Safety and Health on Construction Projects
The Role of Clients

A summary of the client's role under the Safety, Health and Welfare at Work (Construction) Regulations, 2006

Who is a 'Client'?

The Safety, Health and Welfare at Work (Construction) Regulations, 2006 interprets 'client' as a person for whom a project is carried out, in the course or furtherance of a trade, business or undertaking, or who undertakes a project directly in the course or furtherance of such trade, business or undertaking;
You are not a client if you are having construction work done on your own domestic dwelling e.g. an extension on to your kitchen, or you are building your own house.
You are a client if the extension onto your own domestic dwelling is in the course or furtherance of a trade, business or undertaking, or who undertakes a project directly in the course or furtherance of such trade, business or undertaking, e.g. if you are building on an office.

What are the duties of a Client?

The Client must for every project:

- appoint, in writing before design work starts, a competent and adequately resourced project supervisor for the design process (PSDP).
  In order to be competent the PSDP must have adequate training, knowledge, experience to carry out the project the PSDP must have adequate resources available to carry out the project in a safe manner;
- appoint, in writing before construction begins, a competent and adequately resourced project supervisor for the construction stage (PSCS). In order to be competent the PSCS must have adequate training, knowledge, experience and resources;
- be satisfied that each designer and contractor appointed has adequate training, knowledge, experience and resources for the work to be performed;
- co-operate with the project supervisor and supply necessary information;
- keep and make available the safety file for the completed structure. The safety file contains information on the completed structure that will be required for future maintenance or renovation (The client must keep the file in a secure place, either on the premises to which it relates or held centrally, and if the client wishes, it may be stored electronically or on microfiche.);
- provide a copy of the safety and health plan prepared by the PSDP to every person tendering for the project. The safety plan documents show how health and safety on the project will be managed to project completion.
- notify the Authority of the appointment of the PSDP where construction is likely to take more than 500 persons days or 30 working days.

S. 37

File With ______________

SECTION 131 FORM

Appeal NO:_PL 04.248152 & 04.248153 — Defer Re O/H ☐

TO:SEO

Having considered the contents of the submission ~~dated~~/ received 2/8/17

from Noonan Linehan Carroll Coffey I recommend that section 131 of the Planning and Development Act, 2000 (be)/~~not be~~ be invoked at this stage for the following reason(s): In the interests of justice as per Board Direction

E.O.: [signature] Date: 18/10/17

To EO: ______________

Section 131 not to be invoked at this stage. ☐

Section 131 to be invoked – allow 2/4 weeks for reply. ☐

S.E.O.: ______________ Date: ______________

S.A.O: ______________ Date: ______________

MS. Collins

Please prepare BP 70 - Section 131 notice enclosing a copy of the attached submission

to: Applicant & PA

Allow 2/3/(4)weeks – BP 70 4 wks.

EO: [signature] Date: 18/10/17

AA: R. C[signature] Date: 20.10.17

S. 37

File With ______________

CORRESPONDENCE FORM

Appeal No: PL 04.248152 & PL04.248153

Ms. Collins

Please treat correspondence received on 2/8/17 as follows:

1. Update database with new agent for Applicant/Appellant ______	
2. Acknowledge with BP 23	1. RETURN TO SENDER with BP ______
3. Keep copy of Board's Letter ☐	2. Keep Envelope: ☐
	3. Keep Copy of Board's letter ☐

Amendments/Comments Response to S.131

Please put a copy on both files and a copy of Acknowledgment

4. Attach to file	**RETURN TO EO** ☐
(a) R/S ☐ (d) Screening ☐	
(b) GIS Processing ☐ (e) Inspectorate ☐	
(c) Processing ☐ In Section ✓	

	Plans Date Stamped ☐ Date Stamped Filled in ☐
EO: [signature]	AA: [signature]
Date: 3/8/17	Date: 4-8-17

Noonan Linehan Carroll Coffey
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DX 2044 Cork

Addressee

The Secretary
An Bord Pleanála,
Marlborough Street,
Dublin 1

~ By Courier DX ~

AN BORD PLEANÁLA
TIME 11·04 BY Courier
02 AUG 2017
LTR DATED ____ FROM Sm
PL ____

1st August 2017
Our ref: 22007-16/JN/PW
Your refs: PL04.248152 (244439) & PL04.248153 (245824)
PA Reg. Ref. 14/557 & 14/6760

RE: Construction of a substation to replace substation previously granted under PL04.219620 and all ancillary site development works.
Barnadivane, Kneeves, Terelton, County Cork

&

6 no. wind turbines
Lackareagh and Garranereagh
Lissarda and Barnadivane, Terelton, County Cork

Dear Sir/Madam,

We refer to recent correspondence from the Board on these two appeals.

In addition to our clients' Submission enclosed herewith which refers, we wish to make the following additional observations on their behalf.

1. **Judicial Review**
   Our clients continue to rely on those grounds advanced in the Judicial Review proceedings High Court Record Number 2016/614JR which were not dealt with when the said proceedings were compromised by agreement.

2. **New Substation**
   The Applicant Company and their multiple associated companies appear to have made new plans with regard to the Substation intended to serve their various proposed windfarms along the south of the River Lee Valley.

In July they filed an application for Planning Permission with Cork County Council for a Substation next to their proposed Carrigarierk Wind Farm, Cork County Council Planning Reference 17/431.

We have a certain sympathy for the Board in attempting to pin down exactly what constitutes "the project" for the purposes of discharging its obligations under EIA and AA.

The latest application raises at least the possibility if not the probability that the Substation at Barnadivane may never in fact be constructed and that the Substation in Carrigarierk is in reality intended to serve the proposed Barnadivane Wind Farm if it secures approval.

This is obviously a fundamental issue in terms of the Board's responsibilities and we request the Board to address it specifically in its adjudication on the applications currently before it. Essentially the Board needs to be able to identify and describe on the record just what "the project" is. This is a matter about which the public and our clients are entitled to know with precision from the Board.

3. **Property Values**
It is the case that our clients' properties will be devalued should the proposed wind farm and/or substation ever be constructed.

We enclose herewith FCN Working Paper No. 3/2012 - The Impact of Wind Farms on Property Values: A Geographically Weighted Hedonic Pricing Model by Yasin Sunak and Reinhard Madlener, May 2012, revised March 2013, which is a detailed study evidencing the effect of wind turbines on nearby properties.

We submit that this is a matter for the Board to assess both in discharging its responsibilities under the Planning Code and under EIA. Mere assertions by the Applicant that there will be no effect have not been substantiated and we submit have to be disregarded as such and as contrary to available evidence both locally and internationally. If the Board remains in any doubt as to this important issue, we submit that it is required to solicit competent expert valuation advice before coming to a conclusion.

4. **Noise**
Our clients address this issue in their enclosed Submission. In its Ardglass planning refusal (PL04 .246824), the Board refused permission on the basis that the local noise environment would be significantly changed. In that case the predicted increase in ambient noise levels ranged from six to eleven times the present ambient levels. At least that level of increase would be seen at our clients' properties and in their environs.

We therefore request the Board to approach this manner with consistency and to give clear rationale for its conclusion on the noise issue.

Amplitude Modulation has been internally recognised as an adverse impact of noise from turbines of this scale. Mere assertion by the Applicant that this is not a frequent occurrence cannot be sustained and fly in the face of international scientific evidence. The case for assessing the impact of Amplitude Modulation is now unanswerable.

We enclose the following reports which document the extent and impact of Amplitude Modulation at industrial turbines.

a) Audible amplitude modulation - results of field measurements and investigations compared to psychoacoustical assessment and theoretical research, Mike Stigwood, Sarah Large and Duncan Stigwood, August 2013.
b) Initial findings of the UK Cotton Farm Wind Farm long term community noise monitoring project, Mike Stigwood; Duncan Stigwood; Sarah Large, November 2014.
c) The noise characteristics of 'compliant' wind farms that adversely affect its neighbours, Sarah Large; Mike Stigwood, November 2014.

This research by Stigwood and others represents the current state of scientific knowledge on the topic.

You will be aware that the matter is not conditioned at all by the type of condition normally imposed by the Board. Numerous communities around Ireland are already suffering as a result of this lacuna. We therefore require the Board to address it specifically in its conclusion on the noise issue in these cases. In particular, we submit that it must record its assessment of the impact of AM on nearby homes and farms and it must incorporate the result of that assessment into its decision.

Yours faithfully,

Joe Noonan,
NOONAN LINEHAN CARROLL COFFEY

Response to request for further comment on Barnadivane windfarm and substation proposed developments Co Cork by Stephanie Larkin and Michael O'Donovan whose home will be 609m from the nearest wind turbine.

NOISE RELATED CONCERNS

NOISE SENSITIVE RECEPTOR LOCATIONS

We would like to draw the Boards attention to an extract from a recent An Bord Pleanala inspectors report, ref PA0046, relating to noise measuring locations at a wind farm and we quote "the overriding consideration is that the assessor should be able to reasonably justify that there are no other suitable noise sensitive locations in the vicinity of the proposed development and close to a dwelling where background noise levels would be expected to be consistently lower than the levels at the selected position".

The overriding reason given for the noise measuring locations by the applicant in this case is security of the equipment at that site. Consequently the applicants have scoped out the majority, if not all number of non stakeholder dwellings in the vicinity of the windfarm. The remaining location options are therefore heavily biased and not truly representative of the complex array of background noise levels associated with this proposed development.

Noise monitoring location H48 is of grave concern to us as it is not either "typical" or "indicative" as stated in the Guidelines. This is because at this location there is a large farmyard, an automotive repair and bodywork garage and 3 occupied dwellings. There are 2 more dwellings, a pigfarm and farmyard within 150m. There is no other location in the vicinity of the proposed development with such a combination of agricultural, industrial and domestic noise generation. The true nature of this "Cluster of Dwellings" is not mentioned anywhere and has consequentially gone over the heads of those at AWN Consultants in there peer review of the data.

Noise monitoring location H40. Throughout this whole process the choice of the H40 site has been questioned by many different people, including the planning authority, and it is in our opinion a bizarre choice of location to monitor noise because of its distance from turbines T4, T5 & T6 and because of the high altitude. The concerns arise as the applicants have chosen this location as the baseline for background noise value. Turbines T4, T5 & T6 are located in a concave valley topography that is below this location. Therefore at H40 it is not possible in our opinion to measure background noise that can be said to be "typical" and a baseline for background noise for this windfarm application as a whole. It may have validity with regard to T1, T2 and T3.

We believe that the topography at this proposed windfarm site is critical in determining the background noise values but this has been completely ignored by the applicant. Turbines T1, T2 & T3 are located on a hilly plateau but T4, T5 & T6 are located in a concave valley. It is therefore imperative that reliable and "typical" noise sensitive receptors should be identified within the valley and as we have already stated, H48 is grossly untypical and unsuitable.

We do not concur with AWN Consultants who determined the noise sensitive receptor locations to be "typical" for this proposed development. It appears to us that AWN's peer review was done from a desktop and included no actual survey/ fieldwork. Therefore we believe AWN Consultants are not competent to determine the suitability of noise sensitive receptor locations in this case as they are not in possession of sufficient data to be able to make a reliable and safe conclusion. AWN Consultants have provided no coherent rationale as to how they arrived at their decision. If they have not carried out fieldwork to investigate the local topographies and any local commercial activities with regard to the true nature of chosen sites, then they are not in possession of sufficient facts to make a reasoned determination as to why they decided that further background noise monitoring was not necessary as was requested by the RFI from Cork County Council. We consider the outright refusal to carry out further noise surveys and the lack of a detailed account from Cork County Council and ABP as to why this was acceptable, to be a game changer with regard to the completeness and validity of the EIS associated with this application and to be strong grounds for judicial review.

