studies, van Kamp et al (2021) noted the results of two studies in Switzerland investigating effects of AM. One synthesised wind turbine sound and other broadband (pink noise and low frequency AM) sounds, finding that modulation depth and spectral shape affected annoyance ratings. The other presented audio-visual stimuli for wind turbine sound with and without AM. They also found that the visual and acoustic characteristics both affected annoyance, as did subjects' attitude towards wind farms.
Alamir et al (2021)	Alamir et al (2021) considered the need for penalties to apply to the AM characteristic in wind turbine sound. They highlighted experimental results from a study in Finland, which investigated subjective penalties for AM in both wind turbine-like sound and road traffic-like sounds, and suggested penalties for wind turbine AM sounds ranging from negligible at a very low modulation frequency of 0.25 Hz up to +10 dB for a modulation frequency of 2 Hz and large modulation depths of ~8 dB. They also presented results from an experimental pilot study in Australia, which investigated subjective sleep acceptability ratings for low frequency tonal AM wind turbine-like sounds. The results indicated that, for high tonal audibility and AM depth (calculated using the IOA metric), the sleep acceptability was equivalent to a penalty of 5 dB (when rated by those with higher self-reported noise sensitivity; when rated by the lower noise sensitivity group, no clear trend was evident).

Reference	Relevant evidence and discussion: amplitude modulation effects, controls, and mitigation
Mackowski et al (2021)	Mackowski et al (2021) presented a simulation study investigating a conceptual strategy for mitigation of ‘blade swish’ (TEDCAR-AM); the study does not address AM caused by any other contributing mechanisms. A detailed simulation model was validated against a database of sound power spectral data for a specific 3.2 MW turbine. The model was also validated against sound pressure spectra and AM depths measured for a research micro-turbine. The AM depth measurements were quantified using the IOA metric. The mitigation strategy was based on a responsive individual blade pitch angle control system, that modifies the blade pitch angles to minimise the modulation depths predicted by the simulation. The simulation results for idealised conditions indicated that the modulation depth at the target location could be reduced to negligible magnitude. It was shown that the control system could be optimised for a specified location, however the optimisation for one location would result in increased ‘blade swish’ AM at other locations. It was noted that, for multiple locations, the outcome of the optimisation process could be different. It was also noted that increasing wind shear reduces the effectiveness of the AM control because the pitch angle is less effective in controlling the angle of attack.
Hansen (KL) et al (2021) (continued below)	Hansen (KL) et al (2021) further analysed the year-long data from two of the measurement locations surveyed and reported by Nguyen, Hansen (KL), Catcheside et al (2021). These locations had also included response data gathering from an occupant at each of the residences, which were 870 m and 1300 m from turbines. AM depths were derived from the L_{A5}-L_{A95} for periods identified as having AM using the automated AI detection algorithm for AM developed by Nguyen, Hansen (KL), Lechat et al (2021). Annoyance ratings (using the 5-point verbal ISO/TS 15666 scale) and subjective sleep disturbance indicators were recorded by the participants in a diary over the year. The sleep data for one participant were excluded due to the very small number of entries, which meant the sleep diary analysis was based on a single participant. It was noted that all the 'noise events' recorded by the participants related to the indoors, mainly in the bedroom. It is also noted that reported annoyance tended to be more frequent in winter than in summer, and in late evenings, night or early mornings; very few diary events were recorded during the daytime hours 0700-1600. It was noted that semantic descriptions of the sounds during events recorded using the words 'swish' or 'swoosh' appeared to be connected less often with high annoyance than 'rumbling', 'hum' or 'pulsing' (in the supplementary materials for the article, it can be seen that the diary used by the participants included an example entry with noise descriptions of 'pulsing' and 'rumbling' in it, so it’s possible this may have influenced the participants' entries of descriptive words, although this isn’t noted within the article).

Reference	Relevant evidence and discussion: amplitude modulation effects, controls, and mitigation
Hansen (KL) et al (2021) (cont.)	Regression models for high annoyance based on the variables: sound levels, AM prevalence, wind turbine power, and wind speed and direction, showed that: • the indoor A-weighted sound levels explained the largest part of the variance (15%), followed by the indoor G-weighted sound levels (11%), followed by the outdoor A-weighted levels (8%) • all the sound level variables (A-weighted, C-weighted or G-weighted, and outdoors or indoors) were similar in terms of discriminating periods of 'high annoyance' from 'not high annoyance'; the authors noted that no other weighting was significantly better than A-weighting alone, indoors or outdoors, in this respect • increased probability of high annoyance (OR=1.83, p<0.004) was associated with outdoor A-weighted sound levels in the range 40-45 dB(A) when compared against levels in the range 22-34 dB(A), while the increased odds of high annoyance during exposure to higher levels of 45-57 dB(A) compared with the lowest range had borderline significance (OR=2.95, p=0.06) • wind speed and direction were not related to annoyance • outdoor AM prevalence was associated with high annoyance, but indoor AM prevalence was not It was also noted that AM occurred more frequently at night than during the day, and AM depths were in the range 2-11 dB outdoors, 2-8 dB indoors, with a median of 3 dB for both. This result differs slightly from that reported by Nguyen, Hansen (KL), Catcheside et al (2021), which found a slightly higher AM depth indoors than outdoors. This apparent discrepancy is attributable to the truncated dataset analysed by Hansen (KL) et al (2021), which also amalgamated the data for both locations, whereas Nguyen, Hansen (KL), Catcheside et al (2021) analysed the full dataset for the three locations individually, finding significant differences for each location – they attributed this finding to varying levels of residual sound indoors. The authors acknowledged that the small number of participants limits the study generalisability. The design of the diary is noted as a risk of bias towards recording only events that annoyed, rather than including 'events' that were not annoying; the authors highlighted that the data collected indicates this bias occurred, as responses were highly skewed towards high annoyance. The risk of self-selection bias is not specifically identified in the article.

Reference	Relevant evidence and discussion: amplitude modulation effects, controls, and mitigation
Grey literature	
WSP | Parsons Brinckerhoff (2016) (continued below)	WSP | Parsons Brinckerhoff (2016) presented a systemised review of evidence on the human response to AM in wind turbine sound following an agreed protocol. The review covered evidence from 2000 up to 2015-16. The authors reviewed 70 publications concerning aspects of AM response, with an emphasis on the evidence from experimental studies that quantified both the AM exposure and the corresponding subjective responses. Only two observational exposure-response studies were identified, one of which was a pilot test with no generalisable results, while the other used a very small sample size and carried high risks of bias. The main conclusions from the review concerning AM exposure-response relationships included: • The presence of AM increases adverse responses (either annoyance, or in one case, the non-specific perceptive attribute of ''noisiness') in both lab and field settings. • Annoyance associated with AM seems to be greater during late evening, night-time or early morning periods when people tend to be resting, which may be due to either or both increased sensitivity (and residential occupation) or increased AM (due to atmospheric variations influencing wind shear). • One experimental study indicated that sensation of fluctuation in the sound was not apparent to most people until at least 2 dB depth in the modulation of broadband A-weighted sound levels. • The relationship with increasing degree of modulation (in terms of AM depth) with adverse response was not very marked, and considerably less prominent than the relationship between increasing energy time-averaged level and adverse responses. • Two experimental studies used paired comparison tests to derive equivalent response dB adjustments for 'with AM' and 'non-AM' stimuli - these suggested average adjustments of around 2-4 dB, exhibiting a weak trend with modulation depth. The review findings were considered to support the proposed introduction of an AM character penalty to be applied in a planning condition (deemed to be appropriate by default unless evidence presented to the contrary). The form of the penalty recommended took the same as that proposed by RenewableUK following their 2013 study[607], but replacing the RenewableUK AM metric with the metric developed by the IOA.

[607] RenewableUK, 2013. *The development of a penalty scheme for amplitude modulated wind farm noise*. [URL]

Reference	Relevant evidence and discussion: amplitude modulation effects, controls, and mitigation
WSP | Parsons Brinckerhoff (2016) (cont.)	It was advised that a suitable condition should impose enforcement in response to any complaints, and that the manner in which occurrence frequency should be considered would involve focussing the compliance investigation on the periods relating to the complaint (for example, complaints occurring in specific wind conditions or times of day). It was also noted that the proposed control including the penalty had not been considered in the context of statutory nuisance investigations, although this potential application was not definitively ruled out.
Pies et al (2021)	Pies et al (2021) reported an experimental study using recordings and measurements at 3 sites subject to resident complaints. Measurements were made at dwellings situated 600 m, 800 m, and 1000 m from turbines. On the basis of the measurements, an AM detection and quantification procedure was developed, which employs the wavelet transform to derive and rate a 'reconstructed' modulation signal (in a similar manner to the IOA method, but using different means). Full details of the method are not reported (citations are given to several German-language grey literature publications, but it may be useful to consider whether this approach has any specific advantages for practical use (or accurate description of AM perception) compared with the IOA metric). A probability function for expected annoyance was derived based on the AM parameter and overall level (L_{Aeq}), again without full details and relying on references to German-language publications (NB: the paper contains some errors in the formulae provided - the correct expressions can be found in a German-language industry periodical article[608]). The annoyance probability function was tested during a laboratory exercise with 10 subjects. It was stated that the 15 stimuli comprised sound samples taken from real measurements at 5 receptor locations, and the overall levels and modulation depth parameter values are reported (but modulation frequencies are omitted). The test was delivered in a hemi-anechoic room. Annoyance ratings were given on 6-point Likert scale. The mean annoyance ratings for each stimulus were compared with a predicted rating derived by converting the annoyance probability function using a simple scaling factor. The agreement between predicted and mean rated annoyance was reasonable. The results indicated that both the overall sound level and the modulation depth parameter have a strong influence on the subjective annoyance rating, although analysis of the relative strength of each was not reported. In a final step, the predicted annoyance model was compared with a subset of the AM penalty decibel values derived from a lab study by Turku University using synthesised wind turbine-like stimuli (in making this comparison, it was assumed by the authors that their AM depth parameter and Turku study are effectively equivalent) and it was shown that the predicted annoyance and the penalty dB values have a linear relationship for the subset selected.

[608] *Amplitudenmodulation – Wirkung auf den Menschen, Richtcharakteristik und Dopplereffekt* (*Amplitude modulation – effect on humans, directional characteristic and Doppler effect*, in German) ([URL]

Reference	Relevant evidence and discussion: amplitude modulation effects, controls, and mitigation
Lotinga et al (2021)	Lotinga et al (2021) presented a synthesis and meta-analysis of experimental studies investigating the annoyance associated with AM in wind turbine sound. Six previous experimental studies were reviewed, including the RenewableUK/Salford study, two studies in Switzerland by EMPA (The Swiss Federal Laboratories for Materials Science and Technology), a study by Turku University in Finland, the Japan study laboratory components, and a study by Adam Mickiewicz University in Poznan, Poland. The audio stimuli from the studies were reanalysed using the IOA metric. Following a review of each study, three studies were taken forwards for a pooled meta-analysis (the other three were considered to be inconsistent in either the exposure or response measurements and so unsuitable for pooled meta-analysis). The use of the IOA metric was modified to enable application to higher modulation frequencies than the original method allows. The authors proposed that for high modulation frequencies (up to 2 Hz), or large modulation depths, a shorter averaging time (50 ms) is necessary to accurately quantify the modulation depth. A pooled meta-regression was used to determine the primary acoustic parameters with influence on the annoyance ratings, which identified modulation depth, modulation frequency, the interaction between these two parameters, the average sound level, and the spectral balance as the main acoustic variables. The analysis then derived an 'equivalent annoyance' value in decibels from the data, which was proposed to be added as a character penalty to AM wind turbine sound levels. The technique employed to derive the equivalent annoyance penalty values was described as an 'indirect' approach, which used absolute annoyance ratings to estimate an equivalent level value from a reference curve derived from 'negligible AM' sounds. It was noted that this indirect approach produces higher penalty values than had previously been published from studies using 'direct' paired comparisons (eg, the RenewableUK/Salford study[609]), in which participants directly adjusted the level of one sound in an attempt to equalise their judgement of annoyance with a comparison sound. It was speculated that this direct approach may be challenging for participants presented with sounds with quite different characters. The penalty scheme obtained was verified by application to each of the original datasets, indicating improved correlation in all cases, and the correlation improvement was better than identified using the penalty scheme proposed following the BEIS-published review of human response to AM (WSP | Parsons Brinckerhoff, 2016), which was based on data taken from the 'direct' comparison approach (ie the RenewableUK/Salford study and the Japan study).

[609] von Hünerbein, S, King, A, Piper, B & Cand, M, 2013. Work package B2: Development of an AM dose-response relationship. *Wind turbine amplitude modulation: Research to improve understanding as to its cause and effect.* RenewableUK. [URL]

Reference	Relevant evidence and discussion: amplitude modulation effects, controls, and mitigation
Pörschmann et al (2021)	Pörschmann et al (2021) reported an observational and experimental study investigating the effects of wind turbine sound and AM. Preliminary results were presented from the observational study, which included 353 participants from 3 areas within 2.5 km of wind turbines. No exposure estimates were presented, and it was noted that "*there are still noise calculations to be carried out*". The response survey included questions about noise annoyance and specific characteristics of sound influencing annoyance. There is no suggestion that the survey employed any masking of the study intent. A regression model for noise annoyance indicated that the sound characteristics most associated with annoyance were 'swooshing' and 'swinging', followed by 'droning' and 'whistling', suggesting that AM followed by tonality were the most annoying sound characteristics (the other descriptions comprised 'rumbling', 'roaring', 'rustling' and 'pulsating'). The experimental tests used recordings taken from the measurements made at 2 of the sites. The modulation depths were quantified using the L_{A5}-L_{A95}, which showed that the AM clips had modulations depths ~2, 4, 6, 8 dB; the 'no AM' clip was generated using a synthetic superimposition technique on one of the recordings, and was evaluated as having ~1.4 dB AM depth, which was not perceptually detectable. The 79 participants in the listening tests comprised a group drawn from the observational study ('exposed' group) and a group of university staff and students ('non-exposed' group); the split between the two groups was not reported, although it was noted that there were no significant differences between the results from each group. The results showed that sound level had the strongest effect on noise annoyance ratings, with a strong association also observed for AM depth. There was an interaction effect between level and AM depth, which had a smaller effect size. The individual ratings were normalised with the inter-subject mean to reduce inter-subject variability (ie, to reduce the effect of individual use of scaling). The normalised ratings showed that annoyance increased with modulation depth and level, and that AM depth became slightly less important in determining annoyance ratings as the sound levels increased. It was observed that the sharpest increase in annoyance with modulation depth occurred at the lowest value, which the authors took to indicate that AM becomes annoying as soon as it is perceptible.

9.3 REFERENCES

AECOM. (2011). *Wind farm noise statutory nuisance complaint methodology.* Defra.

Alamir, M., Hansen, K., & Catcheside, P. (2021). Penalties applied to wind farm noise: Current allowable limits, influencing factors, and their development. *Journal of Cleaner Production, 295*, 126393.

Ascone, L., Kling, C., Wieczorek, J., Koch, C., & Kühn, S. (2021). A longitudinal, randomized experimental pilot study to investigate the effects of airborne infrasound on human mental health, cognition, and brain structure. *Scientific Reports, 11*, 3190.

Bahsi, N., & Budak, D. (2019). Local people opinion about wind farms in turkey. *Fresenius Environmental Bulletin, 28*(12), 9105-9110.

Barlas, E., Wu, K., Zhu, W., Porté-Agel, F., & Shen, W. (2018). Variability of wind turbine noise over a diurnal cycle. *Renewable Energy, 126*, 791-800.

Barlas, E., Zhu, W., Shen, W., Dag, K., & Moriarty, P. (2017). Consistent modelling of wind turbine noise propagation from source to receiver. *Journal of the Acoustical Society of America, 142*(5), 3297-3310.

Barry, R., Sulsky, S., & Kreiger, N. (2017). Using residential proximity to wind turbines as an alternative exposure measure to investigate the association between wind turbines and human health. *Journal of the Acoustical Society of America, 143*(6), 3278-3282.

Basner, M., & McGuire, S. (2018). WHO Environmental Noise Guidelines for the European Region: A systematic review on environmental noise and effects on sleep. *International Journal of Environmental Research and Public Health, 15*(3), 519.

Basner, M., Brink, M., Bristow, A., de Kluizenaar, Y., Finegold, L., Hong, J., . . . Sorqvist, P. (2015). ICBEN review of research on the biological effects of noise 2011-2014. *Noise & Health, 17*(75), 57-82.

Bastasch, M. (2011). Criteria. In D. Bowdler, & G. Leventhall (Eds.), *Wind turbine noise.* Multi-Science Publishing.

Bolin, K., Conrady, K., Karasalo, I., & Sjöblom, A. (2020). An investigation of the influence of the refractive shadow zone on wind turbine noise. *Journal of the Acoustical Society of America, 148*(2), EL166-EL171.

Bowdler, D. (2012, May/June). ETSU-R-97: An alternative view. *Acoustics Bulletin, 37*(3), pp. 32-34.

Bowdler, D. (2013, September/October). Wind turbine noise Good Practice Guide - 'the good and the bad'. *Acoustics Bulletin, 38*(5), pp. 36-37.

Bowdler, D., Bullmore, A., Davis, R., Hayes, M., Jiggins, M., Leventhall, G., & McKenzie, A. (2009, March/April). Prediction and assessment of wind turbine noise. *Acoustics Bulletin, 34*(2), pp. 35-37.

Brudermann, T., Zaman, R., & Posch, A. (2019). Not in my hiking trail? Acceptance of wind farms in the Austrian Alps. *Clean Technologies and Environmental Policy, 21*, 1603-1616.

Bullmore, A., & Cand, M. (2013). *Wind turbine amplitude modulation: Research to improve understanding as to its cause & effect. Work package F: Collation of work package reports and final reporting.* RenewableUK.

Bullmore, A., & McKenzie, A. (2015). What would an alternative to ETSU-R-97 look like? *Acoustics 2015, 15 October.* Harrogate: Institute of Acoustics.

Caddick, Z., Gregory, K., Arsintescu, L., & Flynn-Evans, E. (2018). A review of the environmental parameters necessary for an optimal sleep environment. *Building and Environment, 132*, 11-20.

Carlile, S., Davy, J., Hillman, D., & Burgemeister, K. (2018). A review of the possible perceptual and physiological effects of wind turbine noise. *Trends in hearing, 22*, 1-10.

Chaban, R., Ghazy, A., Georgiade, E., Stumpf, N., & Vahl, C. (2021). Negative effect of high-level infrasound on human myocardial contractility: In-vitro controlled experiment. *Noise & Health, 23*(109), 57-66.

Chiles, S. (2010). A new wind farm noise standard for New Zealand, NZS 6808:2010. *ICA 2010, 23-27 August.* Sydney: International Commission for Acoustics.

Chiu, C.-H., Lung, S.-C., Chen, N., Hwang, J.-S., & Tsou, M.-C. (2021). Effects of low-frequency noise from wind turbines on heart rate variability in healthy individuals. *Scientific Reports, 11*, 17817.

Clark, C., & Paunovic, K. (2018). WHO Environmental Noise Guidelines for the European Region: A systematic review on environmental noise. *International Journal of Environmental Research and Public Health, 15*(11), 2400.

Clark, C., Crumpler, C., & Notley, H. (2020). Evidence for environmental noise effects on health for the United Kingdom policy context: A systematic review of the effects of environmental noise on mental health, wellbeing, quality of life, cancer dementia, birth, reproductive outcomes, and cognition. *International Journal of Environmental Research and Public Health, 17*, 393.

Conrady, K., Bolin, K., Sjoblom, A., & Rutgersson, A. (2020). Amplitude modulation of wind turbine sound in cold climates. *Applied Acoustics, 158*, 107024.

Cooper, J., Evans, T., & Najera, L. (2012). Comparison of compliance results obtained from the various wind farm standards used in Australia. *Acoustics Australia, 40*(1), 37-44.

Cooper, S. (2021). Wind farm noise – modulation of the amplitude. *Acoustics, 3*(2), 364-390.

Cooper, S., & Chan, C. (2020). Determination of acoustic compliance of wind farms. *Acoustics, 2*(2), 416-450.

Cotté, B. (2018). Coupling of an aeroacoustic model and a parabolic equation code for long range wind turbine noise propagation. *Journal of Sound and Vibration, 422*, 343-357.

Cotté, B. (2019). Extended source models for wind turbine noise propagation. *Journal of the Acoustical Society of America, 145*(3), 1363-1371.

Coulon, M. (2014, July/August). The complex wind speed referencing system in wind farm noise assessment. *Acoustics Bulletin, 39*(4), pp. 30-35.

Cox, R., Cowen, R., Gray, B., Hanning, C., Hulme, M., Sherman, T., . . . Large, S. (2015). INWG wind turbine amplitude modulation & planning control study. *Proceedings of the Institute of Acoustics. 37*, pp. 42-53. Institute of Acoustics.

Davy, J., Burgemeister, K., & Hillman, D. (2018). Wind turbine sound limits: Current status and recommendations based on mitigating noise annoyance. *Applied Acoustics, 140*, 288-295.

Davy, J., Burgemeister, K., Hillman, D., & Carlile, S. (2020). A review of the potential impacts of wind turbine noise in the Australian context. *Acoustics Australia, 48*, 181-197.

Department of the Environment, Planning and Environmental Policy Group. (2010). *Best practice guidance to Planning Policy Statement 18 'Renewable Energy'.* Northern Ireland Executive.

Dutilleux, G., & Fosset, J. (2020). Comparing sound emergence and sound pressure level as predictors of short-term annoyance from wind turbine noise. *Acta Acustica, 3*(4), 10.

Environment Protection Authority. (2009). *Wind farms environmental noise guidelines.* State of South Australia.

Fernandez, F., Burdisso, R., & Arenas, J. (2017). Indoor simulation of amplitude modulated wind turbine noise. *Wind Energy, 20*(3), 507-519.

Fowler, K., Koppen, E., & Matthis, K. (2013). International legislation and regulations for wind turbine noise. *Wind Turbine Noise 2013.* Denver, 28-30 August: INCE-Europe.

Freiberg, A., Schefter, C., Girbig, M., Murta, V., & Seidler, A. (2019). Health effects of wind turbines on humans in residential settings: Results of a scoping review. *Environmental Research, 169*, 446-463.

Garnett, M., & Sutherland, C. (2015). Measuring Compliance With The ETSU-R-97 Simplified Limit. *Proceedings of the Institute of Acoustics. 37*, pp. 33-41. Institute of Acoustics.

Goeme, A. (2015). Comparative analysis of wind turbine noise assessment and rating procedures in the UK, France and the Netherlands. *Wind Turbine Noise 2015, 20-23 April.* Glasgow: INCE-Europe.

Government of Ireland. (2019). *Draft revised wind energy guidelines.*

Greenough, R., & Unwin, D. (2013, May/June). A neglected source of uncertainty in potential wind farm noise assessment using the ETSU-R-97 process. *Acoustics Bulletin, 38*(3), pp. 36-42.

Guski, R., Schreckenberg, D., & Schuemer, R. (2017). WHO Environmental Noise Guidelines for the European Region: A systematic review on environmental noise and annoyance. *International Journal of Environmental Research and Public Health, 14*(12), 1539.

Hansen, C., & Hansen, K. (2020). Recent advances in wind turbine noise research. *Acoustics, 2*(1), 171-206.

Hansen, C., Doolan, C., & Hansen, K. (2017). Wind energy and noise. In C. Hansen, C. Doolan, & K. Hansen, *Wind farm noise: Measurement, assessment and control.* John Wiley & Sons.

Hansen, K., Nguyen, P., Micic, G., Lechat, B., Catcheside, P., & Zajamšek, B. (2021). Amplitude modulated wind farm noise relationship with annoyance: A year-long field study. *Journal of the Acoustical Society of America, 150*(2), 1198-1208.

Hansen, K., Nguyen, P., Zajamsek, B., Catcheside, P., & Hansen, C. (2019). Prevalence of wind farm amplitude modulation at long-range residential locations. *Journal of Sound and Vibration, 455*, 136-149.

Hansen, K., Zajamsek, B., & Hansen, C. (2018). Wind farm noise uncertainty: Prediction, measurement and compliance assessment. *Acoustics Australia, 46*, 59-67.

Harrison, R. (2015). On the biological plausibility of Wind Turbine Syndrome. *International Journal of Environmental Health Research, 25*(5), 463-468.

Hayes McKenzie Partnership. (2006). *The measurement of low frequency noise at three UK wind farms.* Department of Trade & Industry.

Hayes McKenzie Partnership. (2011). *Analysis of how noise impacts are considered in the determination of wind farm planning applications.* Department of Energy & Climate Change.

Heimann, D., & Englberger, A. (2018). 3D-simulation of sound propagation through the wake of a wind turbine: Impact of the diurnal variability. *Applied Acoustics, 141*, 393-402.

Hessler, G., Leventhall, G., Schomer, P., & Walker, B. (2017). Health effects from wind turbine low frequency noise & infrasound: Do wind turbines make people sick? That is the issue. *Sound and Vibration, 51*(1), 34-44.

IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group. (2015). *Discussion document: Methods for rating amplitude modulation in wind turbine noise.* Institute of Acoustics.

IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group. (2016). *Final report: A method for rating amplitude modulation in wind turbine noise.* Institute of Acoustics.

Jennings, S., & Kennedy, J. (2019). Detection and evaluation of amplitude modulation from a wind energy development, Ireland. *Acta Acustica united with Acustica, 105*(6), 1042-1052.

Johansson, A., Bolin, K., & Alvarsson, J. (2019). Annoyance and partial masking of wind turbine noise from ambient sources. *Acta Acustica united with Acustica, 105*(6), 1035-1041.

Kageyama, T. (2016). Adverse effects of community noise as a public health issue. *Sleep and Biological Rhythms, 14*, 223-229.

Keith, S., Michaud, D., Feder, K., Soukhovtsev, V., Voicescu, S., Denning, A., . . . Richarz, W. (2019). Wind turbine audibility calculations inside dwellings. *Journal of the Acoustical Society of America, 145*(4), 2435-2444.

Kendrick, P., von Hünerbein, S., & Cox, T. (2016). The effect of microphone wind noise on the amplitude modulation of wind turbine noise and its mitigation. *Journal of the Acoustical Society of America, 140*(1), EL79-EL83.

Kim, E., & Chung, J. (2019). The memory of place disruption, senses, and local opposition to Korean wind farms. *Energy Policy, 131*, 43-52.

Klein, L., Gude, J., Wenz, F., Lutz, T., & Krämer, E. (2018). Advanced computational fluid dynamics (CFD)–multi-body simulation (MBS) coupling to assess low-frequency emissions from wind turbines. *Wind Energy Science, 3*(2), 713-728.

Large, S., Stigwood, D., & Stigwood, M. (2017). Cotton Farm Wind Farm long term community noise monitoring 4 years on: Testing compliance and AM control methods. *Inter-noise 2017, 27-30 August.* Hong Kong: I-INCE.

Lechat, B., Hansen, K., Micic, G., Decup, F., Dunbar, C., Liebich, T., . . . Zajamsek, B. (2021). K-complexes are a sensitive marker of noise-related sensory processing during sleep: A pilot study. *Sleep, 44*(9), zsab065.

Lenchine, V. (2016). Assessment of amplitude modulation in environmental noise measurements. *Applied Acoustics, 104*, 152-157.

Liebich, T., Lack, L., Hansen, K., Zajamsek, B., Lovato, N., Catcheside, P., & Micic, G. (2020). A systematic review and meta-analysis of wind turbine noise effects on sleep using validated objective and subjective sleep assessments. *Journal of Sleep Research, 30*, e13228.

Lotinga, M., & Lewis, T. (2021). Subjective responses to wind turbine noise amplitude modulation: Pooled analysis of laboratory listening studies and synthesis of an AM character rating penalty. *Wind Turbine Noise 2021, 18-21 May.* Remote from Europe: INCE-Europe.