Critical Wind Speeds and Turbine Choice

Recent research in Ireland and further afield has found serious flaws in how background noise is being assessed through established "Best Practice" and "Governmental Guidelines". This, coupled with the recent press release by Minister Coveney, of new stricter noise guidelines for wind turbines, is an admittance that the current guidelines are unreliable, not robust and unfit for purpose.

Below I have reproduced the final conclusions of a research paper from 2012 which was conducted in the south west of Ireland called "Assessing noise from wind farm developments in Ireland: A consideration of critical wind speeds and turbine choice"

E.A. King, F. Pilla, J. Mahon

- The critical wind speed is dependent on both the turbine choice and the background noise environment. It is a non-transferable value and must be re-calculated if different turbines are used for a development or if turbines are used in different background noise environments.
- The critical wind speed may change throughout the night-time period. Of the 40 turbine/location combinations examined, 25% of tests yielded a different critical wind speed throughout the night-time period.

Thus it may be concluded that noise assessments should not be restricted to the sole use of the critical wind speed but rather consider a range of critical wind speeds, particularly in the case of a night-time noise assessment. Such a consideration may also allow a separate wind shear be calculated throughout the night time period. It is also apparent that further detailed guidance on the assessment of noise from wind turbines in Ireland is required.

Current guidance is limited and is likely to suffer from different interpretations, in a similar manner to the UK's experience.
edepositireland.ie/.../Assessing%20noise%20from%20wind%20farm%20development...

This independent research paper demonstrates admirably the complexities and pitfalls when attempting to measure background noise and predicting turbine noise even when following "Best Practice". It calls into question the absolute determinations of noise predictions by Fehily Timoney.

In 2012 a research paper was published by the Mechanical Engineering Department of Adelaide University entitled

"Wind farm noise -what is a reasonable limit in rural areas?" Kristy Hansen, Nicholas Henrys, Colin Hansen, Con Doolan and Danielle Moreau School of Mechanical Engineering, Adelaide University, Australia.

ABSTRACT Wind farms are a rapidly growing source of renewable energy, but can be a source of persistent noise complaints, despite compliance with the relevant wind farm noise regulation being achieved. This paper presents a review of wind farm noise assessment criteria and methodology with a focus on the South Australian guidelines. The results of this review indicate that the noise limits may not be appropriate for some locations which are characterised by very low background sound levels at night time. The assumption in the guidelines that background noise is capable of reducing annoyance from wind farm noise is also not necessarily borne out in reality. Measurements of the outdoor-to-indoor noise reduction for a typical dwelling, with the window open, show that the reduction is slightly lower than assumed by the guidelines, and varies significantly with frequency. Measured low frequency noise and infrasound complied with all criteria addressed in the literature with the exception of one. Reliable compliance measurements are often difficult to achieve for wind farm noise, therefore it seems appropriate to adopt a conservative approach in setting noise limits and predicting noise emissions.
https://www.acoustics.asn.au/conference_proceedings/AAS2012/papers/p42.pdf

This paper also casts a serious shadow over Government Guidelines for wind farms and deals especially with the alleged masking effects of Background Noise and also Tonality and Amplitude Modulation. They also look at the unreliability of Manufacturers noise level data and the lack of research of the effects of Topography on noise predictions.

Recent court cases and multiple Local Council investigations into excessive turbine noise being generated at windfarms has added to the doubt about the robustness of the current guidelines and the ability of developers to accurately predict turbine noise.

We strongly urge The Board to set aside this application until new noise guidelines are in place and local authorities are equipped to accurately monitor wind farm turbine noise emissions.

RECREATIONAL ACTIVITY

There is signposted walk, which also runs along part of a recognised scenic route along the south western boundary of the proposed development and another walk which bisects the site on the road which goes between T3 & T4 to the east.

There are 2 local walking groups using these walks on a weekly basis. There are also many locals and more informal walking groups using this amenity. Therefore we ask why a noise sensitive location wasn't chosen to represent "areas of special recreational amenity importance" as is stated in the Guidelines.

VISUAL IMPACT AND RESIDENTIAL AMENITY

If this wind farm is granted permission a number of houses in this area will find themselves between 2 windfarms, the proposed wind farm and the permitted one nearby at Garranareigh, with turbines on more than one side of their house. This would amount to a serious reduction in the residential amenity of their property as they would effectively be living within a windfarm and have no relief from turbine noise etc. as they will be exposed to several all wind directions including the prevailing winds.

The visual impact of 2 wind farms in close proximity with turbines of differing heights, 105m at the existing site and 131m at the proposed will create an inharmonious and extremely visible industrial feature on the landscape. This is in contravention of the Guidelines. It is stated by the applicant that the existing windfarm is just over 800m from the nearest turbine in the proposed development which will effectively create a single windfarm. The Board should consider if it would grant permission for the existing and proposed windfarm with differing turbine heights if they were a single project.

The Board should not grant permission for this development of increased turbine height and should allow the applicant to fall back on their 'do nothing scenario' which is to build the permitted 14 x 105m turbines which were chosen to blend in with the Garranareigh wind farm as per the Guidelines. The fact that the permission for the 14 turbine windfarm has lapsed is a result of the greed of the applicant and is not the fault of the ordinary local residents.

The Guidelines state 'turbine height is critical in landscapes of relatively small scale, or comprising features and structures such as houses and must be carefully considered so as to achieve visual balance and not to visually dominate'.

A further quote from the Guidelines says ' wind energy developments within relatively close proximity to one another, while in different landscape character contexts, may be so close as to be within the same visual unit and, therefore, should involve the same siting and design approach'.

And another quote from the Guidelines says 'the creation of a 'visual stacking' effect from a sensitive view point should be avoided'.

The large altitudinal differences between the Barnadivane proposed turbines which are all located very close together and the Garranareigh windfarm nearby which is located on a plateau creates an extremely unbalanced design unit.

SHADOWFLICKER

We note in the PA0046 An Bord Pleanala inspectors report, which recommended refusal, that the inspector recommends that the effect of shadow flicker on 2 story houses, not just houses with windows at 2m high, should be modelled. We note Fehily Timoney failed to do this and request that they do so now so that the effect of shadow flicker is not underestimated. Virtually all houses in the area are 2 story, one story houses are the exception. The Board should also note that the recent press release re Guideline revisions includes strengthened and more stringent shadow flicker parameters.

We would also like to see the correlation of relevant meteorological data with the predicted shadow flicker results as I have been unable to find this information in the details provided by the applicant. As it stands we are not satisfied with the robustness of the shadow flicker results.

PROPERTY VALUATIONS

We believe that the Board should ask Fehily Timoney why they have been so dismissive of the Keane Mahony Smith auctioneers assessment of valuation of properties in the vicinity of windfarms in Cork. Fehily Timoney go on to state that the Keane Mahony Smith contribution has not been peer reviewed or published. Our retort to this is that nothing produced by Fehily Timoney in relation to this application has been either peer reviewed or published, the corollary of this is that we and the Board should dismiss and treat with a high degree of flippancy everything produced by Fehily Timoney. However, as Fehily Timoney and Keane Mahony Smith are both professional and registered companies we suggest that their findings should be treated with due respect.

In further defence of KMS's expertise and their evaluations, they are based on their professional knowledge of the Cork and Irish property market. Please note that the property valuation studies quoted by Fehily Timoney relate to UK and US market. It is a very well known fact that settlement patterns in Ireland are dispersed (one off housing) while in the UK they are very much village and town based. This makes the comparison with the UK market even more irrelevant. In fact this dispersed settlement pattern in Ireland is proving to be the greatest challenge to wind farm developers, and accounts for the shockingly low set back distance of 500m currently in operation. Futhermore, Fehily Timoney admit that further research is needed into homes located closest to wind facilities for which the least amount of data is available. In our opinion, this statement makes a mockery of their conclusions as all the houses concerned with this application are located on the wind farm boundary.

Fehily Timoney's assertion that living beside one or 2 wind farms (in this case one to the east and one to the west) is of no consequence to the value of H71, we must therefore conclude from this that there are absolutely no negative implications arising from living between one or 2 wind farms. We do not agree with this assessment and it would appear neither does KMS.

We can further add that property valuations are routinely done by auctioneers for financial institutions re: mortgage applications etc. These institutions take no issue with the validity of same.

EXTENT OF LOCAL OPPOSITION

For the record there were 259 submissions against this development submitted to Cork County Council. Later in the planning process there were in the region of a further 100 observations. The Board knows better than anyone that this number of submissions is very significant in a national context, for any type of industrial development. We can truthfully testify that almost everyone to a man, woman and child in the vicinity of this proposed development who is not a stakeholder is firmly opposed to it. We do not feel that this citizens representation has been given due consideration and weight at any point of the process by either Cork County Council or the Board.

In all aspects of the EIS and RFI's including the recently circulated information regarding property valuations, Fehily Timoney have given no regard to the level of opposition to this proposal. To make it clear to Fehily Timoney and the Board, 259 people are opposed to this proposed development. It was imperative for Fehily Timoney to actually read the submissions to evaluate how many of those are concerned about property values and to provide a coherent and reasoned argument directly targeted at concerned residents who live on the boundaries of this proposed wind farm so as to allay their fears and for the Board not to adhere to the trite, crass and oversimplification of the property valuation dilemma now facing the residents as purported by Fehily Timoney.

We want to make it clear to the Board that we believe they cannot base their decisions purely upon 2020 targets and perceived Government renewable energy objectives while at the same time totally ignoring a large block of citizens' genuine concerns which they have intimated through their lawful engagement with the planning process over a number of years.

PROJECT SPLITTING

It is our opinion that the strategy of the developer concerned here is that he is leveraging one planning permission against another to incrementally and significantly alter the fundamental nature of the original planning application. This has led to multiple versions of the Barnadivane Wind Farm Project now running into double figures when the permutations with regard to Shehymore and Carrigareirk wind farms, the newly proposed Carrigarierk substation (planning ref. 17/431) and the multiple grid connections between Shehymore, Carrigareirk, Barna and Dunmanway are taken into account. We have no idea what the final project will look like nor do we believe does the developer or the Board. To emphasise this point most recently the developer has stated in the application for a new 110kv substation at Carrigareirk (planning ref. 17/431), that the permitted grid connections between Shehymore or Carrigareirk to Barnadivane could be reversed to facilitate Barnadivane wind farm connecting to the grid at Dunmanway. This final permutation has been made possible because the applicant managed to split the Barnadivane wind farm project into a wind farm application and a substation application. It is obvious that there is functional interdependence between the wind farm and the substation. We believe that Cork County Council and the Board have facilitated project splitting in this instance through not rejecting these applications. The Barna wind farm project can now best be described as an unholy mess or a dogs dinner, whichever you prefer. We want the Board to understand that we, as ordinary citizens, are incapable of comprehending what the final Barndivane wind farm project will look like and consequently are placed in the position of not fully knowing what we are dealing with. If neither the Board nor the developer can place the final ramifications of the Barnadivane wind project before us for comment then how do they expect us to make informed comment to them. It then follows that our right to natural justice is being impinged.