Lubner, R., Kondamuri, N., Knoll, R., Ward, B., Littlefield, P., Rodgers, D., . . . Kozin, E. (2020). Review of audiovestibular symptoms following exposure to acoustic and electromagnetic energy outside conventional human hearing. *Frontiers in Neurology, 11*, 234.

Mackay, J., Coulon, M., & Baldwin, J. (2016). The use of proxy measurements to determine wind farm noise compliance, what are the options, is there a need for further guidance? *Proceedings of the Institute of Acoustics. 38*, pp. 245-251. Institute of Acoustics.

Mackowski, L., & Carolus, T. (2021). Wind turbine trailing edge noise: Mitigation of normal amplitude modulation by individual blade pitch control. *Journal of Sound and Vibration, 510*, 116279.

Makarewicz, R., & Golebiewski, R. (2015). Influence of blade pitch on amplitude modulation of wind turbine noise. *Noise control engineering journal, 63*(2), 195-201.

Makarewicz, R., & Golebiewski, R. (2019). The Influence of a low level jet on the thumps generated by a wind turbine. *Renewable and Sustainable Energy Reviews, 104*, 337-342.

Marshall Day Acoustics. (2013). *Examination of the significance of noise in relation to onshore wind farms.* Sustainable Energy Authority of Ireland.

McLaughlin, D. (2012, July/August). Wind shear and its effect on wind turbine noise assessment. *Acoustics Bulletin, 37*(4), pp. 39-42.

Merino-Martinez, R., Pieren, R., & Schäffer, B. (2021). Holistic approach to wind turbine noise: From blade trailing-edge modifications to annoyance estimation. *Renewable and Sustainable Energy Reviews, 148*, 111285.

Michaud, D., Guay, M., Marro, L., & Than, J. (2018). Response to: Using residential proximity to wind turbines as an alternative exposure measure to investigate the association between wind turbines and human health, by Barry, Sulsky, Kreiger (2018) J. Acoust. Soc. Am. 143(6), 3278-3282 (L). *Journal of the Acoustical Society of America, 144*(1), 330-331.

Michaud, D., Keith, S., Guay, M., Voicescu, S., Denning, A., & McNamee, J. (2021). Sleep actigraphy time-synchronized with wind turbine output. *Sleep, 44*(9), zsab070.

Micic, G., Zajamsek, B., Lack, L., Hansen, K., Doolan, C., Hansen, C., . . . Catcheside, P. (2018). A review of the potential impacts of wind farm noise on sleep. *Acoustics Australia, 46*, 87-97.

Mills, S., Bessette, D., & Smith, H. (2019). Exploring landowners' post-construction changes in perceptions of wind energy in Michigan. *Land Use Policy, 82*, 754-762.

Mucci, N., Traversini, V., Lorini, C., De, S. S., Galea, R., Bonaccorsi, G., & Arcangeli, G. (2020). Urban noise and psychological distress: A systematic review. *International Journal of Environmental Research and Public Health, 17*(18), 6621.

Nguyen, D., Hansen, K., Zajamsek, B., & Catcheside, P. (2020). Evaluation of wind farm noise amplitude modulation synthesis quality. *Applied Acoustics, 166*, 107349.

Nguyen, P., Hansen, K., Catcheside, P., Hansen, C., & Zajamsek, B. (2021). Long-term quantification and characterisation of wind farm noise amplitude modulation. *Measurement, 182*, 109678.

Nguyen, P., Hansen, K., Lechat, B., Catcheside, P., Zajamsek, B., & Hansen, C. (2021). Benchmark characterisation and automated detection of wind farm noise amplitude modulation. *Applied Acoustics, 183*, 108286.

Oerlemans, S. (2015). Effect of wind shear on amplitude modulation of wind turbine noise. *International Journal of Aeroacoustics, 14*(5-6), 715-728.

Okada, Y., Yoshihisa, K., & Hyodo, S. (2019). Directivity of amplitude modulation sound around a wind turbine under actual meteorological conditions. *Acoustical Science and Technology, 40*(1), 40-48.

Onakpoya, I., O'Sullivan, J., Thompson, M., & Heneghan, C. (2015). The effect of wind turbine noise on sleep and quality of life: A systematic review and meta-analysis of observational studies. *Environmental International, 82*, 1-9.

Parra, J., Valdebenito, I., & Lobos, V. (2018). Management strategy for wind farms noise control in Chile. *Inter-noise 2018, 26-29 August.* Chicago: I-INCE.

Peri, E., & Tal, A. (2021). Is setback distance the best criteria for siting wind turbines under crowded conditions? An empirical analysis. *Energy Policy, 115*, 112346.

Perkins, R. (2014). Wind turbine noise - a review of progress to date, and where to next? *Proceedings of the Institute of Acoustics. 36*, pp. 592-600. Institute of Acoustics.

Perkins, R. (2015). IOA wind farm guidance - where to next. *Proceedings of the Institute of Acoustics. 37*, pp. 1-3. Institute of Acoustics.

Perkins, R. (2015, March/April). Wind turbine noise - progress to date, and where to next? *Acoustics Bulletin, 40*(2), pp. 42-45.

Perkins, R., Cand, M., Davis, R., Hayes, M., & Jordan, C. (2013). The production of a good practice guide to assess wind turbine noise in the United Kingdom using ETSU-R-97. *Wind Turbine Noise 2013, 28-30 August.* Denver: INCE-Europe.

Pies, K., & Martinez, S. (2021). Assessment and rating of Wind turbine noise immission at dwellings – the influence of amplitude modulation, aerodynamic noise sources and the Doppler effect. *Wind Turbine Noise 2021, 18-21 May.* Remote from Europe: INCE-Europe.

Pörschmann, C., Großarth, S., Arend, J., Schmitter, S., Schreckenberg, D., & Wunder, K. (2021). Amplitude modulations increase annoyance due to wind turbine noise immission. *Inter-noise 2021, 1-5 August.* Washington: I-INCE.

Poulsen, A., Raaschou-Nielsen, O., Peña, A., Hahmann, A., Nordsborg, R., Ketzel, M., . . . Sørensen, M. (2018). Short-term nighttime wind turbine noise and cardiovascular events: A nationwide case-crossover study from Denmark. *Environment International, 114*, 160-166.

Qu, F., & Tsuchiya, A. (2021). Perceptions of wind turbine noise and self-reported health in suburban residential areas. *Frontiers in Psychology, 12*, 3357.

Rand, J., & Hoen, B. (2017). Thirty years of North American wind energy acceptance research: What have we learned? *Energy Research & Social Science, 29*, 135-148.

Saveedra, R., & Samanta, B. (2015). Noise and vibration issues of wind turbines and their impact - a review. *Wind Engineering, 39*(6), 693-702.

Schild, J., & Venathec, V. (2015). State of the art and new perspectives for the development of noise regulation of wind farms. *Wind Turbine Noise 2015, 20-23 April.* Glasgow: INCE-Europe.

Sedaghatizadeh, N., Arjomandi, M., Cazzolato, B., & Kelso, R. (2017). Wind farm noises: Mechanisms and evidence for their dependency on wind direction. *Renewable Energy, 109*, 311-322.

Simos, J., Cantoreggi, N., Christie, D., & Forbat, J. (2019). Wind turbines and health: A review with suggested recommendations. *Environnement, Risques & Santé, 18*(2), 149-159.

SLR & Hoare Lea. (2015). *Wind farm impacts study: Review of the visual, shadow flicker and noise impacts of onshore wind farms. Final report.* ClimateXChange.

Summers, S., & Parry, G. (2017). Experience of reviewing wind farm noise assessments for Scottish local authorities and the implementation of the IOA Good Practice Guide. *Wind Turbine Noise 2017, 2-5 May.* Rotterdam: INCE-Europe.

Summers, S., & Parry, G. (2021). Further experience of reviewing noise assessments for wind farms in Scotland and the implementation of the IOA Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise. *Wind Turbine Noise 2021, 18-21 May.* Remote from Europe: INCE-Europe.

Sutherland, C. (2014, September/October). Practical challenges with post completion measurements of the ETSU-R-97 simplified 35dB(A) planning condition for wind turbines. *Acoustics Bulletin, 39*(5), pp. 34-38.

Taylor, J., & Klenk, N. (2019). The politics of evidence: Conflicting social commitments and environmental priorities in the debate over wind energy and public health. *Energy Research & Social Science, 47*, 102-112.

Tham, R., Morgan, G., Dharmage, S., Marks, G., & Cowie, C. (2020). Scoping review to understand the potential for public health impacts of transitioning to lower carbon emission technologies and policies. *Environmental Research Communications, 2*(6), 065003.

Thorsson, P., Persson Waye, K., Ogren, M., Smith, M., Pedersen, E., & Forssen, J. (2019). Creating sound immission mimicking real-life characteristics from a single wind turbine. *Applied Acoustics, 143*, 66-73.

Tonin, R. (2018). A review of wind turbine-generated infrasound: Source, measurement and effect on health. *Acoustics Australia, 46*, 69-86.

Turunen, A., Tiittanen, P., Yli-Tuomi, T., Taimisto, P., & Lanki, T. (2021). Self-reported health in the vicinity of five wind power production areas in Finland. *Environment International, 151*, 106419.

Turunen, A., Tiittanen, P., Yli-Tuomi, T., Taimisto, P., & Lanki, T. (2021). Symptoms intuitively associated with wind turbine infrasound. *Environmental Research, 192*, 110360.

van Kamp, I., & van den Berg, F. (2018). Health effects related to wind turbine sound, including low-frequency sound and infrasound. *Acoustics Australia, 46*, 31-57.

van Kamp, I., & van den Berg, F. (2021). Health effects related to wind turbine sound: An update. *International Journal of Environmental Research and Public Health, 18*(17), 9133.

van Kamp, I., Simon, S., Notley, H., Baliatsas, C., & van Kempen, E. (2020). Evidence relating to environmental noise exposure and annoyance, sleep disturbance, cardio-vascular and metabolic health outcomes in the context of IGCB (N): A scoping review of new evidence. *International Journal of Environmental Research and Public Health, 17*, 3016.

van Kempen, E., Casas, M., Pershagen, G., & Foraster, M. (2018). WHO Environmental Noise Guidelines for the European Region: A systematic review on environmental noise and cardiovascular and metabolic effects: a summary. *International Journal of Environmental Research and Public Health, 15*(2), 379.

Walsh, U. (2015). *Report on the Committee's Inquiry into Wind Energy Volume 7 Appendix 7: Specialist Advisor Report.* Northern Ireland Assembly.

Wilson, G., & Dyke, S. (2016). Pre- and post-installation community perceptions of wind farm projects: The case of Roskrow Barton (Cornwall, UK). *Land Use Policy, 52*, 287-296.

WSP | Parsons Brinckerhoff. (2016). *Wind turbine AM review: Phase 2 report.* Department for Business, Energy & Industrial Strategy.

WSP | Parsons Brinckerhoff. (2016). *Wind turbine AM review: Phase 2 report Issue 3.* Department for Business, Energy and Industrial Strategy.

Wszolek, T., Pawlik, P., Mleczko, D., & Chronowska, J. (2020). Analysis of the usefulness of measurement on a board at ground level for assessing the noise level from a wind turbine. *Archives of Acoustics, 45*(1), 165-175.

Yauwenas, Y., Zajamsek, B., Reizes, J., Timchenko, V., & Doolan, C. (2017). Numerical simulation of blade-passage noise. *Journal of the Acoustical Society of America, 142*(3), 1575-1586.

Yauwenas, Y., Zajamsek, B., Reizes, J., Timchenko, V., & Doolan, C. (2021). Directivity of blade-tower interaction noise. *JASA Express Letters, 1*(6), 063601.

Zagubień, A. (2018). Analysis of Acoustic Pressure Fluctuation around Wind Farms. *Polish Journal of Environmental Studies, 27*(6), 2843-2849.

Zagubień, A., & Wolniewicz, K. (2020). The assessment of infrasound and low frequency noise impact on the results of learning in primary school - case study. *Archives of Acoustics, 45*(1), 93-102.

Zajamsek, B., Yauwenas, Y., Doolan, C., Hansen, K., Timchenko, V., Reizes, J., & Hansen, C. (2019). Experimental and numerical investigation of blade-tower interaction noise. *Journal of Sound and Vibration, 443*, 362-375.

Appendix C

STAKEHOLDER ENGAGEMENT QUESTIONNAIRE & RESPONSE ANALYSIS

10 APPENDIX C1: STAKEHOLDER ENGAGEMENT QUESTIONNAIRE

Introduction
The UK Government Department for Business, Energy and Industrial Strategy is undertaking a **scoping review** of current UK onshore wind turbine noise assessment guidance. The purpose of the review is to determine whether the guidance adequately ensures that wind turbine noise is managed effectively and consistently in line with current Government policies on noise and achieving 'Net Zero'[610] greenhouse gas emissions by 2050, accounts for contemporary technological and acoustical developments, and (if not), what updates may be necessary to achieve this. This survey is divided into three main parts: 1) questions about topics addressed in the current UK wind turbine noise guidance, 2) questions about wind turbine technology and wind farm design, and 3) a request for any other evidence or suggestions that may be relevant to the intentions of this scoping review. At this **scoping stage**, no guidance development is being undertaken; the current review will inform a decision on whether any future guidance development is required, but any potential subsequent development of guidance is likely to be accompanied by a consultation stage. Accordingly, responses to this survey do not need to include highly detailed information such as might be entered in response to engagement on specific proposals for guidance development. However, please ensure you raise any **key issues** that you feel should be considered at this stage. Please also note that the scope of the review encompasses **onshore** wind turbines only. This review and engagement does not affect any material considerations of the current UK onshore wind turbine noise assessment guidance within ongoing planning applications and decisions, which remain as referenced in the relevant authority policies. You will be given the opportunity at the end of the survey to indicate whether you would like to discuss your responses in more detail by telephone interview. No guarantee can be given at this stage that a telephone interview will be possible - this will depend on the numbers of respondents indicating a preference for telephone contact. Your responses to this engagement will be an important part of ensuring that the wind turbine noise assessment guidance in the UK is consistent with Government policies, and remains suitable.

[610] Achieving the Government's ambitious 2050 Net Zero target will require significant increases in renewable electricity generation, and we will need to increase deployment across a range of technologies, including onshore wind. Our recent Energy White Paper: *Powering our net zero future* stated that we will need sustained growth in the capacity of onshore wind over the next decade, alongside solar PV and offshore wind.

Statement on use of survey respondent data

All survey response data will be managed in compliance with UK legislation and regulations, including the Data Protection Act 2018 and the General Data Protection Regulation (GDPR).

As part of this survey, we will ask you to confirm the following personal data:

- confirmation of your organisation and role
- contact details (email and telephone number)

This personal data is required so that we can ensure that all responses are from genuine stakeholders, to enable response analysis by organisation type, and so that you can be included in any further engagement during this exercise.

Anonymised response data from this survey will be included in a published report to be made available on the Government web domain www.gov.uk. Any published responses will have potentially identifying information removed.

Your data will be stored securely in compliance with UK legislation and regulations until this scoping review and the delivery of all associated outputs (internal and published documents etc) have been completed, after which your personal data will be deleted.

Our personal information charter, which sets out the standards you can expect when we collect, hold or use your personal information, can be accessed using the following web link: https://www.gov.uk/government/organisations/department-for-business-energy-and-industrial-strategy/about/personal-information-charter

Declaration of consent to use of data

Do you consent to having your details and responses collected and managed in the manner described? (Choose one answer. If you answer 'No, I do not want to take part in this survey' to this question, please could you confirm the reason for not taking part in the box provided?)

☐ Yes, I am happy to take part in this survey and have my data collected and managed in the manner described

☐ No, I do not want to take part in this survey

Reason for not taking part (if answering 'no'):

Definitions

PLEASE READ THIS PAGE CAREFULLY BEFORE CONTINUING WITH THE SURVEY

Term	Meaning
Current UK wind turbine noise assessment guidance	*ETSU-R-97 The Assessment and Rating of Noise from Wind Farms (1996), the Institute of Acoustics Good Practice Guide to the Application of ETSU-R-97 (2013) and its six Supplementary Guidance Notes (2014)* It is acknowledged that further individual devolved UK administration noise guidance is also in place, both wind turbine specific and non-specific. It is also acknowledged that the SGNs to the IOA GPG do not officially form part of the guidance endorsed by all devolved administrations, due to the publication dates (specifically, the Northern Ireland Assembly and Scottish Government endorsements preceded the SGN publications). However, it is believed that the IOA GPG SGNs are widely viewed as representing best practice guidance around the UK.
Government policies on noise and Net Zero	*The UK devolved administration governmental policies on noise and achieving net zero targets for greenhouse gas emissions relevant in any UK nation to which your professional experience is applicable* If your experience encompasses more than one UK nation, please provide details of any divergence in your responses as they concern the context of the policies of each devolved administration, as appropriate.
Amplitude modulation	*A sound characteristic associated with the regular rotation of the wind turbine blades, sometimes described as 'swishing', 'whooshing', 'whoomphing', or 'thumping'*
Tonality	*A sound characteristic sometimes described as 'droning', 'humming', 'ringing', or 'whistling'*

Notes on completing survey offline

This document has been designed to be completed using a computer. The response boxes will automatically resize to the input text.

Please do not print out this survey form to enter handwritten responses, as these will not be processed. The completed form must be returned in its original electronic DOCX format.

Respondent details

Please enter your details as indicated:

Name	
Organisation represented	
Role or job title	
Email address	
Telephone number	

Comments:

Please could you indicate the type of response you are providing:

☐ Individual view (on behalf of organisation)

☐ Collated views of multiple respondents (on behalf of organisation)

☐ Other (please specify in comments below)

Comments:

Familiarity with the current UK wind farm noise assessment guidance
Q1.1: Which description most closely describes your level of familiarity with the current UK wind turbine noise assessment guidance? (Choose one answer) ☐ A) Very familiar / expert understanding / very frequent use in practice ☐ B) Familiar / good working knowledge / regular use in practice ☐ C) Passing familiarity / some understanding / occasional use in practice ☐ D) Unfamiliar / no understanding
If you answered A, B or C to Question 1.1, **please proceed to Question 1.2** If you answered D to Question 1.1, please could you: i) provide contact information for an individual at your organisation who is able to answer A, B or C to question Q1.1 (ie, has some familiarity with the current UK wind turbine noise assessment guidance); [ ] ii) **proceed to Question 2.1**

Adequacy of current UK wind farm noise assessment guidance
Q1.2: Which description most closely matches your view on the adequacy of the current UK wind turbine noise guidance in ensuring wind turbine noise is managed effectively and consistently in line with Government policies on noise and Net Zero? (Choose one answer) ☐ A) Adequate, no updates necessary ☐ B) Mostly adequate, but requires some updating or amendment ☐ C) Inadequate and requires substantial revision ☐ D) Not sure
If you answered A to Question 1.2, **please proceed to Question 2.1** If you answered B, C or D to Question 1.2, **please proceed to Question 1.3**

Topics requiring updating
Q1.3: Which (if any) of the following topics relevant to the current UK wind turbine noise assessment guidance do you consider need to be updated? (Choose as many as applicable) ☐ Fundamental approach (holistic view of the guidance on managing wind turbine noise) ☐ Baseline determination (pre-development environment) ☐ Measurements of sound or meteorology ☐ Consideration of atmospheric, meteorological, or topographical influences on sound ☐ Evaluation of sound characteristics ☐ Sound predictions ☐ Noise impact assessment (including cumulative impact) ☐ Noise controls (including noise limits, effects thresholds, and use of planning conditions) ☐ Compliance determination and enforcement ☐ Uncertainty ☐ Anything else not listed above (please specify in comments) Comments:

Description of required updates
Q1.4: Please could you briefly outline the updates you believe need to be made to the current UK wind turbine noise assessment guidance, and identify any publicly accessible evidence you are aware of that would support or inform the updates indicated? (Please enter your responses under the headings indicated below that are most closely applicable to your suggestion, and use as much space as needed to address the key issues)
(Q1.4) Fundamental approach (holistic view of the guidance on managing wind turbine noise)

(Q1.4) Baseline determination (pre-development environment)
(Q1.4) Measurements of sound or meteorology
(Q1.4) Consideration of atmospheric, meteorological, or topographical influences on sound
(Q1.4) Evaluation of sound characteristics (including amplitude modulation and tonality)
(Q1.4) Sound predictions (including modelling and mapping)
(Q1.4) Noise impact assessment (including cumulative impact)
(Q1.4) Noise controls (including noise limits, effects thresholds, and use of planning conditions)
(Q1.4) Compliance determination and enforcement
(Q1.4) Uncertainty

(Q1.4) Anything else not listed above (please specify)

Experience or knowledge of wind farm or turbine design influence on sound emissions

Q2.1: Do you have any specific experience or research knowledge of the potential influence of wind farm or wind turbine design or age on sound emissions? (Choose one answer)

☐ Yes

☐ No

If you answered 'yes' to Question 2.1, **please proceed to Question 2.2**

If you answered 'no' to Question 2.1, **please proceed to Question 3.1**

Influence of modern wind turbine or farm design on sound emissions

Q2.2: Please could you briefly outline how the design of more modern wind turbines has influenced the sound emissions (including sound characteristics), compared with wind turbine designs prevalent around the time of the preparation of ETSU-R-97?

Q2.3: Please could you briefly outline any knowledge or evidence for how the age or wear and tear of wind turbines could influence the sound emission characteristics, including AM?

Q2.4: Please could you briefly outline any suggestions you have for how the prevalence of AM from various turbine models and ages could be investigated?

Q2.5: Please could you briefly outline any knowledge or evidence for how the design of wind farm layouts could influence cumulative noise impacts?

Any other evidence

Q3.1: Please could you identify any publicly accessible evidence you are aware of that could be relevant to the development of any future UK wind turbine noise assessment guidance and is not already mentioned in your previous responses?

Guidance development and maintenance

Q3.2: Please could you briefly outline any suggestions you have for how any future UK wind turbine noise assessment guidance could be developed and maintained to provide a stable platform for development planning and assessment, while ensuring that it is kept up to date with robust scientific evidence?

Interview preference

Would you like to indicate a preference to be contacted by telephone to provide further responses to these survey questions? (Choose one answer. Answering 'yes' to this question confirms you would like to be contacted by telephone using the number you have provided)

☐ Yes

☐ No

Feedback
Thank you for completing this survey. Your responses to this engagement will be an important part of ensuring that the wind turbine noise assessment guidance in the UK is consistent with Government policies, and remains suitable. If you have any feedback on this questionnaire or the engagement process, please send your comments to windfarmnoiseguidance@wsp.com

11 APPENDIX C2: STAKEHOLDER LIST

Type	Organisation	Survey response	Type of response	Comment on type of response
UK Government	Defra	Offline	Individual view (on behalf of organisation)	-
UK Government	UK Health Security Agency	Online	Individual view (on behalf of organisation)	-
UK Government	Planning Inspectorate	Offline	-	Joint response from UK PINS and WG PINS
Welsh Government	Public Health Wales	Offline	Other (please specify below)	PHW Environmental Public Health Service only (not representing entire of PHW)
Welsh Government	Planning and Environment Decisions Wales	Joint response with PINS	-	Joint response from UK PINS and WG PINS [as PEDW then was]
Scottish Government	Scottish Government	Offline	Individual view (on behalf of organisation)	-
Local planning authority (England)	Great Yarmouth Borough Council	Online	Individual view (on behalf of organisation)	-
Local planning authority (England)	Tendring District Council	Online	Individual view (on behalf of organisation)	Views encompassing several officers within relevant team
Local planning authority (England)	North Kesteven District Council	Online	Individual view (on behalf of organisation)	-
Local planning authority (England)	Redcar and Cleveland Borough Council	Offline	Other (please specify below)	Joint response by officers from the Environmental Protection Team who respond to planning consultations and noise complaints.
Local planning authority (England)	King's Lynn and West Norfolk Borough Council	Online	Individual view (on behalf of organisation)	-
Local planning authority (England)	South Cambridgeshire District Council	Online	Individual view (on behalf of organisation)	-
Local planning authority (England)	Medway Council	Online	Other (please specify below)	Individual response only on behalf of Environmental Protection Team. This should not therefore be considered as a response on behalf of the entirety of Medway Council.
Local planning authority (England)	Hambleton District Council	Online	Individual view (on behalf of organisation)	-
Local planning authority (England)	North Somerset Council	Online	Individual view (on behalf of organisation)	On behalf of Environmental Protection

Type	Organisation	Survey response	Type of response	Comment on type of response
Local planning authority (Northern Ireland)	Fermanagh and Omagh District Council	Offline	Individual view (on behalf of organisation)	-
Local planning authority (Northern Ireland)	Causeway Coast and Glens Borough Council	Offline	Individual view (on behalf of organisation)	-
Local planning authority (Northern Ireland)	Armagh, Banbridge and Craigavon	Offline	Collated views of multiple respondents (on behalf of organisation)	Collated view from the officers within the Environmental Health Department of the Council (one organisation). The following comments are submitted on an Environmental Health technical-only basis and should not be viewed as the views of the body Corporate nor of the political members nor their representative parties.
Local planning authority (Northern Ireland)	Mid Ulster District Council	Offline	Collated views of multiple respondents (on behalf of organisation)	-
Local planning authority (Northern Ireland)	Derry City and Strabane District Council	Offline	Other (please specify below)	The comments provided in the survey represent those of the Environmental Health Service and not the wider Council/organisation.
Local planning authority (Northern Ireland)	Antrim and Newtownabbey Borough Council	Online	Individual view (on behalf of organisation)	-
Local planning authority (Scotland)	Aberdeenshire Council	Online	Individual view (on behalf of organisation)	-
Local planning authority (Scotland)	Highland Council	Offline	Collated views of multiple respondents (on behalf of organisation)	-
Local planning authority (Scotland)	South Lanarkshire Council	Offline	Collated views of multiple respondents (on behalf of organisation)	-
Local planning authority (Scotland)	Shetland Islands Council	Offline	Individual view (on behalf of organisation)	-
Local planning authority (Scotland)	East Ayrshire Council	Online	Collated views of multiple respondents (on behalf of organisation)	-
Industry professional association	RenewableUK	Joint response with SR	Collated views of multiple respondents (on behalf of organisation)	Joint response by RenewableUK and Scottish Renewables, representing views of members of both organisations

Type	Organisation	Survey response	Type of response	Comment on type of response
Industry professional association	Scottish Renewables	Joint response with RUK	Collated views of multiple respondents (on behalf of organisation)	Joint response by RenewableUK and Scottish Renewables, representing views of members of both organisations
Industry professional association	Institute of Acoustics	Offline	Collated views of multiple respondents (on behalf of organisation)	-
Industry professional association	Association of Noise Consultants	Offline	Collated views of multiple respondents (on behalf of organisation)	This response was compiled following a working group meeting of acoustic consultants who have significant experience with onshore wind farm assessments. Please note that this response includes all items that were identified by those contributing comments and that there were varying opinions over the importance of some of these.
Industry professional association	BSi PEL/88 Committee	Online	Collated views of multiple respondents (on behalf of organisation)	-
Civic organisation	Independent Noise Working Group	Online	Collated views of multiple respondents (on behalf of organisation)	-