BAT ROOSTS and WINTERING and BREEDING BIRDS

We have tried to meaningfully engage with the planning process all along the line. To this end we have provided the planning authority and ABP with information regarding the location of a bat roost on our property and on our neighbour's farms. We have offered an invitation to Fehily Timoney to engage with us in an assessment of our bat roost. I refer The Board to all of the previous information that we have submitted in this regard as we will not submit it again.

We are abjectly dismayed that we have not received a single comment with regard to the bat roost located in the attic of our house from CCC, ABP or F&T. Our final word on this is that if ABP does not ensure that a robust and reliable bat survey is carried out as part of the EIS with this application, we intend to take the matter to The European Court and to petition The European Parliament and lodge a complaint with The European Ombudsman.

We have also provided information on breeding and wintering birds on site. This information has been totally ignored and derided as being unverified. I refer The Board to all of the previous information that we have submitted in this regard.

We will add that this year as usual we have observed multiple breeding pairs of snipe on site, multiple pairs of grasshopper warbler, multiple wintering snipe and the usual solitary woodcock foraging which roosts in coniferous forestry at the boundary of the site. These birds and many others do not appear in the EIS. Speaking as ornithologists, we must now dismiss the EIS as woefully incomplete and mystifying. How F&T arrived at these results is something that needs to be resolved and we intend to get to bottom of it, one way or the other.

We are gravely concerned about the snipe that are breeding only tens of metres from proposed turbines as their breeding and foraging areas will be largely destroyed by the development. Snipe are in serious trouble and their breeding locations are currently being evaluated. We take that responsibility seriously and will be submitting our findings to the new Bird Atlas survey. We are extremely disappointed that CCC, ABP or F&T cannot take two lifelong ornithologists seriously. Asking F&T to review their data is in our opinion, a box ticking exercise that wastes everybody's time and does an injustice to the breeding birds at this site. Demanding new bird surveys by independent competent and reliable observers would have been more appropriate. If The Board has any interest, they will find that our names are well known among the birdwatching fraternity in Cork.

As we do not expect to see any change in The Board's attitude to this, we wish to notify The Board that we intend to take the matter to The European Court and to petition The European Parliament and lodge a complaint with The European Ombudsman.

USE OF PROPOSED WIND FARM SITE FOR AMMENITY PURPOSES

In APPENDIX 2 Revised CEMP for Barnadivane proposed wind farm, September 2015, Section 1, page 2, 1.3, The Site.

The applicant states "There are no recreational activities associated with this site"

This is misinformation as local hunting groups like Killmurray Harriers and those from further afield (Cork City) annually use this site for hunting both hares and foxes. Neighbours that I have talked to, including Denis Buckley and Patrick Manning have said they will attest to this fact if the Bord wishes to have further proof or the Bord can contact Killmurray Harriers if they want.

A National hare coursing event was held on the lands of Barry O'Sullivan (Stakeholder) previously.

This sort of misinformation in the EIS has eroded any faith we had in its validity and we have found misinformation like this to be common throughout. We are subsequently concerned as to why the Planning Authority or The Bord seem to be apparently unconcerned when this misinformation is pointed out by an ordinary citizen of the State of Ireland and no action is taken to rectify the matter. In the above situation, the applicant has succeeded in putting misinformation into the public domain. We believe that misinformation should be rectified on the files as it continues to mislead the public who are engaged with the planning process and undermines its validity.

SUBSTATION

The An Board Pleanala inspector's report of the Barnadivane substation is a resounding rejection of the application and proposed development on several points. It is very puzzling to us, therefore, how the Board was able to dismiss all of the relevant points raised by the inspector with regards to a recommendation of refusal.

POINTS RAISED BY THE INSPECTOR:

Visual Impact with regard to scenic routes in proximity to the site.

Zone of Theoretical Visibility are Incomplete

Visual impact of cutting of site

Visual impact with regard to human environment not properly assessed

Introduction of such a significant industrial installation will dramatically alter the receiving wider landscape

Project splitting concerns

The inspector goes on to say in the conclusion "I consider that the development of the substation as currently proposed on this site, would substantially dominate the surrounding landscape and in my opinion, would be contrary to the provisions of THE DEPT. OF ENVIRONMENT, HERITAGE & LOCAL GOVERNMENT PLANNING GUIDELINES FOR WIND ENERGY (JUNE 2006). I consider that the development, if permitted at this location, would adversely impact upon the visual amenities of the area, warranting refusal".

Having regard to the extensive points raised by the inspector appointed by An Bord Pleanala to review this planning application we believe the Board has not properly discharged its duty in regard to the reasons offered for the dismissal for the negative findings of this report. The Board is obliged to provide a reasoned and coherent process as to how it arrived at its decision to grant permission for this application. We believe it has not done so and we ask it to rectify this issue or we will seek recourse to judicial review.

EIRGRID COMPLIANCE

We believe that there are unresolved issues with regard to the alleged revised Eirgrid substation layout, size, capacity and location. We have asked for direct confirmation or evidence to be provided from Eirgrid for the alleged need for a 60mw substation but this has failed to materialise. We want the Board to know that we are unwilling to accept the word of the applicant, and will not take him on trust in this regard. As citizens of this state who are trying to lawfully engage with this process, we request The Board to provide us with a reasoned and logical reason as to why they have apparently ignored or rejected our previous requests for this vital information.

We also want to see evidence for and the nature of a grid connection at Barnadivane and evidence for and the nature of a grid connection at the newly proposed substation at Carrigarierk to

Dunmanway. We need this information to properly access the full implications and extent of the Barnadivane wind farm project. The Barnadivane Wind Farm Project is in constant flux and we believe it behoves The Bord to "Steady the ship" and to stop the applicant from continuously altering and amending this application in the interests of fairness and justice for ordinary citizens.

PLANTING PLAN

We just wish to reiterate what we have already said in this regard. As a horticulturist with over 20 years' experience in the industry managing garden centres and landscape nurseries, garden landscape designer and hort teacher, I wish to state that the planting plan lodged by the applicant is unworkable, inadequate and pointless. It appears to be the work of an amateur as it is full of factual errors, misinformation, parts of it are senseless and demonstrates a mind which has not managed to engage with the requirements of the brief. It is not possible to be more negative about the planting plan. I refer The Board back to my initial submission in this regard where I give a more detailed analysis of the plan.

I am therefore mystified as to why the inspector or The Board made no reference whatsoever to the planting plan or my submission.

Does ABP therefore think that the planting plan had no relevance when it came to their decision making process? Does ABP think that my submission was rubbish and as such was not worth commenting on? Is there another explanation?

Again we feel our observations made in good faith are not worthy of comment or further investigation and leaves us feeling the planning process is one sided and lacks due care where citizens take the trouble to make relevant comments.

However, we believe that a credible planting plan is a critical part of this proposed development and having studied previous relevant court cases have come to the conclusion that a clear and workable planting plan must be put before The Board for adjudication and cannot be cobbled together and agreed afterwards with the relevant Local Authority.

We therefore again ask The Board to get a competent person with relevant experience to assess the planting plan as proposed and to have those findings published for public viewing and comment.

E.ON Energy Research Center
FCN | Institute for Future Energy Consumer Needs and Behavior

FCN Working Paper No. 3/2012

The Impact of Wind Farms on Property Values: A Geographically Weighted Hedonic Pricing Model

Yasin Sunak and Reinhard Madlener

May 2012
Revised March 2013

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The Impact of Wind Farms on Property Values:

A Geographically Weighted Hedonic Pricing Model

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ABSTRACT

Wind power is the most important renewable energy source in many countries today, characterized by a rapid and extensive diffusion since the 1990s. However, it has also triggered much debate with regard to the impact on landscape and vista. Therefore, siting processes of wind farm projects are often accompanied by massive public protest, because of visual and aural impacts on the surrounding area. These mostly negative consequences might be reflected in property values and house prices. The aim of this paper is to investigate the impacts of wind farms on the surrounding area through property values, by means of a hedonic pricing model, using both a spatial fixed (viewshed) effects (accounting for spatially clustered unobserved influences) and a Geographically Weighted Regression model (accounting for spatial heterogeneity). The analysis is the first of its kind undertaken for a local region in Continental Europe (North Rhine-Westphalia, Germany). Viewsheds are calculated for each property using a digital surface model. Focusing on proximity and visibility effects caused by wind farm sites, we find that proximity, measured by the inverse distance to the nearest wind turbine, indeed causes significant negative impacts on the surrounding property values. Thereby, local statistics reveal varying spatial patterns of the coefficient estimates across and within the city areas and districts. In contrast, no evidence is found for a statistically significant impact of the visibility of the wind farm turbines.

Keywords: Wind power, Hedonic pricing, Spatial fixed effects, Geographically Weighted Regression

JEL Classification: C31, Q2, Q42, R31

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I. INTRODUCTION

Against the background of climate change and increasing concerns about security of energy supply, the expansion of the renewable energy supply and the substitution of fossil fuel-based energy sources have become key topics on political agendas worldwide. Therefore, national energy policies are increasingly focusing on the promotion of wind, solar, biomass, geothermal, and other energy sources through extensive support schemes. As a result, the share of renewable sources has substantially increased in many countries since the 1990s. Although the further expansion and promotion of renewable energies is crucial with regard to a substantial transition to a more sustainable future energy mix, renewable energy projects, just like conventional ones, often trigger public concern and resistance.

In Germany, considerable growth in the share of renewable energies is attributable to the introduction of the *Act of Granting Priority to the Renewable Energy Sources* (Erneuerbare-Energien-Gesetz, EEG) in 2000, amended in 2004, 2009, and 2012 (EEG, 2000, 2004, 2009, 2012). Introducing this regulatory framework for the promotion of electricity and heat from renewable energy sources, which is essentially based on feed-in tariffs guaranteed over 20 years, had a substantial impact on the speed and extent of the diffusion of renewable energy technologies. Particularly, the wind energy sector in Germany saw a rapidly increasing contribution, with a total of 22,297 installed wind turbines (onshore and offshore) and an installed capacity of 29,075 MW by 2011 (Figure 1). Although wind energy already accounts for the highest share of electricity production within the renewable energy sector[1], its annual growth rate of installed capacity in 2011 of about 7% was still fairly high. In terms of the total electricity consumption in Germany in 2011, wind power accounted for a share of 7.6% (BMU, 2012).

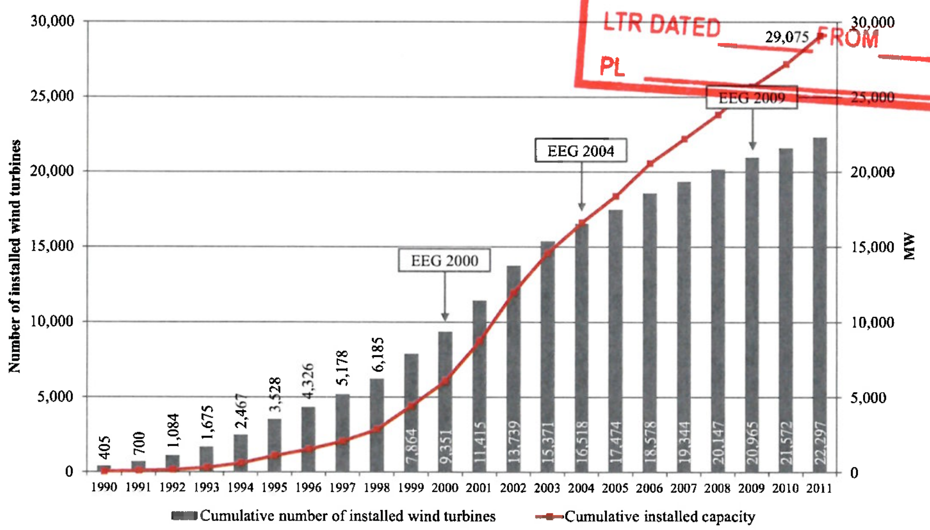

FIGURE 1
Development of the wind energy sector in Germany, 1990-2011
Source: BMU (2012), own illustration

[1] Wind energy accounted for 38.1%, biomass energy for 30.3%, hydro power for 16.0% and photovoltaics for 15.6% of the total amount of electricity produced by the renewable energy sector in 2011.