12 APPENDIX C3: STAKEHOLDER ENGAGEMENT RESPONSE ADDITIONAL ANALYSIS

12.1 METADATA ANALYSIS

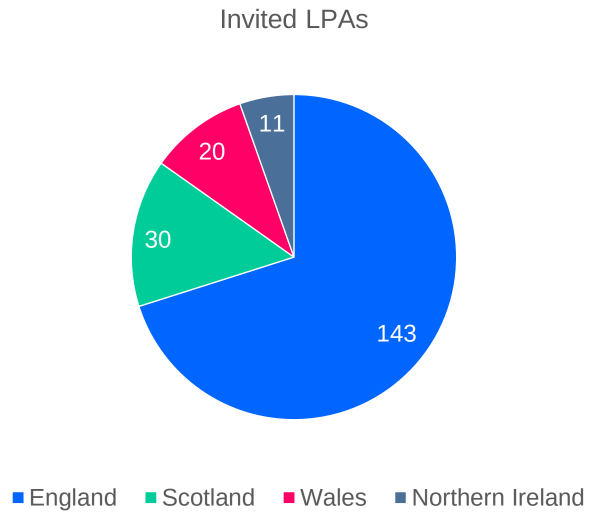


Figure 12-1: Stakeholder engagement: invited LPAs by devolved administration

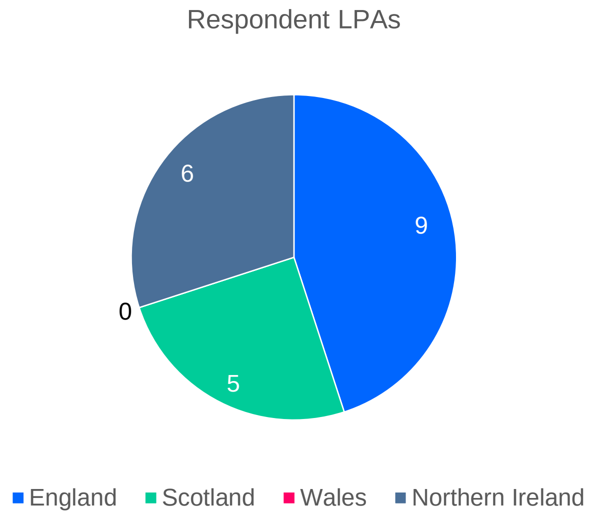


Figure 12-2: Stakeholder engagement: respondent LPAs by devolved administration

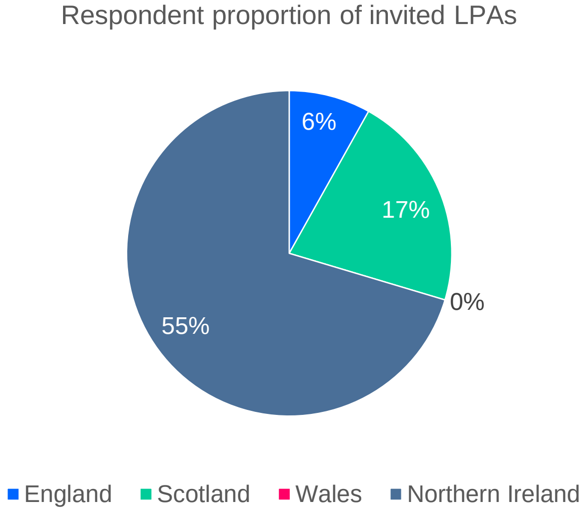


Figure 12-3: Stakeholder engagement: proportional respondent LPAs by devolved administration

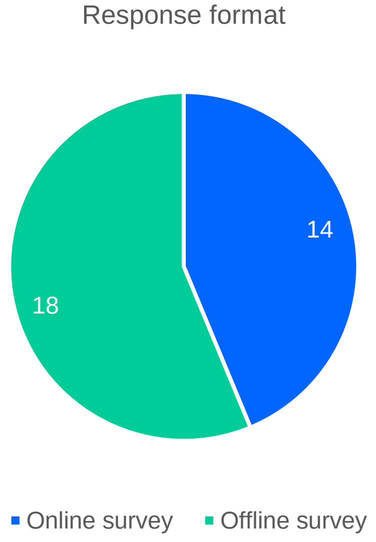


Figure 12-4: Stakeholder response format

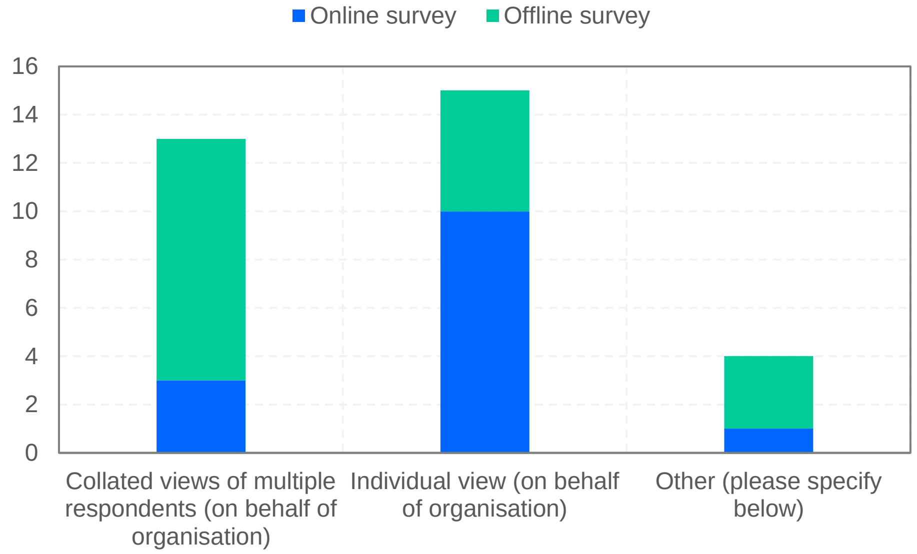


Figure 12-5: Stakeholder response format by type of response

Examination of the ‘other’ response type comments indicated that these were all ‘collated views’, but the respondents wished to clarify the limitations of the collation of multiple respondents’ views. Combining the ‘other’ response type with the ‘collated views’ type produced Figure 12-6.

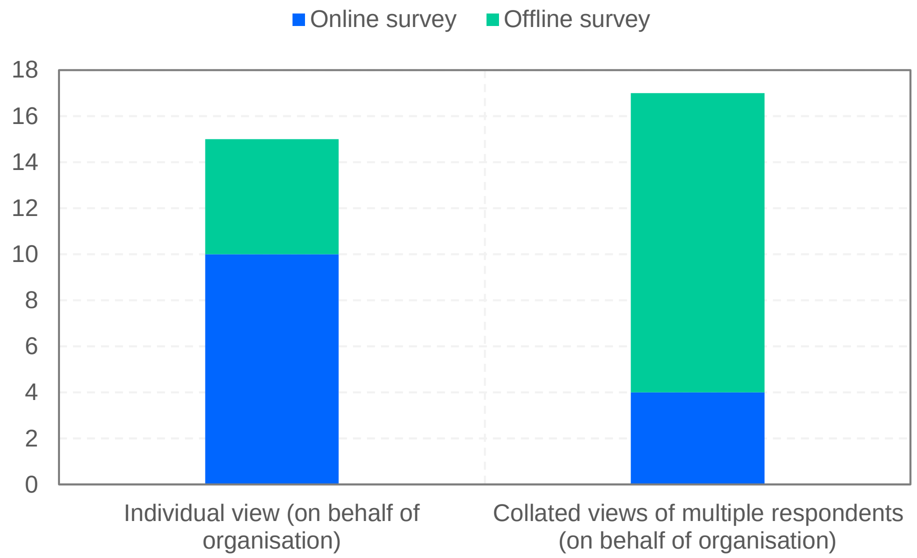


Figure 12-6: Stakeholder response format by type of response (‘other’ type combined with ‘collated views’)

12.2 RESPONSE ANALYSIS

12.2.1 SURVEY SECTION 1: VIEWS ON CURRENT GUIDANCE

Q1.2: Which description most closely matches your view on the adequacy of the current UK wind turbine noise guidance in ensuring wind turbine noise is managed effectively and consistently in line with Government policies on noise and Net Zero?

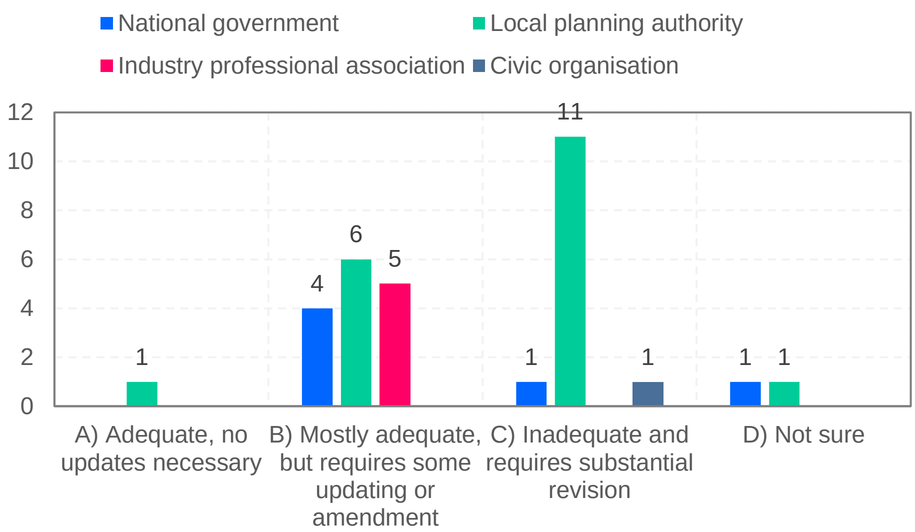


Figure 12-7: Stakeholder views on need for updates to current guidance (by respondent type)

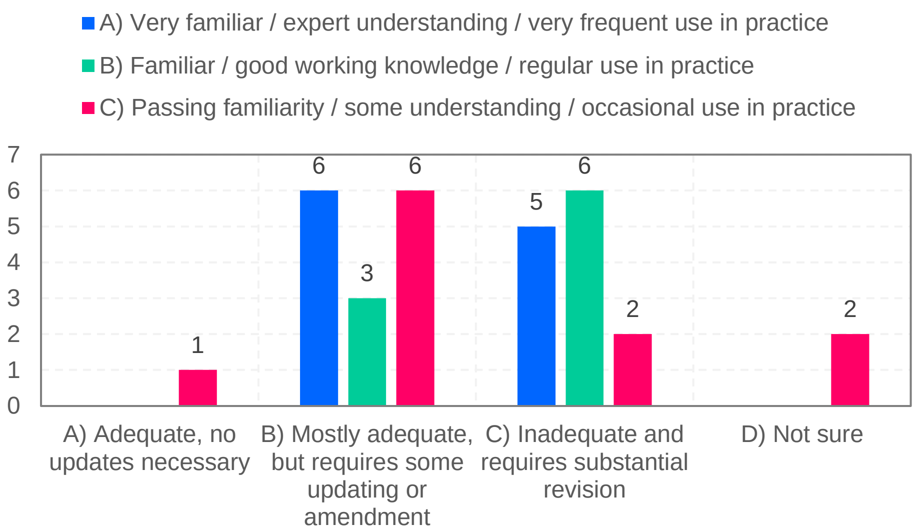


Figure 12-8: Stakeholder views on need for updates to current guidance (by familiarity with guidance)

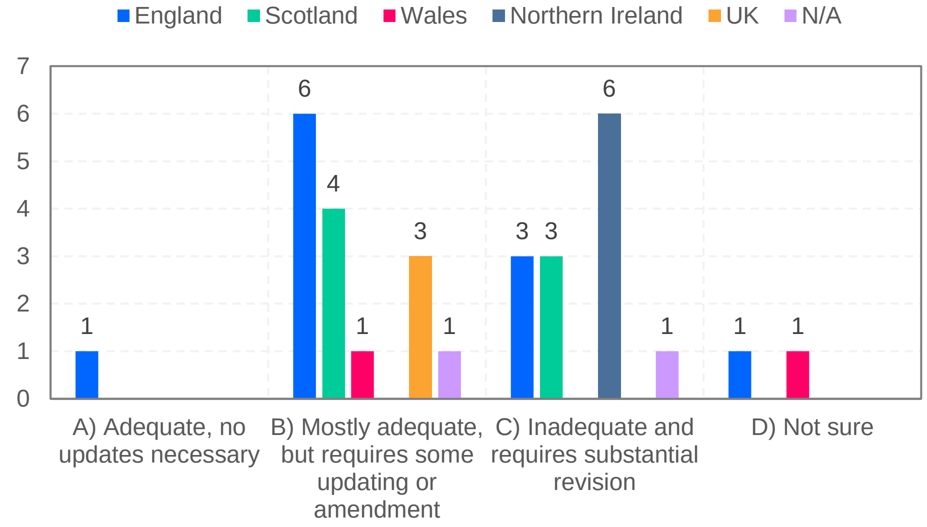


Figure 12-9: Stakeholder views on need for updates to current guidance (by devolved administration)

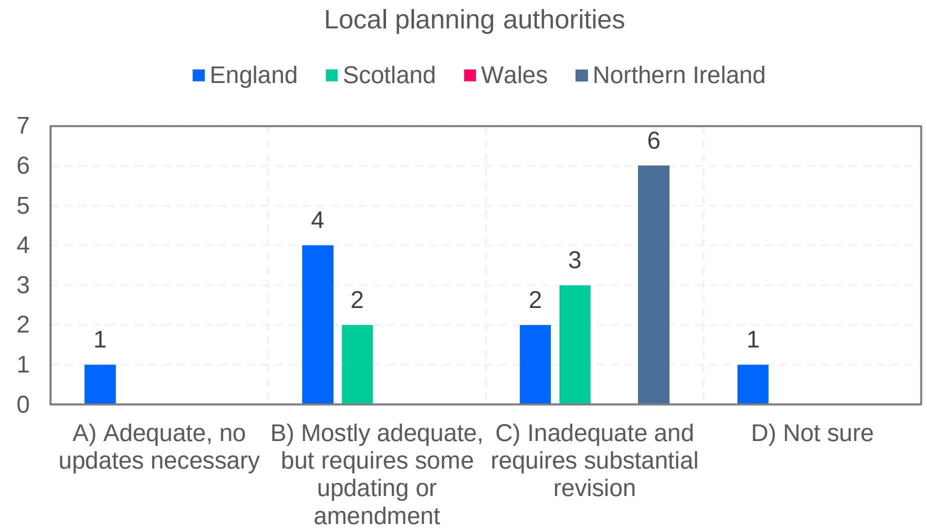


Figure 12-10: Stakeholder LPA views on need for updates to current guidance (by devolved administration)

Q1.3: Which (if any) of the following topics relevant to the current UK wind turbine noise assessment guidance do you consider need to be updated?

Figure 12-11: Stakeholder views on topics within guidance that require updating (by respondent type)

Figure 12-12: Stakeholder views on topics within guidance that require updating, separated by views on the need for updates to current guidance

Q1.4: Please could you briefly outline the updates you believe need to be made to the current UK wind turbine noise assessment guidance, and identify any publicly accessible evidence you are aware of that would support or inform the updates indicated?

Compliance determination and enforcement

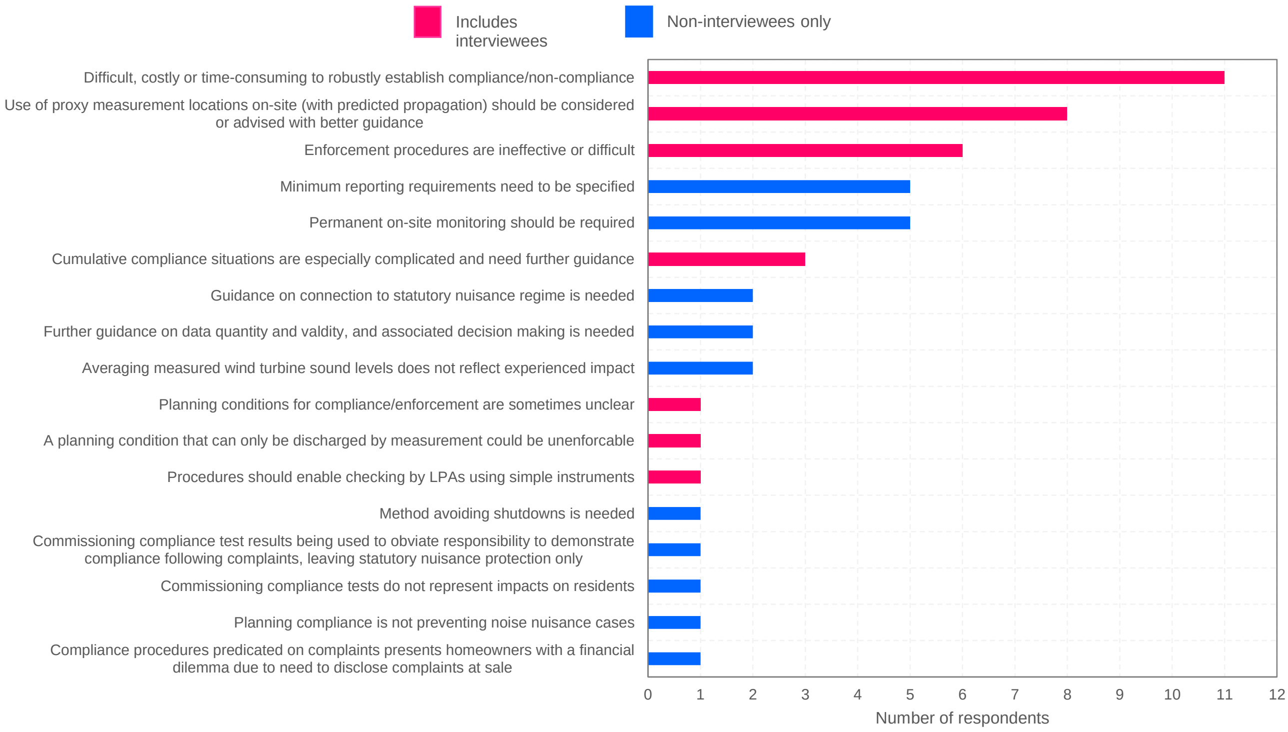


Figure 12-13: Thematic analysis of stakeholder responses concerning ‘compliance determination and enforcement’

Table 12-1: Key quotations from stakeholder responses concerning ‘compliance determination and enforcement’

Theme	Key quote
Difficult, costly or time-consuming to robustly establish compliance/non-compliance	*An abundance of poor-quality compliance reports carried out by acoustic consultants with limited expertise, understanding or interest in wind turbine noise means that demonstrating compliance with the existing noise limits is very often exceptionally time consuming and expensive (for the wind turbine operator and for the planning authority/environmental health officer). Very often there is no agreement that compliance has been robustly demonstrated and so we end up with a 'stalemate' situation and no solution. In any event, even on the rare occasions that compliance with the noise limits can be demonstrated, this relates to the sound level only, and the sound level that has been determined by significant averaging over time, rather than the real impact of the noise on windfarm neighbours, and so demonstrating compliance does not resolve the complaints meaning that the entire exercise is pretty pointless.*

Theme	Key quote
Use of proxy measurement locations on-site (with predicted propagation) should be considered or advised with better guidance	*It is considered by many members that there is considerable confidence in turbine noise predictions carried out in line with the IOA GPG and consideration should be given to evaluating compliance through a combination of prediction and 'at source' measurements on a sample number of turbines in line with IEC 61400-11 which could be a more robust method than the current way of determining noise levels to demonstrate compliance. Assessment of noise character/features should however still be undertaken at noise-sensitive receptors.*
Enforcement procedures are ineffective or difficult	*In the event that enforcement action is required, either through planning enforcement or statutory nuisance legislation, the resources available to wind turbine operators far exceed that available to publicly funded, resourced stretched local government and far exceed the value of any financial penalty (reasonably) available to the court. Therefore, enforcement is currently a very weak tool.* *Existing widely accepted planning conditions do not address the effect of the noise either and so planning enforcement is an ineffective tool.*
Permanent on-site monitoring should be required	[We] *have experience of significant difficulties in post-completion compliance monitoring due to variation in metrological conditions and the use of different operating modes. It is suggested that the use of on-site permanent monitors should be considered as a means of addressing compliance concerns. We do not believe this would represent a disproportionate cost in the vast majority of cases.*
Cumulative compliance situations are especially complicated and need further guidance	*This is a significant area of concern where there are several wind farms sited in the same locality. In the event of a complaint, the standard condition requires the operator to undertake compliance monitoring. As stated previously, this is undertaken by an "independent" consultant. However, where there are multiple wind farms and the problem could be due to cumulative noise, it could be extremely difficult, if not impossible, to adequately investigate the cause of such complaints.*

Baseline determination

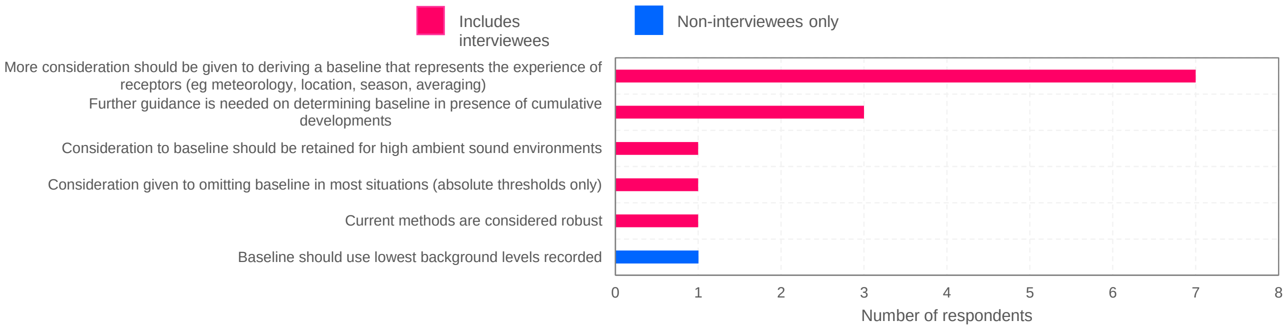


Figure 12-14: Thematic analysis of stakeholder responses concerning 'baseline determination'

Table 12-2: Key quotations from stakeholder responses concerning 'baseline determination'

Theme	Key quote
More consideration should be given to deriving a baseline that represents the experience of receptors (eg, meteorology, location, season, averaging)	[We] *believe that insufficient weight is given to the derivation of a baseline which should be representative of the sound climate experienced by receptors.*
More consideration should be given to deriving a baseline that represents the experience of receptors (eg, meteorology, location, season, averaging)	*Responses raised the potential for improvements which could be made to the extent to which background noise measurements at a single location for a necessarily limited period can be representative of the amenity areas of a property and, where relevant, surrounding properties, in a rural or remote area where wind turbines are typically located.*
Further guidance is needed on determining baseline in presence of cumulative developments	*The existing guidance makes it clear that background noise levels should be determined in the absence of the influence of existing turbines. Given the increasing number of operational turbines, and the tendency for new developments to be located next to existing wind farms, this is becoming increasingly complex. Four options are provided in the IOA GPG (in Section 5.2.3) but further guidance on the application of the existing guidance (and those four options) would be useful.*

Measurements of sound or meteorology

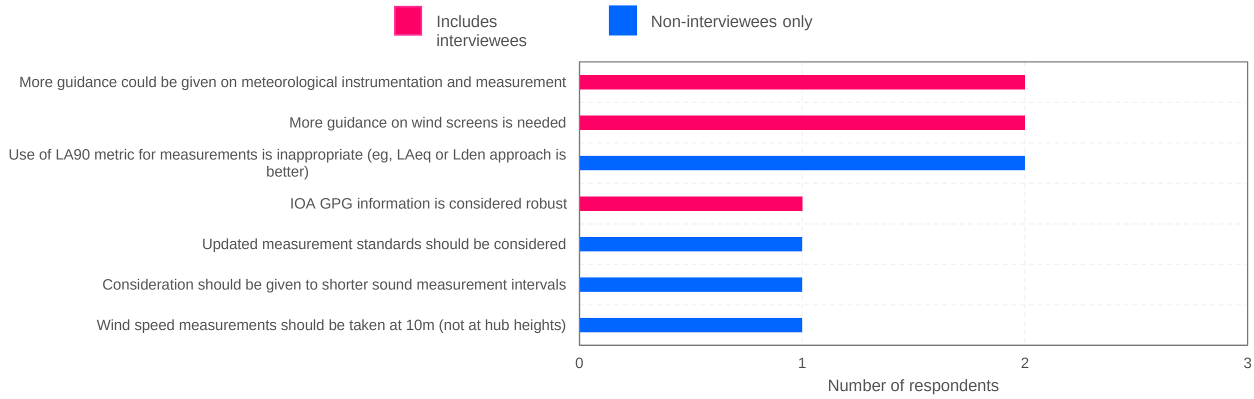


Figure 12-15: Thematic analysis of stakeholder responses concerning 'measurements of sound or meteorology'

Table 12-3: Key quotations from stakeholder responses concerning 'measurements of sound or meteorology'

Theme	Key quote
More guidance could be given on meteorological instrumentation and measurement	*Could more guidance be provided on the location of meteorological measurements? The acquisition of wind data section in the IOA GPG could be expanded.*
More guidance on wind screens is needed	*Additional technical information regarding the appropriate choice of wind screen may be useful as this is an area where there is some disagreement about the interpretation and application of the existing guidance.*
Use of L_{A90} metric for measurements is inappropriate (eg, L_{Aeq} or L_{den} approach is better)	*Use of the L90 metric is out of sync with that used in noise assessments in the UK and worldwide*

Consideration of atmospheric, meteorological or topographical influences on sound

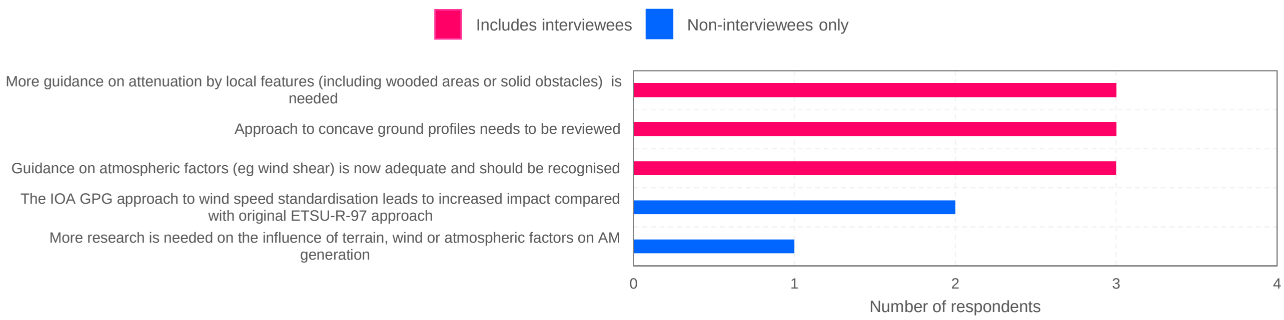


Figure 12-16: Thematic analysis of stakeholder responses concerning 'consideration of atmospheric, meteorological or topographical influences on sound'

Table 12-4: Key quotations from stakeholder responses concerning 'consideration of atmospheric, meteorological or topographical influences on sound'

Theme	Key quote
More guidance on attenuation by local features (including wooded areas or solid obstacles) is needed	*A review is required for the screening effect of topography and buildings. The IOA GPG does not allow for additional ground attenuation effects from forests, etc. It is suggested that some attenuation may be realised which is not being recognised to date, and more research in this area would be welcomed.*
Approach to concave ground profiles needs to be reviewed	*The "valley correction" requires more explanation and possibly reworking of the method as it provides false positives.*

Theme	Key quote
Guidance on atmospheric factors (eg, wind shear) is now adequate and should be recognised	*ETSU-R-97 was not wholly clear on the issue of suitable wind speed references and wind shear: this was discussed and clarified within the IOA GPG and so it would make sense to update the ETSU-R-97 guidance in line with this improved understanding.*

Table 12-5: Dissenting views from stakeholder responses concerning 'consideration of atmospheric, meteorological or topographical influences on sound'

Theme	Dissenting theme	Key quote
Guidance on atmospheric factors (eg, wind shear) is now adequate and should be recognised	*Guidance on wind shear standardisation leads to greater adverse impact*	*ETSU-R-97 and its later adjustment the IoA GPG (Good Practice Guide) uses hub height wind speeds to calculate the 10m wind speed at receptor sites. There can be significant discrepancies between actual measured 10m height wind speeds and GPG calculations of 10m hight wind speeds. Huntingdonshire District Council published details which showed the GPG result as simply a mirror image of the hub height wind speed data but just a few dB lower. whereas actual 10m measurements showed a much lower dB reading and further research locally for longer periods, identified variations of over 5dB between actual measured wind speed at 10m height and the GPG 10m height wind speeds derived from hub height readings. The GPG calculations favoured the wind farm operator. The development of larger bladed and taller turbines likely compounds the measured and derived 10m height wind speed discrepancies. As previously stated, wind speeds should be measured at 10m height.*