The heavily promoted expansion of renewable energy technologies is mostly justified by referring to the advantages and benign attributes associated with them. In the case of wind power, these attributes are, e.g., a "green" and in particular CO_2-free energy generation without fuel costs as well as reasonable land consumption (Ackermann and Söder, 2002; Manwell, et al., 2009, pp.443-447; BWE, 2012). However, not only advantages and positive effects are associated with wind farm sites. Firstly, the amount of electricity produced is to some extent unreliable and unpredictable due to unsteady wind conditions. Secondly, the hub heights of wind turbines, both newly constructed and after repowering[2], have been increased over the last years in order to further raise efficiency (Junginger et al., 2005; Sieros et al., 2012). As a consequence, the upscaling of wind turbine nacelles to heights of 100 m and more, and corresponding blade diameters, has led to a substantial change of landscape and vista.

The negative externalities caused by wind farm sites have led to major public concern that particularly refers to the impact on the environment and landscape. The latter tends to result in massive public protest, because of apparent visual[3] and aural[4] impacts on the surrounding area, with negative consequences that are supposed to be reflected in property values and housing prices. Public debates accompanying siting processes solely involve the argument of the expected devaluation of property or house prices as a consequence of siting in the proximity of a property or a house. Apart from the existing economic and regulatory complexity of siting processes, social acceptance and, especially in the case of wind farms, "NIMBY" (Not In My Backyard) attitudes become increasingly virulent (Wolsink, 2000; van der Horst, 2007; Wolsink, 2007). However, with decreasing social acceptance regarding siting decisions, the sound and transparent estimation and valuation of potential environmental impacts and other acceptance-biasing aspects should play a paramount role within the siting process, in order to mitigate public protest and related unanticipated and underestimated (external or internal) project costs.

The aim of this paper is to investigate the impacts of wind farms on the surrounding area through property values, by means of a hedonic pricing model, using spatial fixed effects (accounting for spatially clustered unobserved influences) and a Geographically Weighted Regression (GWR) model (accounting for spatial heterogeneity). The main focus lies on the investigation of site proximity and visual impacts of wind farms, such as the impact of visibility and shadow flickering, as these are the dominant subject of public debates associated with siting processes.

In a first step, we apply three different spatial fixed effects models in order to capture effects of unobserved spatial factors.[5] Since spatial fixed effects models have been applied to the case of wind farm effects before (e.g. Heintzelman and Tuttle, 2011 and Hoen et al., 2009, 2011), we improve upon the already applied methodologies in the literature, investigating the

[2] Repowering is the replacement of older turbines in favor of new and more efficient ones, which most often also have a higher installed capacity (Madlener and Schumacher, 2011; Sieros et al., 2012).

[3] Visual impacts comprise general visibility and shadow flickering effects (Álvarez-Farizo and Hanley, 2002).

[4] Aural impacts refer to turbine noise and sound pressure (Rogers et al., 2006; Harrison, 2011).

[5] The three spatial fixed effects model specifications are varying according to their geographical scale, where smaller scales of the fixed effects allow for tighter control with regard to omitted variable bias (Heintzelman and Tuttle, 2011). The spatial fixed effects included in our analysis are fixed city effects, fixed city district effects and fixed cadastral district effects. For a detailed description of the model specifications see section 3.

importance of the view on the facility by means of a fixed viewshed effect model specification. Controlling for visibility effects will emphasize and highlight the importance of distance to the facility, therefore, providing a more sophisticated measure of proximity than commonly applied. A specific element is the application of Geographical Information System (GIS) techniques[6], which allow for an accurate derivation of viewsheds[7] for each property in a 3D environment on the basis of high resolution geodata.

In a second step, we additionally apply a GWR analysis in order to gain a more detailed picture of local impacts and spatially varying relationships compared to global estimation results. This particularly includes the consideration of spatial correlation and the analysis of the biasing influence of spatial non-stationarity on the estimation results. To the best of our knowledge, there is no other hedonic pricing analysis applied to wind farm impacts yet that specifically adopted a GWR approach in combination to other regression techniques in order to emphasize the importance of local dependencies. Hence, the merit of our contribution is the specific investigation of spatial patterns and locational dependencies in the frame of a hedonic pricing model applied to the case of a wind farm site.

There is a number of studies investigating the impact of wind farm sites on the surrounding area from a social acceptance point of view, using survey-based approaches (e.g. Krohn and Damborg, 1999; Wolsink, 2000; Álvarez-Farizo and Hanley, 2002). The number of studies that aim at quantifying economic impacts of wind farms on the surrounding area is much lower. Albeit there are several studies in this context using non-market valuation techniques, with the hedonic pricing approach most commonly being applied (e.g. Hoen et al., 2009; Canning and Simmons, 2010)[8], to our knowledge there are only a few analyses in the peer-reviewed literature so far (Sims and Dent, 2007; Sims et al., 2008; Laposa and Mueller, 2010; Heintzelman and Tuttle, 2011; Hoen et al. 2011), which are briefly discussed in the following.

Sims and Dent (2007) investigated the impact of a wind farm near Cornwall, UK, on house prices, using a hedonic pricing approach and comparative sales analysis. Applying straightforward OLS regression, they found some correlation between the distance to a wind farm and property values. Due to data limitations, the overall model results had a fairly weak explanatory power.

Sims et al. (2008) modeled the impact of wind farm proximity to houses for a region near Cornwall, UK. There was some evidence to suggest that noise and flicker effects as well as visibility may influence property value in a wind farm's vicinity. However, the hedonic analysis, in which standard OLS regression techniques were used, showed no significant impacts caused by the wind farm.

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[6] GIS software is a powerful tool for enhancing the spatial precision of estimation techniques. With the capability to capture, store, manage, analyze, and display space-related information, GIS software systems are frequently used for underpinning hedonic pricing models. In this context, implementation possibilities are quite diverse, such as analyzing spatial heterogeneity (Geoghegan et al., 1997) or developing Digital Elevation Models (DEM), in order to apply visibility analyses (Paterson and Boyle, 2002; Lake et al., 2010).

[7] Viewsheds display areas of land, water, or other environmental elements that are visible to the human eye from a fixed vantage point (in our case the considered properties). The visibility of a large-scale wind farm in the close vicinity of a property might have a significant impact on its value.

[8] There is also research on the impact of wind farm proximity, applying a simple quantitative approach (Sterzinger et al., 2003), and published in the form of project reports. Sterzinger et al. (2003) compared property transactions within a five-kilometer radius around the site, using a group of comparable control transactions outside of this range, but without controlling for other factors explaining property prices.

Laposa and Müller (2010) examined the impact of wind farm project announcements on property values for northern Colorado, US. Including observations before and after the announcement of the wind farm project, they applied a hedonic pricing model accounting for announcement and spatial characteristics of three location groups. The results obtained indicated no significant impact of the planned project's announcement.

Exploring the impacts of new wind facilities on property values in northern New York, US, by means of a fixed effects hedonic pricing model, Heintzelman and Tuttle (2011) found that nearby wind facilities can significantly reduce property values. Decreasing the distance to the wind farm to one mile indicated a property price devaluation of between 7.73% and 14.87%. In addition, they controlled for omitted variables and endogeneity biases by applying a repeat-sales analysis.

In a peer-reviewed and published version of the Hoen et al. (2009) project report, Hoen et al. (2011) investigated 7,459 sales of single-family houses surrounding 24 wind farm sites in the US. They applied various hedonic pricing model specifications, using spatial fixed effects to account for spatial dependence and spatial autocorrelation. A main focus was put on the impact of view and distance to the site. Overall, they found no statistically significant effects on property sales prices.

Table 1 provides an overview of selected hedonic pricing analyses on wind farm impacts.

TABLE 1
Overview of hedonic pricing studies

Study	Study area	*n*	Time period [years]	Pre-/Post-construction	Distance to wind farm [km]	Repeat sales	Property value impact
Sims and Dent (2007)	Cornwall, UK	919	5.5	post	< 16	no	negative
Sims et al. (2008)	Cornwall, UK	199	7.5	post	0.8-1.6	no	none
Laposa and Müller (2010)	Colorado, US	2,910	9	pre	< 80	no	none
Heintzelman and Tuttle (2011)	New York (state), US	11,331	10	pre/ post	< 86	yes	negative
Hoen et al. (2009, 2011)	US (24 sites)	7,459	11.5	pre/ post	< 17.6	yes	none
Canning and Simmons (2010)	Ontario, Canada	83	2.5	post	n.a.	yes	none

Source: own illustration

As most of the hedonic pricing studies on wind farms were conducted in the UK and the US, respectively, such a study investigating the impacts of wind farms in a Continental European location (North Rhine-Westphalia, Germany) can be expected to yield new insights. The reason is that, in contrast to the regional dimensions of the areas typically considered in US studies, regional structures and thus study areas in Europe are often much smaller, which likely affects the results and insights gained. A wind farm near the German cities of Rheine and Neuenkirchen in the federal state of North Rhine-Westphalia (NRW), constructed in 2002, is chosen for applying the selected model specifications. We are not aware of any other scientific study on wind farm impacts using German real estate market data.

The remainder of this paper is organized as follows. Section II provides the theoretical background and literature overview. Section III introduces the hedonic pricing model and the estimation techniques applied. Furthermore, section III presents the dataset and the description of the estimation variables. Section IV reports on the results obtained from the different model specifications. Section V concludes and also draws some attention to future research needs.

II. THEORETICAL BACKGROUND AND RELATED LITERATURE

The methodology adopted in this paper is associated with non-market valuation techniques. These comprise various techniques for estimating the value of goods and services that are not traded in markets and whose value is, therefore, not revealed in market prices (Tietenberg and Lesiw, 2009, p.35). This applies particularly to environmental goods, such as air and water quality, as well as landscape and related positive or negative externalities.

There are different methods in the field of non-market valuation, which can be categorized according to the individuals' preferences that are either stated or revealed. *Stated preference methods*, such as contingent valuation or choice modeling, are based on practical survey techniques, essentially investigating the willingness to pay (WTP) for obtaining a particular good (Kriström, 2002; Bateman, 2010; Tisdell, 2010, p.203; Krueger et al., 2011). Alternatively, *revealed preference methods* rest upon the assumption that individuals' preferences can be derived from their consumption behavior (Tietenberg and Lesiw, 2009, p.39; Tisdell, 2010, p.203), and comprise methods like the travel cost method and the hedonic pricing method.

Rosen (1974) pioneered the economic formalization of a hedonic pricing model, although earlier studies tackled the approach of implicit markets (Tiebout, 1956) and statistical relationships between air quality and housing values (Ridker and Henning, 1967). According to Rosen (1974), hedonic pricing models seek to explain the overall price $p=p(x)$ of a differentiated product that is characterized by a bundle of n attributes $x = (x_1, \ldots, x_n)$. The hedonic function, therefore, results from the market interaction of demand and supply. Product differentiation implies the availability of alternative bundles, so that in market equilibrium p equals each consumer's bid for the differentiated product (Rosen, 1974).

In the field of environmental economics, hedonic pricing models are widely used to estimate the WTP for improvements in environmental goods (Palmquist, 2002), most frequently applied to the housing or property market. Houses or properties are compound products, characterized by sets of structural (e.g. house/lot size, age, and type of building), neighborhood (e.g. income distribution, crime rate, and taxes), spatial (e.g. distances to local amenities or disamenities) and environmental (e.g. noise levels, air quality, and vista) attributes.

Hedonic studies show a wide range of application fields. Commonly, they are used for investigating air quality (Nelson, 1978; Kim et al., 2003; Chay and Greenstone, 2005), water quality (Steinnes, 1992; Leggett and Bockstael, 2000; Poor et al., 2007), noise (Espey and Lopez, 2000; Theebe, 2004; Baranzini and Ramirez, 2005; Dekkers and van der Straaten, 2009) and proximity to hazardous facilities (Kohlhase, 1991; Nelson et al., 1992; Simons et al., 1997). Moreover, hedonic models are increasingly applied in the field of energy and the environment (Gamble and Downing, 1982; Clark et al., 1997; Clark and Allison, 1999; Des Rosiers, 2002). While the number of studies on the impact of renewable energy technologies, including wind farms, has been rapidly growing in the past, to date only few peer-reviewed articles exist in the scientific literature.

III. HEDONIC PRICING MODEL

Estimation methods

An attempt to estimate the impacts of wind farm proximity in the framework of a hedonic pricing study has to take into account the possible bias caused by model misspecification, particularly through omitted variables. In this context, the main concern refers to regional or local factors which remain unobserved. In case of unobserved factors, partly explaining the variation in property prices or being correlated with included variables, the model estimations will likely be biased and, therefore, unreliable (Chay and Greenstone, 2005; Greenstone and Gayer, 2009; Kuminoff et al., 2010).

The unobserved variables bias can directly be addressed by applying a spatial fixed effects model specification. Spatial fixed effects basically capture spatially clustered unobserved influences in the considered study area through incorporating a set of dummy variables, e.g. representing city districts of the study area. According to this example, the fixed city district effect will then implicitly absorb all unobserved factors within the defined geographical scale of this fixed effect. However, the effect of this approach in capturing spatially clustered unobserved factors crucially depends on the definition of the geographical scale. The definition of the geographical scale is accompanied by a tradeoff between the level of control and the variation in the explanatory variables (Heintzelman and Tuttle, 2011). Therefore, a higher level of control for omitted variables, i.e. a small geographical scale of the fixed effect, results in less variation in the explanatory variables due to the limited scope of the fixed effect (Heintzelman and Tuttle, 2011). The definition of several scales for spatial fixed effects in different model specifications seems reasonable in order to derive a comprehensive picture of the ability of spatial fixed effects in terms of capturing spatially clustered unobserved factors.

Accompanied by spatially clustered omitted variables, we have to be aware of spatial dependence and spatial heterogeneity. Spatial dependence refers to dependencies among spatially contiguous observations within the dataset which cause spatial autocorrelation (Anselin and Getis, 2010). Thus, based on Tobler's First Law of Geography, spatially nearby observations are stronger correlated to each other than observations farther away (Tobler, 1970). Likewise, unobserved factors for one observation may be correlated to unobserved factors for a neighboring observation, inevitably causing spatial autocorrelation. Therefore, not controlling for spatial autocorrelation would bias our estimations. We address this spatial dependence problem by applying spatial fixed effects and error clustering in a procedure proposed by Heintzelman and Tuttle (2011). According to this, using spatial fixed effects is methodologically related to the application of a spatial lag model, where the spatially weighted average of neighboring observations in the spatial lag model is given here by the scale of the fixed effects. Similarly, the error clustering is related to employing a spatial error model allowing for correlation of error terms.[9] Besides the wide application of spatial econometric techniques, such as the use of the spatial lag and spatial error model, "spatial fixed effects are clearly the preferable strategy for addressing spatially correlated omitted

[9] For further details on the spatial lag and error model see e.g. Anselin (1988).

variables in cross-section data" (Kuminoff et al., 2010, p.158), as spatial fixed effects offer a less rigid and more flexible structure on spatial relationships between included and omitted variables (Kuminoff et al., 2010).

The hedonic pricing model in a spatial fixed effects and error-clustering specification is given by:

$$\ln p_{ijt} = \alpha_j + \lambda_t + W_{ijt}\beta + S_{ijt}\gamma + N_{ijt}\delta + \eta_{jt} + \varepsilon_{ijt}, \qquad [1]$$

where p_{ijt} is the sales price of property i in group j at time t, α_j represents the spatial fixed effects, λ_t denotes the set of time dummy variables (month and year), W_{ijt} represents the wind-farm-related variables, S_{ijt} describes a set of structural variables, N_{ijt} denotes the neighborhood variables, η_{jt} and ε_{ijt} are grouped and individual-level error terms, and β, γ as well as δ are the parameters to be estimated.[10]

We use three different spatial fixed effects specifications which are derived according to the administratively defined structure of the study area. The study area contains two cities which again consist of four defined city districts and 39 cadastral districts, respectively.[11] From large to small geographical scale, the first three group the observations with regard to their location in one of the cities (2 groups), in one of the city districts (4 groups) and in one of the cadastral districts (39 groups). In a fourth specification, the fixed viewshed effects model, we group the observations according to the number of visible turbines (10 groups). Compared to the three specifications first mentioned, the fixed viewshed effects are not deduced from administrational structure, but rather from an underlying spatial structure. The fixed viewshed effects should essentially absorb the influence of wind farm visibility on properties, therefore, highlighting the importance of pure proximity in the sense of distance measures. In many hedonic pricing studies focusing on wind farm impacts, simple distance measures are used as a proxy for various effects that are caused by proximity to the facility. But besides the measurement of distance, proximity can also be investigated in the sense of visibility, shadow flickering effects and aural impacts. Therefore, applying the fixed viewshed effect specification, we try to provide a more differentiated picture on potential impacts caused by the presence of wind farms.

Spatial heterogeneity is a further concern that we should be aware of. Spatial heterogeneity refers to the presence of spatial non-stationarity within the dataset, as the measurement of a relationship depends on where the measurement is taken (Fotheringham et al., 2002, p.9). There might be various dependencies between spatially nearby observations, so that spatial relationships may vary across the considered study area. We address one form of spatial heterogeneity again by using spatial fixed effects. Furthermore, we explore spatial heterogeneity in our dataset by means of a GWR, as this approach allows for a comprehensive view on spatial relations providing local statistics.

[10] We apply a semi-log specification. The semi-log specification is a commonly used regression form in hedonic pricing studies (Clark and Allison, 1999; Baranzini and Ramirez, 2005; Heintzelman and Tuttle, 2011), which allows for an intuitive interpretation of the results. The estimated coefficients can be interpreted as elasticities if the independent variable enters the model in the log scale and as semi-elasticities if the variable does not enter in the log scale (Gujarati and Porter, 2009, p.162). In the case where the independent variable is a dummy variable, the coefficients are interpreted as median impacts (Gujarati and Porter, 2009, p.298). In addition, using a semi-log regression form often reduces heteroscedasticity (Gujarati and Porter, 2009, p.394).

[11] A more detailed description on the study area is provided in the data subsection further below.

Most importantly, compared to conventional regression models, the GWR provides separate, local regressions for each observation, instead of generating a single, global regression. Therefore, it is possible to account for different local relationships, weighting each observation adaptively.

According to this, the GWR model specification is given by:

$$\ln p_{it} = W_{it}\beta(u_i,v_i) + S_{it}\gamma(u_i,v_i) + N_{it}\delta(u_i,v_i) + \varepsilon_{it}, \qquad [2]$$

where (u_i,v_i) indicates the coordinates of the ith observation. Again, following Tobler (1970), the GWR has to be calibrated in a way that observations near to observation i have more influence on the estimation of the parameters ($\beta(u_i,v_i)$, $\gamma(u_i,v_i)$, $\delta(u_i,v_i)$) than data located farther away from i. The calibration of the model is set by spatial kernels which can be fixed or adaptively fitted to the spatial distribution of the regression points. Figure 2 graphically illustrates a spatial kernel and a GWR with adaptive spatial kernels.

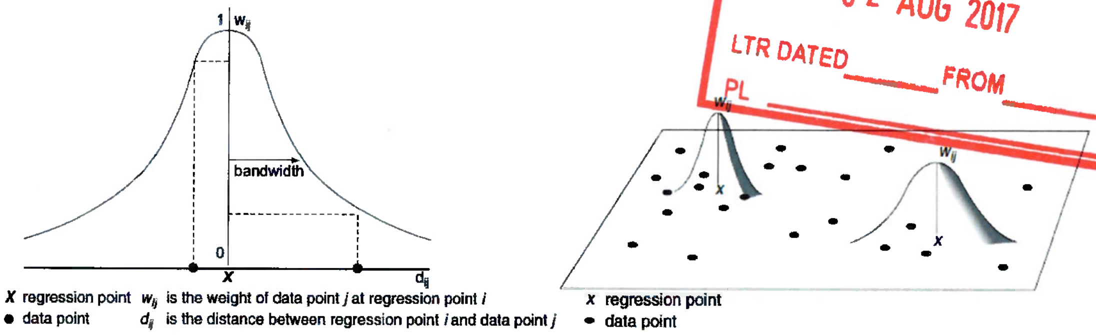

FIGURE 2
A spatial kernel and a GWR with adaptive spatial kernels
Source: Fotheringham et al. (2002), pp.44 and 47

The estimation of the parameters for each location depends on the particular weighting function chosen in order to capture the spatial differences in a certain area. According to the weighting function and its bandwidth, the weight of the data point w_{ij} decreases with increasing distance to the regression point d_{ij}. The definition of the optimal bandwidth of the weighting function is crucial for the precision of the GWR. Therefore, it might be useful not to assume fixed spatial kernels with fixed bandwidth for each regression point, but rather adaptive kernels that take account of differing density of data points around regression point i (Figure 2).

In order to determine the optimal spatially-varying weighting method, we adopt an adaptive kernel that uses an Nth-nearest neighbor weighting of point i with a bi-square decay function.[12] Following Fotheringham et al. (2002), p.58, that is,

[12] We are aware that the appropriability of the Nth-nearest neighbor weighting is an empirical matter, as this is a nonparametric approach, forcing each observation to have the same number of neighbors (Anselin, 2002). However, accounting for spatial variations in the framework of a GWR, the Nth-nearest neighbor weights provide a straightforward method capturing the 'bump of influence' around i, without assuming that the given administrational structure of the study area (e.g. through cadastral districts) really represents local variations

$$w_{ij} = \begin{cases} [1-(d_{ij}/b)^2]^2 \text{ if } j \text{ is one of the } N\text{th-nearest neighbors of } i \text{ and} \\ b \text{ is the distance to the } N\text{th-nearest neighbor} \\ 0 \text{ otherwise.} \end{cases} \quad [3]$$

The determination of the weighting function and optimal bandwidth selection was obtained by minimizing the corrected Akaike Information Criterion (AIC_c) (Fotheringham et al., 2002, p.61).