Sound predictions

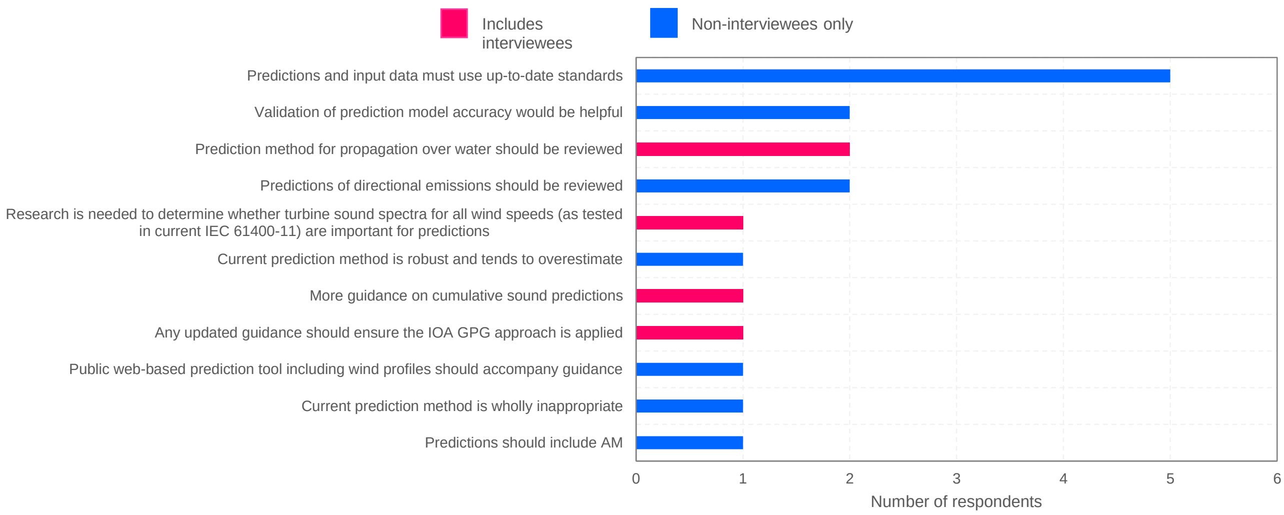


Figure 12-17: Thematic analysis of stakeholder responses concerning 'sound predictions'

Table 12-6: Key quotations from stakeholder responses concerning ‘sound predictions’

Theme	Key quote
Predictions and input data must use up-to-date standards	[We] *would have concerns about the large number of second-hand single turbines incentivised in the development of onshore wind in* [Northern Ireland]. *The noise data associated with such turbines does not comply with modern standards and we believe that any future predictions within noise assessments must use up-to-date standards.*
Validation of prediction model accuracy would be helpful	*Assessment of how accurate modelling is when actual wind farms are developed, this could assist in increasing the validity of modelling scenarios.*
Predictions of propagation over water should be reviewed	*IOA SGN 6 was originally intended to deal with noise propagation over water from wind turbines, whether on-shore or off-shore, but development was limited as Crown Estates were believed to be developing their own guidance on this topic. This guidance has to date not been issued, and so the question remains as to what guidance should be followed, and whether this should be captured in good practice guidance. This should be considered in any update. As such,* [we] *would suggest that SGN6 is removed, and a discussion of ground correction over water added to the main text of the IOA GPG.*
Predictions of directional emissions should be reviewed	*Further consideration of the approach used to model directivity (which in our experience is cautious) and the potential for predictions to overestimate levels at large set back distances may be beneficial.*
More guidance on cumulative sound predictions	*There has also been eight years of applications since the publication of the IOA GPG, so it should now be possible to provide more guidance on how to predict noise in cumulative situations.*

Uncertainty

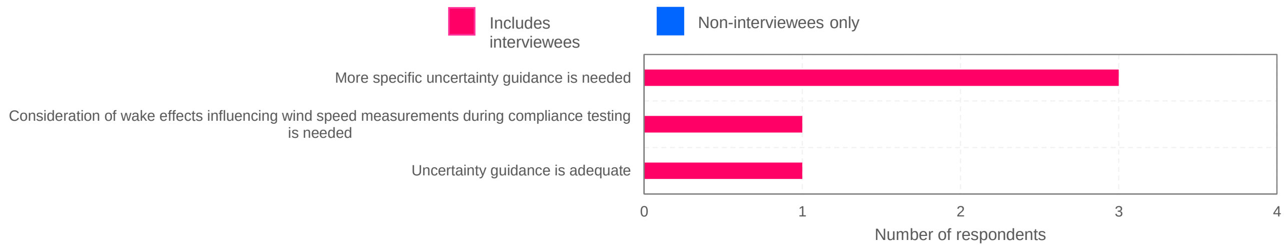


Figure 12-18: Thematic analysis of stakeholder responses concerning ‘uncertainty’

Table 12-7: Key quotations from stakeholder responses concerning 'uncertainty'

Theme	Key quote
More specific uncertainty guidance is needed	*When used in planning ETSU-R-97/GPG relies heavily on the production of noise impact assessment diagrams (NIA) at each designated receptor and time periods. Each NIA uses three quantities each averaged over ten minutes: an indexing measured mean wind speed, the measured background, and the ISO-9613 method predicted turbine noise. In processing, and in the use of the NIA in developing planning conditions on any subsequent development, all three quantities are treated as being exact, subject to no uncertainty. It is easy to show that this is not the case: all are subject to measurement error, random variation and even, in the case of the background noise, method induced uncertainty over the choice of statistical function fitted to the data. It is standard procedure to apply uncertainty to noise assessments; it is therefore bizarre that ETSU-R-97 does not most especially because there's plenty of uncertainty from manufacturer specifications, to wind shear calculations, to the efficacy of using ETSU-R-9 to protect public health and wellbeing. As such, uncertainty in favour of the public, should be a critical matter for consideration.*
More specific uncertainty guidance is needed	[Some members] *recognise that the approach is not consistent with that promoted in the latest version of BS4142, the standard on which ETSU-R-97 is loosely based (albeit an older version). Some members would welcome a more prescriptive approach to dealing with uncertainty, and guidance on how it should be undertaken.*

Table 12-8: Dissenting views from stakeholder responses concerning 'uncertainty'

Theme	Dissenting theme	Key quote
More specific uncertainty guidance is needed	*Guidance on uncertainty is adequate*	*The majority of members consider that the topic of uncertainty has been addressed satisfactorily in the IOA GPG*

Anything else not listed above

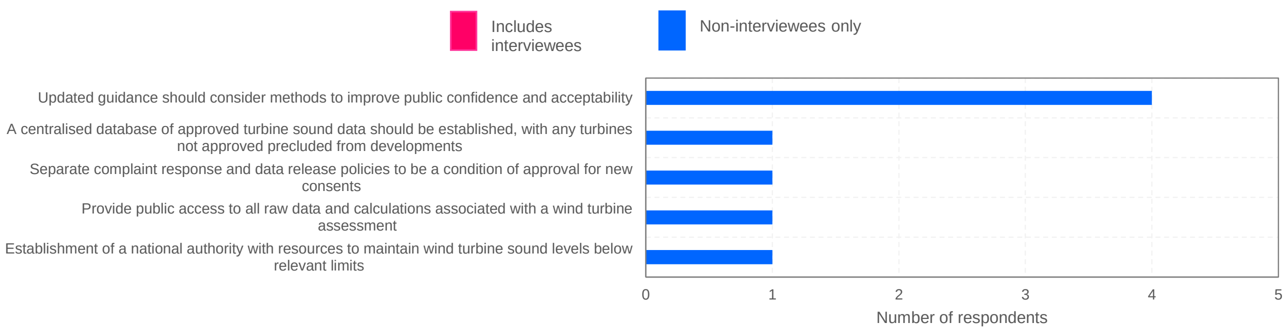


Figure 12-19: Thematic analysis of stakeholder responses concerning 'anything else not listed above'

Table 12-9: Key quotations from stakeholder responses concerning ‘anything else not listed above’

Theme	Key quote
Updated guidance should consider methods to improve public confidence and acceptability	[We have] *experience of significant adverse community response to proposed and existing turbines. We are not convinced that the means of assessment and the benefits of renewable energy development are adequately considered and communicated within the guidance itself nor within the engagement and consultation processes undertaken. We believe any such update should consider methods to improve public confidence and acceptability.*

Compiled topics

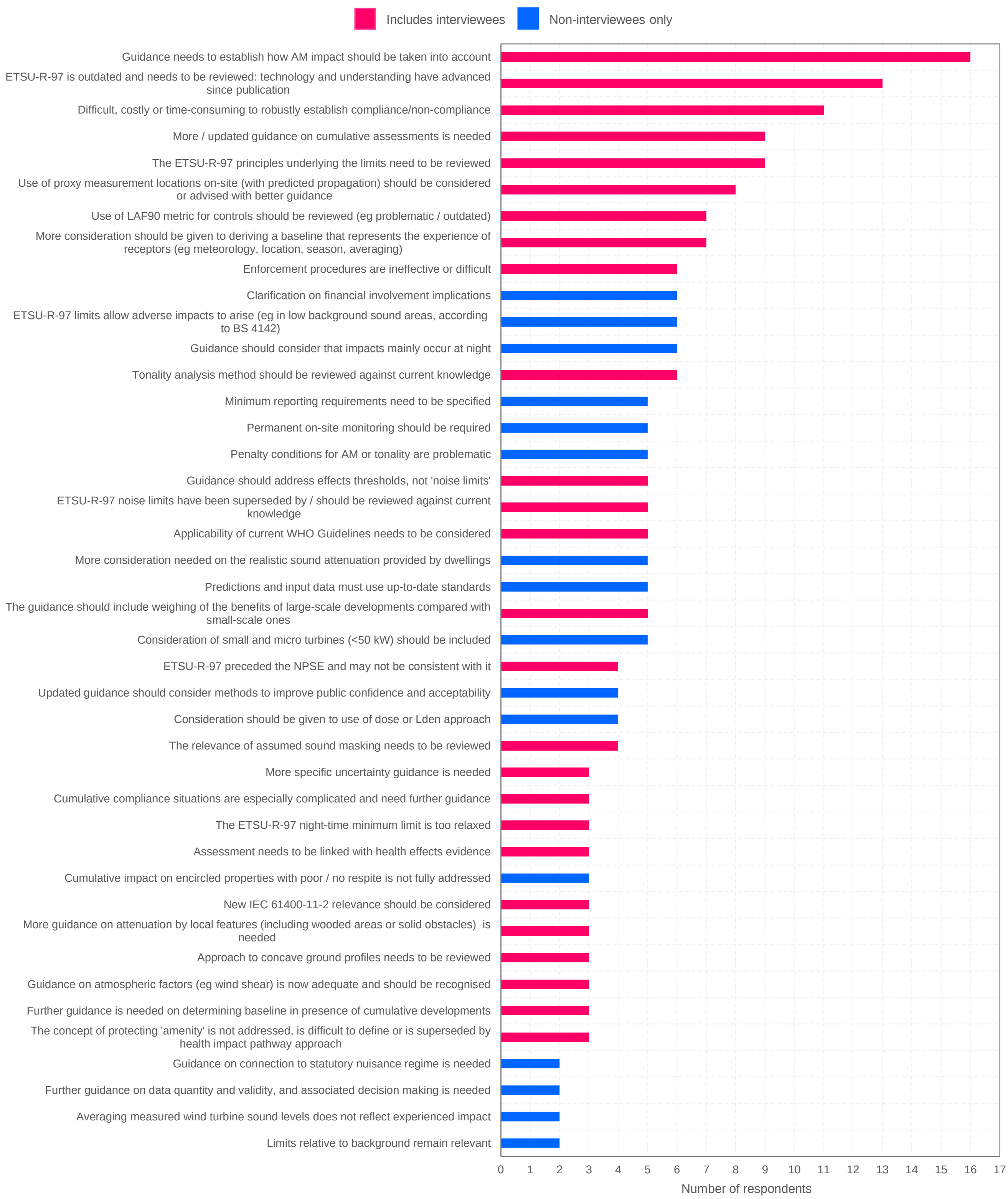


Figure 12-20: Thematic analysis of stakeholder responses for all topics compiled (part 1 of 3)