In summary, we address spatial autocorrelation caused by spatially clustered unobserved factors and spatial heterogeneity in the sense of spatial non-stationarity using various spatial fixed effects model specifications. Additionally, we emphasize the relevance of spatial heterogeneity through the application of a GWR. We explicitly explore the importance of locally varying relationships, exposing additional insights that can be derived from local statistics compared to global regressions.

The data

Investigating the impact of a wind farm site on surrounding property values, this study focuses on property sales within an area of 119 km^2 in the north of the German federal state of NRW, including parts of the city of Rheine and the city of Neuenkirchen. Both cities, at least two city districts in the case of Rheine (Mesum and Hauenhorst), are in the immediate proximity of the considered wind farm site. This northern region of NRW can be defined as a semi-urban region mainly characterized by medium- and small-sized towns.[13] In 2011, a population of 26,900 lived within a radius of about 5.5 kilometers around the site.

As Figure 3 illustrates, the considered study area contains two cities (the city of Rheine and the city of Neuenkirchen), each consisting of two city districts. City districts of Rheine are Mesum and Hauenhorst, and Neuenkirchen (city area) and St. Arnold in the case of Neuenkirchen. Besides the apparent spatial structure depicted in Figure 3, the German land register provides further spatial classifications. In the German land register, cadastral districts are the smallest spatial unit that groups a particular number of parcels in respect of their location. According to the cadastral register of the region, each property, i.e. each parcel, is assigned to a particular cadastral district. The property sales in our dataset can be grouped correspondent to 39 cadastral districts. As described in the estimation methods subsection above, the different spatial administrative structures defined are used to incorporate spatial fixed effects in our hedonic pricing model.

In 2000, the local administration announced the construction of a wind farm consisting of nine turbines, which was eventually built in July 2002. The nine turbines, each with a capacity

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appropriately. There is a vast body of literature on the specification of the weight matrices in spatial analysis. For a detailed discussion on the construction of weights see e.g. Smirnov and Anselin (2001) and Anselin (2002).

[13] The definition of town-size categories for German cities is taken from Bähr and Jürgens (2005). According to their categorization, towns with a population of about 2,000 to 5,000 are small rural towns, cities with a number of inhabitants ranging from 5,000 to 20,000 are small-sized cities, cities with 20,000 to 100,000 inhabitants are medium-sized cities and large cities are defined by comprising more than 100,000 inhabitants. Rheine is a medium-sized town with an overall population of about 76,500 in 2011 (IT.NRW, 2012). In 2011, Mesum's population was about 8,400 and Hauenhorst had about 4,500 inhabitants. Neuenkirchen is a small-sized town with about 14,000 inhabitants in 2011 (IT.NRW, 2011). Corresponding to Neuenkirchen is also the village of St. Arnold (population about 3,000), which is about one kilometer away from the actual city area in a northerly direction.

of 1.5 MW, have hub heights of 100 meters and rotor sizes of 77 meters. Particularly in view of the fact that this area of northern NRW is very flat regarding its relief, with an average altitude only varying between 30 and 90 m above sea level, the wind farm substantially influences the landscape. Figure 3 illustrates the study area and the location of the wind farm site.

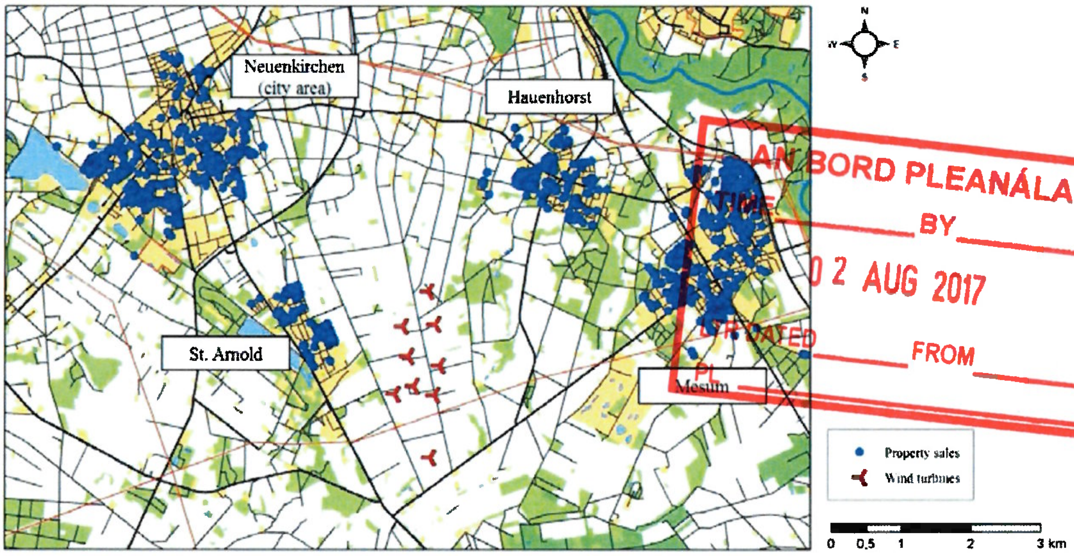

FIGURE 3
Study area
Source: Own illustration, based on data provided by the Geodatenzentrum NRW (2011)

Property market data for the two cities contained 1,405 property sales within the period of 1992 until 2010 and was provided by the Expert Advisory Boards (*Gutachterausschüsse*) of the federal district of Steinfurt[14] and the city of Rheine. The dataset included the sales prices of the properties, lot sizes, sales dates, and the address-based location. All property prices in the dataset were deflated by the German Construction Price Index, published by the German Federal Statistical Office, with 2005 as the base year.[15] The distance of the observations to the wind farm site ranges between 945 m to 5,555 m, so that, compared to other hedonic studies (cf. Table 1), the properties are very close to the site. Table 2 gives an overview of the observations and their distribution according to cities, city districts, wind farm announcement and construction.[16]

A major difference to most of the hedonic pricing studies in the literature is the usage of property values, i.e. prices of parcels of land, and not house prices. This is mainly due to data availability issues and privacy restrictions of address-based house price data in Germany.[17] Nevertheless, we assume that properties are likewise suitable for conducting a hedonic pricing study, as their values are also sensitive to changes in the surrounding location. Only the

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[14] Rheine and Neuenkirchen are cities that both belong to the federal district of Steinfurt. In this context, the term 'federal district' is equivalent to a 'county council'.

[15] Available online at https://www.destatis.de/EN/FactsFigures/Indicators/ShortTermIndicators/Prices/bpr110.html (accessed January 14, 2012).

[16] Re-sales were not excluded from the data sample as these only account for a small share of the total sales. As a consequence, the re-sales data does not provide a sufficient basis for applying a repeat sales analysis.

[17] The data provided by the Expert Advisory Boards only contained the price for the property in terms of a parcel of land (separated from prices for homes).

selection of the (structural) variables differs, compared to hedonic pricing studies using house prices.[18] Furthermore, in our study we only consider developed and undeveloped properties for residential utilization.[19] The regional land use, such as residential utilization, is defined in the regional development plan.

TABLE 2
Summary statistics – Property sales in the study area, 1992-2010

	N	Percentage
Total no. of observations	1,405	100.0
City of Rheine	690	49.1
City district Hauenhorst	220	15.7
City district Mesum	470	33.4
City of Neuenkirchen	715	50.9
City district Neuenkirchen (city area)	556	39.6
City district St. Arnold	159	11.3
Total sales	1,202	85.6
Total re-sales	203	14.4
Pre-announcement	724	51.5
Post-announcement	681	48.5
Pre-construction	872	62.1
Post-construction	533	37.9

Table 3 provides summary statistics of the 15 wind-farm-related variables and the other 17 explanatory variables that were tested in different model specifications in order to explain the variation in the property prices.

The set of wind-farm-related variables tries to measure the wind farm presence in different ways. First of all, the set includes Euclidean distance measurements as the most commonly used proxies of wind farm effects.[20] We used the inverse distance from each property to the nearest wind turbine, which also allowed for the consideration of the date of construction.[21] Besides the inverse distance measure from each property to the wind farm, we also tried to identify local distance effects within five kilometers around the wind farm, using dummy variables containing properties in 0.5 km steps.

Negative environmental effects often associated to wind farm sites refer to the shadow flickering effect caused by the rotor blades in relation to the position of the sun (Hau, 2006). In order to capture the shadow flickering effects caused by the rotor blades, we determined the potentially affected areas, taking into account the heights of the turbine, the rotor blade

[18] Hedonic pricing studies using house prices include a large set of structural variables, such as the number of rooms, the age of the house, or the availability of a garage, which are irrelevant for properties in terms of parcels of land. For parcels of land, structural variables can be limited to the lot size and the development status, whereas more emphasis has to be put on neighborhood variables, capturing locational attributes.

[19] In comparison to an untilled parcel, we include four types of possible development statuses: a parcel with a single-family house, a parcel with a duplex house, a parcel with a row house, and a parcel with a multi-family house.

[20] All distance variables, also those that were used to capture general neighborhood features, were calculated using GIS software. We used the ESRI ArcGIS Desktop software package (Version 9.3.1), including the Spatial Analyst Tool, Spatial Statistics Tool, and the 3D Analyst Tool.

[21] Using inverse distance measures to the nearest turbine, the measured values increase with decreasing distance. Note also that values for property sales with sales dates before the turbines' existence measure the inverse distance to the next existing wind farm in neighboring regions at that time.

diameter and the positions of the sun during a day. Identifying the affected areas, we were able to determine the temporary presence of shadow flickering effects for each property during the year.[22] In this context, we tested a simple dummy variable as well as a variable that explicitly takes into account shadow flickering caused by multiple turbines.

TABLE 3
Descriptive statistics

	Variable	Units	Mean	Std. dev.	Min	Max
Wind-farm-related	ln *Inverse Wind farm distance*	ln *m*	-9.26	0.99	-10.02	-6.89
	Distance 0.5 - 1 km	dummy	0.00	0.06	0	1
	Distance 1 - 1.5 km	dummy	0.03	0.18	0	1
	Distance 1.5 - 2 km	dummy	0.01	0.11	0	1
	Distance 2 - 2.5 km	dummy	0.06	0.24	0	1
	Distance 2.5 - 3 km	dummy	0.01	0.11	0	1
	Distance 3 - 3.5 km	dummy	0.04	0.20	0	1
	Distance 3.5 - 4 km	dummy	0.09	0.28	0	1
	Distance 4 - 4.5 km	dummy	0.04	0.19	0	1
	Distance 4.5 - 5 km	dummy	0.09	0.28	0	1
	Shadow flickering	dummy	0.03	0.18	0	1
	Shadow flickering (no. of turbines)	classes	0.08	0.47	0	3
	Visibility (no. of visible turbines)	classes	0.29	0.99	0	9
	Announcement effect	dummy	0.45	0.50	0	1
	Construction effect	dummy	0.38	0.49	0	1
Structural	ln *p*	ln €	10.43	0.84	4.34	12.59
	ln *Lot size*	ln m²	6.18	0.70	1.10	9.83
	Waterfront	dummy	0.00	0.07	0	1
	Type single-family house	dummy	0.55	0.50	0	1
	Type duplex house	dummy	0.17	0.38	0	1
	Type row house	dummy	0.02	0.15	0	1
	Type multi-family house	dummy	0.02	0.15	0	1
Neighborhood/ Spatial	ln *CBD*	ln *m*	-6.83	1.12	-8.28	2.30
	ln *Supermarket*	ln *m*	-6.28	0.60	-7.45	-2.52
	ln *Commercial area*	ln *m*	-7.36	0.88	-8.56	-3.71
	ln *School*	ln *m*	-6.41	0.60	-8.01	-4.25
	ln *Forestland*	ln *m*	-5.29	0.90	-6.54	2.30
	ln *Major road*	ln *m*	-5.25	0.89	-6.72	-2.11
	ln *Road*	ln *m*	-2.48	0.42	-4.53	-0.02
	Street noise	classes	1.07	0.38	1	5
	ln *Railroads*	ln *m*	-7.53	1.28	-8.91	-3.54
	ln *Transmission line*	ln *m*	-6.85	0.74	-7.72	-3.47
	ln *Lake*	ln *m*	-6.40	0.73	-7.52	-3.23

To measure the visibility of the wind farm site, we calculated viewsheds for each property. Viewsheds refer to the visible area from an observer's perspective, in our case from a property. A precise measurement of the view crucially depends on capturing all features in the landscape that are visible from the observer's point of view. The view of a certain feature in the landscape might be hindered by heights, slopes, vegetation, or buildings. In order to calculate viewsheds as precisely as possible, we applied a digital surface model[23] with an

[22] We consider properties as impacted by shadow flickering effects, if these are located in the affected areas.
[23] The digital surface model is essentially based on multipoint information that contains x and y coordinates as well as the z-value, referring to longitude, latitude, and height. The surface model for the whole study regions

accuracy of one meter, which was provided by the Geodatenzentrum NRW.[24] The digital surface model included height level information of the terrain, the vegetation, and buildings, and allowed us to calculate a raster of the area terrain. On the basis of raster data, we were able to conduct a viewshed analysis using the ESRI ArcGIS Spatial Analyst and 3D Analyst tool. Figure 4 illustrates the results of the viewshed analysis, indicating the areas with a view of the wind farm. Overall, for 128 properties in the dataset at least one turbine was visible.[25] The calculated viewsheds were used to specify the fixed viewshed effects model described in the estimation methods subsection above.

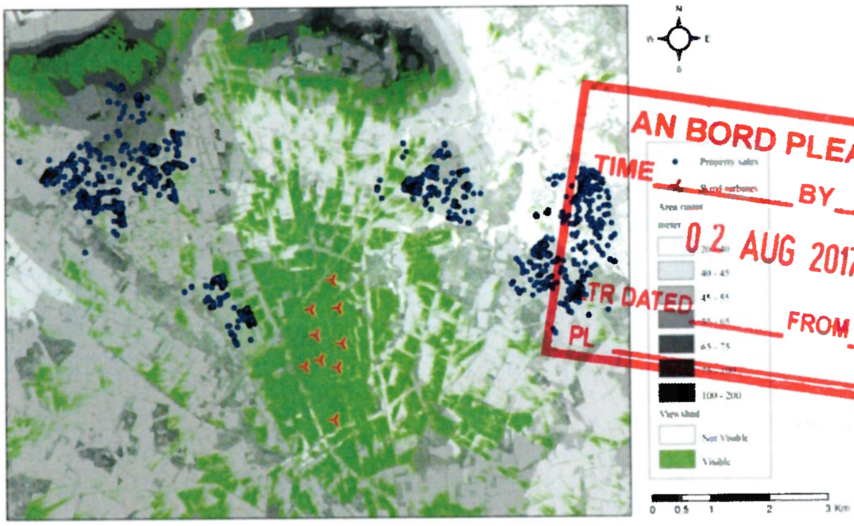

FIGURE 4
Visibility analysis
Source: Own calculation and illustration, based on data provided by the Geodatenzentrum NRW (2011)

The dummy variables capturing possible effects of project announcement and construction base on the date of the wind farm project announcement (June 2000) and date of the wind farm construction (August 2002), respectively.

Substantial aural impacts of wind turbines that result in an increase of the dB-level above the average ambient noise level in urban or semi-urban regions[26] are only measureable within the immediate vicinity of a turbine of about 350 m (Hau, 2006; Rogers et al., 2006; Harrison,

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consists of about 120 million data points. For reasons of data operability, the multipoint surface information was converted into a surface raster. Raster data on surface information correspond to a surface as a grid of equally sized cells that comprise the attribute values for representing the x and y coordinates and the z-value. We are aware of the suggested potential inaccuracies using predicted viewshed pointed out in the GIS literature (Maloy and Dean, 2001; Riggs and Dean, 2007). There is a tradeoff regarding the effort of conducting systematic field visits for a whole region, which would guarantee an accurate definition of visibility, and the use of GIS techniques, which, dependent on the data resolution, might produce inaccuracies. However, we do believe that in our case a sufficient degree of accuracy of the viewshed calculations is ensured, given the precision of the obtained digital surface model. The digital surface model used recorded elevations every single meter and is, therefore, more precise compared to the digital terrain models investigated and reviewed in the GIS literature mentioned before.

[24] The Geodatenzentrum NRW provides geodata on the basis of the ordnance survey. Available online at www. geodatenzentrum.nrw.de/ (accessed November 2, 2011).

[25] The visibility analysis only included properties that were sold after the construction of the wind farm.

[26] The average noise level in urban areas is 55 dB during the day and 40 dB at night, respectively. In semi-urban or rural areas these values range between 50 dB during daytime and 35 dB at night, respectively (Hau, 2006).

2011). As in our case the shortest distance to a property is 945 m, aural impacts are not considered.

The structural variables, such as the sales price, the lot size, and the four types of development statuses of the properties, were directly taken from the property sales dataset provided by the Expert Advisory Board. We investigated the impact of different development statuses, compared to an undeveloped, untilled parcel. The waterfront variable was derived using data services of the Topographic Information Management of the federal state of NRW (Topographisches Informationsmanagement NRW).[27] Most importantly, we expect a highly positive relationship between the property price and the lot size.

The spatial variables characterizing the neighborhood for each property also predominately contain Euclidean (inverse) distance measures to the amenities and disamenities in the surrounding area, e.g. shopping opportunities or proximity to the road network. Data on the neighborhood features and their location was obtained from statistical offices on the state, district, and city level.[28] Commonly used data on neighborhood variables, such as crime rates, unemployment or income distribution was only available at the city district level or even city level. As these variables only vary over time and the four different city districts (or two cities), effects are implicitly captured by the spatial fixed effects and time dummies.

IV. RESULTS

In this section, we firstly discuss the results obtained from the different spatial fixed effects model specifications, focusing on the wind-farm-related variables. Secondly, we further investigate wind farm proximity and visibility in a GWR model.

Spatial fixed effects

Table 4 provides an overview of the estimation results obtained from applying different spatial fixed effects specifications.

According to the overall model performance, we find that all four spatial fixed effects specifications perform very well with regard to the adjusted R^2 obtained.[29] The specification with the tightest controls for spatially clustered omitted variables, the fixed cadastral district specification, performs best. Overall, we obtained mostly consistent results across all specifications regarding the expected signs.

We use a stepwise procedure of introducing the wind-farm-related variables in order to prevent multicollinearity, particularly in the case of the different distance measures.

[27] Available online at http://www.tim-online.nrw.de/tim-online/nutzung/index.html (accessed February 2, 2012).

[28] The data was obtained upon request from the federal statistical office of NRW, the federal district administration of Steinfurt and the city administrations of Rheine and Neuenkirchen.

[29] We tested for autocorrelation, multicollinearity and heteroskedasticity by applying the Durbin-Watson test, variance inflation factor (VIF) and the White test, respectively.

TABLE 4

Estimation results for the different spatial fixed effects specifications

Variable ‡	Fixed city effects Coef (SE)		Fixed city district effects Coef (SE)		Fixed cadastral district effects Coef (SE)		Fixed viewshed effects Coef (SE)	
ln *Inverse wind farm distance*	-.067***	(.024)	-.053**	(.043)	-.047**	(.022)	-.098***	(.042)
Distance 0.5 - 1 km	-.287**	(.139)	-.215*	(.152)	-.297**	(.148)	-.286*	(.303)
Distance 1 - 1.5 km	-.153*	(.101)	-.079	(.105)	-.175*	(.102)	-.180	(.291)
Distance 1.5 - 2 km	-.107	(.111)	-.044	(.141)	-.115	(.131)	-.108	(.290)
Distance 2 - 2.5 km	-.080	(.091)	-.118	(.106)	-.116	(.072)	.031	(.285)
Distance 2.5 - 3 km	-.178	(.216)	-.218	(.199)	-.300	(.199)	-.110	(.370)
Distance 3 - 3.5 km	-.176	(.123)	-.194*	(.109)	-.195	(.133)	-.128	(.290)
Distance 3.5 - 4 km	-.114	(.109)	-.139	(.107)	-.155	(.147)	-.098	(.273)
Distance 4 - 4.5 km	.011	(.115)	-.000	(.115)	-.142	(.124)	.035	(.321)
Distance 4.5 - 5 km	.009	(.114)	.006	(.123)	-.108	(.143)	.051	(.308)
Shadow flickering	-.091**	(.043)	-.022	(.054)	-.058	(.047)	-.157***	(.039)
Shadow flickering (no. of turbines)	-.034**	(.016)	-.001	(.019)	-.023	(.017)	-.054***	(.014)
Announcement effect	-.032	(.103)	-.039	(.087)	.044	(.097)	-.077*	(.042)
Construction effect	-.102	(.068)	-.108***	(.039)	-.119*	(.068)	-.028	(.039)
ln *Lotsize*	1.069***	(.037)	1.069***	(.033)	1.082***	(.030)	1.063***	(.027)
Waterfront	.076	(.280)	.005	(.286)	.026	(.313)	.051	(.341)
Type single-family house	.183***	(.054)	.175***	(.022)	.138***	(.068)	.180***	(.079)
Type duplex house	.293***	(.058)	.282***	(.027)	.235***	(.073)	.291***	(.082)
Type row house	.270**	(.106)	.241**	(.057)	.164**	(.093)	.222**	(.079)
Type multi-family house	.326***	(.077)	.311***	(.056)	.295***	(.098)	.343***	(.069)
ln *CBD*	.049***	(.036)	.048***	(.043)	.029**	(.030)	.030***	(.023)
ln *Supermarket*	.058***	(.051)	.053***	(.050)	.027	(.057)	.077***	(.042)
ln *Commercial area*	.067***	(.038)	-.035*	(.025)	.017	(.057)	.029*	(.023)
ln *School*	.016	(.025)	.024	(.030)	-.019	(.038)	-.004	(.035)
ln *Forestland*	-.021**	(.020)	-.022**	(.032)	-.019	(.032)	-.014	(.022)
ln *Major road*	-.026**	(.027)	-.024**	(.025)	-.031**	(.030)	.005	(.010)
ln *Road*	.099***	(.048)	.102***	(.038)	.090***	(.040)	.109**	(.048)
Street noise	-.022	(.023)	-.031*	(.017)	-.013	(.026)	-.036*	(.022)
ln *Railroads*	-.056***	(.043)	-.029*	(.042)	.007	(.074)	.017	(.024)
ln *Transmission line*	-.014	(.013)	-.001	(.035)	.024	(.085)	.012	(.024)
ln *Lake*	-.023*	(.024)	-.006	(.024)	-.027	(.044)	-.027*	(.025)
(Intercept)	2.891***	(.717)	3.551***	(.991)	2.986**	(1.397)	3.293***	(.779)
Number of observations	1,405		1,405		1,405		1,405	
Adjusted R^2	0.889-0.890		0.890-0.892		0.903-0.904		0.886-0.888	
AIC_c	458.5-469.8		440.3-454.4		311.5-318.5		495.7-517.2	
Time dummies (year and month)	Yes		Yes		Yes		Yes	
Clustered errors	Yes		Yes		Yes		Yes	

*, ** and *** indicates significance at the 10%, 5% and 1% levels, respectively.