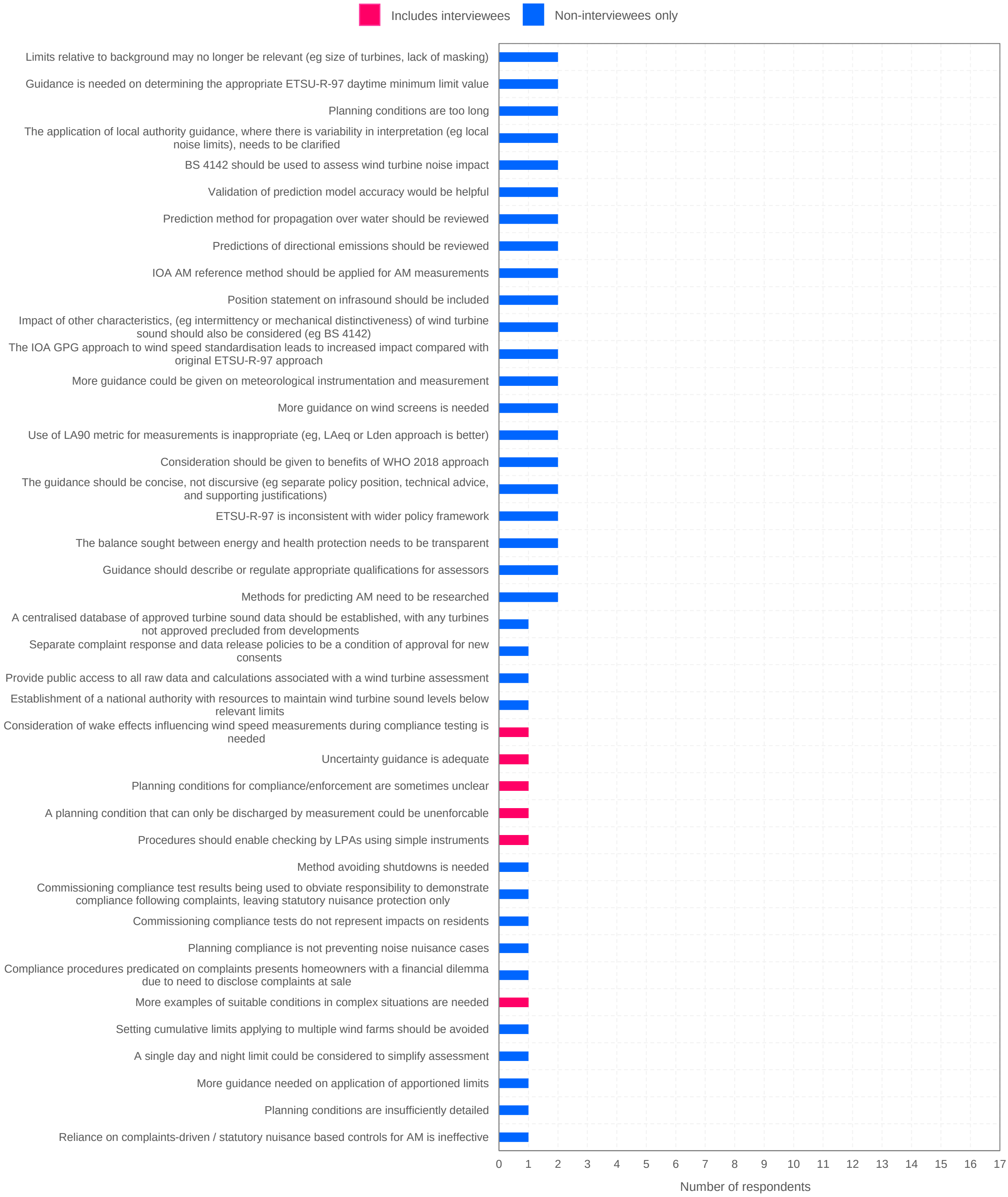


Figure 12-21: Thematic analysis of stakeholder responses for all topics compiled (part 2 of 3)

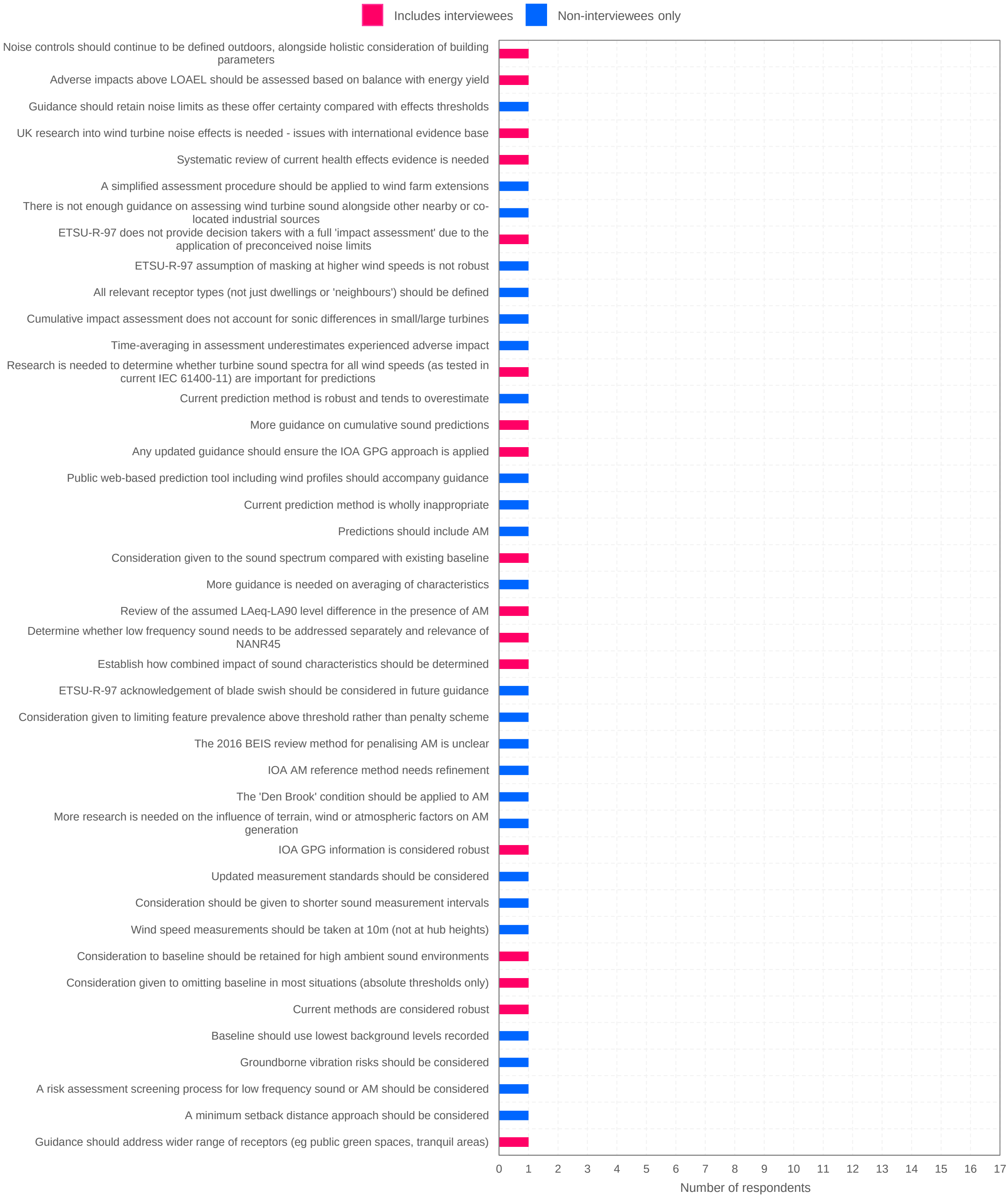


Figure 12-22: Thematic analysis of stakeholder responses for all topics compiled (part 3 of 3)

Table 12-10: Thematic analysis of stakeholder responses for all topics compiled

Theme	Count
Guidance needs to establish how AM impact should be taken into account	16
ETSU-R-97 is outdated and needs to be reviewed: technology and understanding have advanced since publication	13
Difficult, costly or time-consuming to robustly establish compliance/non-compliance	11
The ETSU-R-97 principles underlying the limits need to be reviewed	9
More / updated guidance on cumulative assessments is needed	9
Use of proxy measurement locations on-site (with predicted propagation) should be considered or advised with better guidance	8
More consideration should be given to deriving a baseline that represents the experience of receptors (eg, meteorology, location, season, averaging)	7
Use of LAF90 metric for controls should be reviewed (eg, problematic / outdated)	7
Tonality analysis method should be reviewed against current knowledge	6
Guidance should consider that impacts mainly occur at night	6
ETSU-R-97 limits allow adverse impacts to arise (eg, in low background sound areas, according to BS 4142)	6
Clarification on financial involvement implications	6
Enforcement procedures are ineffective or difficult	6
Consideration of small and micro turbines (<50 kW) should be included	5
The guidance should include weighing of the benefits of large-scale developments compared with small-scale ones	5
Predictions and input data must use up-to-date standards	5
More consideration needed on the realistic sound attenuation provided by dwellings	5
Applicability of current WHO Guidelines needs to be considered	5
ETSU-R-97 noise limits have been superseded by / should be reviewed against current knowledge	5
Guidance should address effects thresholds, not 'noise limits'	5
Penalty conditions for AM or tonality are problematic	5
Permanent on-site monitoring should be required	5
Minimum reporting requirements need to be specified	5

Theme	Count
The relevance of assumed sound masking needs to be reviewed	4
Consideration should be given to use of dose or Lden approach	4
Updated guidance should consider methods to improve public confidence and acceptability	4
The concept of protecting 'amenity' is not addressed, is difficult to define or is superseded by health impact pathway approach	3
Further guidance is needed on determining baseline in presence of cumulative developments	3
Guidance on atmospheric factors (eg, wind shear) is now adequate and should be recognised	3
Approach to concave ground profiles needs to be reviewed	3
More guidance on attenuation by local features (including wooded areas or solid obstacles) is needed	3
New IEC 61400-11-2 relevance should be considered	3
Cumulative impact on encircled properties with poor / no respite is not fully addressed	3
Assessment needs to be linked with health effects evidence	3
The ETSU-R-97 night-time minimum limit is too relaxed	3
Cumulative compliance situations are especially complicated and need further guidance	3
More specific uncertainty guidance is needed	3
Guidance should describe or regulate appropriate qualifications for assessors	2
The balance sought between energy and health protection needs to be transparent	2
ETSU-R-97 is inconsistent with wider policy framework	2
The guidance should be concise, not discursive (eg, separate policy position, technical advice, and supporting justifications)	2
Consideration should be given to benefits of WHO 2018 approach	2
Use of LA90 metric for measurements is inappropriate (eg, LAeq or Lden approach is better)	2
More guidance on wind screens is needed	2
More guidance could be given on meteorological instrumentation and measurement	2
The IOA GPG approach to wind speed standardisation leads to increased impact compared with original ETSU-R-97 approach	2

Theme	Count
Impact of other characteristics, (eg, intermittency or mechanical distinctiveness) of wind turbine sound should also be considered (eg, BS 4142)	2
Position statement on infrasound should be included	2
IOA AM reference method should be applied for AM measurements	2
Predictions of directional emissions should be reviewed	2
Prediction method for propagation over water should be reviewed	2
Validation of prediction model accuracy would be helpful	2
BS 4142 should be used to assess wind turbine noise impact	2
The application of local authority guidance, where there is variability in interpretation (eg, local noise limits), needs to be clarified	2
Planning conditions are too long	2
Guidance is needed on determining the appropriate ETSU-R-97 daytime minimum limit value	2
Limits relative to background may no longer be relevant (eg, size of turbines, lack of masking)	2
Limits relative to background remain relevant	2
Averaging measured wind turbine sound levels does not reflect experienced impact	2
Further guidance on data quantity and validity, and associated decision making is needed	2
Guidance on connection to statutory nuisance regime is needed	2
Methods for predicting AM need to be researched	2
Guidance should address wider range of receptors (eg, public green spaces, tranquil areas)	1
A minimum setback distance approach should be considered	1
A risk assessment screening process for low frequency sound or AM should be considered	1
Groundborne vibration risks should be considered	1
Baseline should use lowest background levels recorded	1
Current methods are considered robust	1
Consideration given to omitting baseline in most situations (absolute thresholds only)	1
Consideration to baseline should be retained for high ambient sound environments	1
Wind speed measurements should be taken at 10m (not at hub heights)	1

Theme	Count
Consideration should be given to shorter sound measurement intervals	1
Updated measurement standards should be considered	1
IOA GPG information is considered robust	1
More research is needed on the influence of terrain, wind or atmospheric factors on AM generation	1
The 'Den Brook' condition should be applied to AM	1
IOA AM reference method needs refinement	1
Establish how combined impact of sound characteristics should be determined	1
The 2016 BEIS review method for penalising AM is unclear	1
Consideration given to limiting feature prevalence above threshold rather than penalty scheme	1
ETSU-R-97 acknowledgement of blade swish should be considered in future guidance	1
Determine whether low frequency sound needs to be addressed separately and relevance of NANR 45	1
Review of the assumed LAeq-LA90 level difference in the presence of AM	1
More guidance is needed on averaging of characteristics	1
Consideration given to the sound spectrum compared with existing baseline	1
Predictions should include AM	1
Current prediction method is wholly inappropriate	1
Public web-based prediction tool including wind profiles should accompany guidance	1
Any updated guidance should ensure the IOA GPG approach is applied	1
More guidance on cumulative sound predictions	1
Current prediction method is robust and tends to overestimate	1
Research is needed to determine whether turbine sound spectra for all wind speeds (as tested in current IEC 61400-11) are important for predictions	1
Time-averaging in assessment underestimates experienced adverse impact	1
Cumulative impact assessment does not account for sonic differences in small/large turbines	1
All relevant receptor types (not just dwellings or 'neighbours') should be defined	1

Theme	Count
ETSU-R-97 assumption of masking at higher wind speeds is not robust	1
ETSU-R-97 does not provide decision takers with a full 'impact assessment' due to the application of preconceived noise limits	1
There is not enough guidance on assessing wind turbine sound alongside other nearby or co-located industrial sources	1
A simplified assessment procedure should be applied to wind farm extensions	1
Systematic review of current health effects evidence is needed	1
UK research into wind turbine noise effects is needed - issues with international evidence base	1
Guidance should retain noise limits as these offer certainty compared with effects thresholds	1
Adverse impacts above LOAEL should be assessed based on balance with energy yield	1
Noise controls should continue to be defined outdoors, alongside holistic consideration of building parameters	1
Reliance on complaints-driven / statutory nuisance-based controls for AM is ineffective	1
Planning conditions are insufficiently detailed	1
More guidance needed on application of apportioned limits	1
A single day and night limit could be considered to simplify assessment	1
Setting cumulative limits applying to multiple wind farms should be avoided	1
More examples of suitable conditions in complex situations are needed	1
Compliance procedures predicated on complaints presents homeowners with a financial dilemma due to need to disclose complaints at sale	1
Planning compliance is not preventing noise nuisance cases	1
Commissioning compliance tests do not represent impacts on residents	1
Commissioning compliance test results being used to obviate responsibility to demonstrate compliance following complaints, leaving statutory nuisance protection only	1
Method avoiding shutdowns is needed	1
Procedures should enable checking by LPAs using simple instruments	1
A planning condition that can only be discharged by measurement could be unenforceable	1
Planning conditions for compliance/enforcement are sometimes unclear	1

Theme	Count
Uncertainty guidance is adequate	1
Consideration of wake effects influencing wind speed measurements during compliance testing is needed	1
Establishment of a national authority with resources to maintain wind turbine sound levels below relevant limits	1
Provide public access to all raw data and calculations associated with a wind turbine assessment	1
Separate complaint response and data release policies to be a condition of approval for new consents	1
A centralised database of approved turbine sound data should be established, with any turbines not approved precluded from developments	1

Kings Orchard
1 Queen Street
Bristol
BS2 0HQ

wsp.com