‡ Following the regression procedure of Heintzelman and Tuttle (2011), the wind-farm-related variables (ln *Inverse Wind farm distance*, *Shadow flickering*, *Shadow flickering (no. of turbines)*, *Announcement effect* and *Construction effect*) were included individually to the set of structural, neighborhood and spatial variables. The set of the nine distance variables were included jointly. Because of high consistency in the estimates for the structural, neighborhood and spatial variables, we have taken the coefficients from the ln *Inverse Wind farm distance* regression representatively. In the bottom part of the table we present the ranges for the adjusted R^2 and the AIC_c, respectively.

Regarding the wind-farm-related variables, most importantly, the inverse distance to the nearest turbine is negatively significant across all models. Therefore, a 1% increase in the inverse distance (i.e. a decrease of distance to the nearest turbine) decreases the property sales price by -.047% to -.098%.[30] Taking into account the different geographical scales of the fixed effects, tighter controls lead to less significance and lower coefficients, confirming the

[30] For an average property price of about €42,500, the estimated coefficients correspond to a decrease of €19.98 to €41.65 for a 1% decrease of distance to the nearest turbine.

mentioned tradeoff between control for omitted variables and variation. The fixed viewshed effect model yields the highest coefficient (-.098 at the 1% significance level) for the inverse distance variable. Therefore, controlling for visibility effects underlines the importance of proximity measured by simple distance.

Further, investigating the distance to the wind farm site through a set of dummy variables, negative wind farm impacts are mostly detectable in the close vicinity within the first 1.5 km around the site. Hence, within the first kilometer around the wind farm, prices decreased by 21.5% to 29.7% according to the estimations. In case of the fixed cadastral district model, the estimate of -29.7% is even significant at the 5% level. For a distance of 1 km to 1.5 km, the negative impact decreases and is only significant at the 10% level in the case of the fixed city effect and fixed cadastral effect model (-15.3 and -17.5, respectively). The negative impact within 3 and 3.5 km in the fixed city district effects model seems quite ambiguous, but is more or less negligible and significant at the 10% significance level only.[31]

Based on the shadow flickering variables, the estimates hardly allow a clear interpretation. The coefficients of the shadow flickering dummy are quite diverse across the different spatial fixed effects models, ranging from -.022 to -.157. Furthermore, the estimates only became significant in the fixed city effects (at the 5% level) and fixed viewshed effects (at the 1% level) model, respectively. As the measurable effects of shadow flickering are only limited to parts of one city district (St. Arnold) and, therefore, only to a small number of observations, this variable might not be adequate in representing a potential effect caused by shadow flickering. A further explanation, also regarding the highly negative coefficient in the fixed viewshed effects model, might be that, in essence, the shadow flickering dummy is quite similar to a small-scale distance dummy. The same argumentation applies to the second shadow flickering variable.

Regarding a possible effect of announcing the wind farm project, no significance was found in the fixed city effects, fixed city district effects and fixed cadastral district effects model specifications. Despite a small negative effect (-.077%) at the 10% level in the fixed viewshed effects model, the impact of announcing the project remains highly doubtful.

The construction of the wind farm negatively impacted property sales in the two best-performing model specifications overall, with significance levels of 1% (fixed city district effects) and 10% (fixed cadastral effects), respectively. Thus, properties that were sold after the construction of the wind farm showed price decreases between 10.8% and 11.9%. Despite the different significance levels, there is evidence for a negative construction effect, particularly as we used time dummies for years and months to capture annual and seasonal variations.

The other explanatory variables mostly also perform well in the sense of an intuitive interpretation. As expected, the lot size of a property is the most important determinant of its sales price, with estimated coefficients of 1.062 to 1.082. Therefore, a 1% increase in the lot size of a property increases its value by approximately 1%. Positively related to the property prices is also the development status compared to an undeveloped or untilled parcel.

[31] Note that the number of transactions within each distance category varies substantially, particularly regarding the number of transactions after the announcement and construction of the wind farm. In some cases, the distance dummies only contain a very few transactions, therefore, implying a limited interpretability. Table A1 in the Appendix provides an overview over the distance dummies' statistics.

The proximity to the city center (variable ln *CBD*) and to supermarkets is also positively significant across nearly all models. This goes along with the common circumstance that properties in the city center have higher values than properties in remote areas. Furthermore, the proximity to forestland was found to be negatively correlated to property values, with significance at the 5% level in the case of the fixed city effects and fixed city district effects specification. In this case the forestland variable cannot be interpreted as an indicator for an environmental amenity but rather representing less centrality of the location.

Major roads in the close vicinity of properties have significant negative impacts on their values, whereas the proximity to roads is positively significant across all models. While the proximity to a major road implies negative effects of high traffic density (ln *Major road*), the proximity to the cities' road network indicates positive effects, such as a higher degree of accessibility (ln *Road*).

The proximity to railroads, which is also frequently investigated by means of hedonic pricing studies (e.g. Bowes and Ihlanfeldt, 2001; Theebe, 2004), only appeared negatively significant in the fixed city effects and city district effects models (at the 1% and 10% level, respectively). Using fixed cadastral district and fixed viewshed effects, the railroads variable turned out to be insignificant and changed sign as well. In this case, the results obtained barely allow for a clear interpretation.

No statistical evidence was found for the impact of proximity to schools, transmission lines, lakes as well as for higher street noise or the availability of a waterfront.

Geographically weighted regression

In a similar model setup, compared to specifications described in the last subsection, specifically regarding the composition of the included variables, we applied a GWR model to estimate local coefficients and significance levels for the two variables ln *Inverse wind farm distance* and *Visibility (no. of visible turbines)*. The inverse distance to the wind farm is analyzed in a local GWR model in order to reveal a more complex picture of the local variation of the estimates and significance. The information provided by the variable *Visibility (no. of visible turbines)* was used to specify the fixed viewshed effects model in the previous subsection. Therefore, this variable is analyzed in a GWR model in order to assess the local distribution of possible visibility effects and to derive more insights about the predictive performance of a fixed viewshed model. Statistics on the GWR coefficient estimates for both model specifications are provided in the Appendix (Tables A2 and A3).

Both local model specifications performed very well in respect of the given quasi-global adjusted R^2 (.910 for both variables) and AIC_c (308.1 for the distance variable and 312.5 for the visibility variable). Therefore, comparing the model performance of the local GWR and the global spatial fixed effects specifications on the basis of the two indicators, the local model exhibits a similar performance power like the fixed cadastral effects model. Figures 5 and 6 map the local coefficient estimates and significance levels for the investigated variables.

According to Figure 5(a), which provides an overview of GWR model coefficients for ln *Inverse wind farm distance*, we can identify strong spatial variation within the study area. The strongest impacts are located predominantly in Neuenkirchen (city area) and not, as expected, in areas which are in the immediate vicinity of the wind farm site. Now also taking into account the local variation of the significance levels (Figure 5(b)), there is a clear difference between properties located in the west and the east of the study area. In the east of the study area, particularly in Mesum, the inverse distance variable mainly becomes significant only at the 10% level or even not significant at all. On the contrary, properties located in the west, especially in Neuenkirchen (city area) and St. Arnold, are negatively influenced with significance levels at 1% and 5%, respectively. Properties in the immediate vicinity of the wind farm (St. Arnold and Hauenhorst) are also significantly negatively affected (mainly at the 5% level). In the city district Neuenkirchen (city area), we can identify the strongest significance, whereas the significance decreases towards the city center. Overall, the local estimations for the inverse distance to the wind farm provide evidence for a stronger negative impact on the city of Neuenkirchen than on the city of Rheine.

(a)

(b)

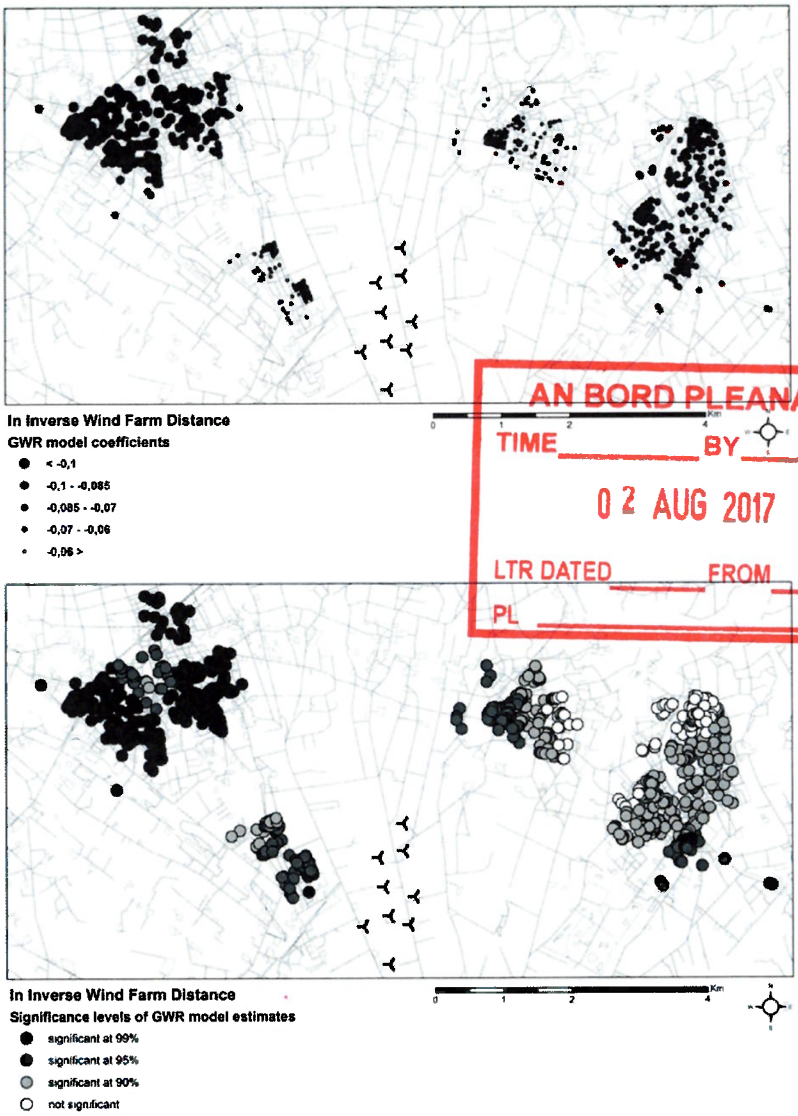

FIGURE 5

GWR model coefficients (a) and significance levels (b) for variable ln *Inverse wind farm distance*

Figure 6(a) maps the GWR model coefficients for the variable *Visibility (no. of visible turbines)*. Thus, negative coefficients are solely located in the immediate vicinity of the wind farm site. As the properties in the close neighborhood to the site likely have an unimpaired view on several turbines, these findings seem reasonable. But considering the local distribution of the significance levels of the visibility variable (Figure 6(b)), no statistical significance of a visibility impact can be detected for the entire study area. Only in the immediate vicinity of the site, significance levels strengthen, but still remain insignificant (with p-values between 0.1 and 0.25). Overall, no statistical evidence was found for the particular consideration of wind farm visibility.

(a)

(b)

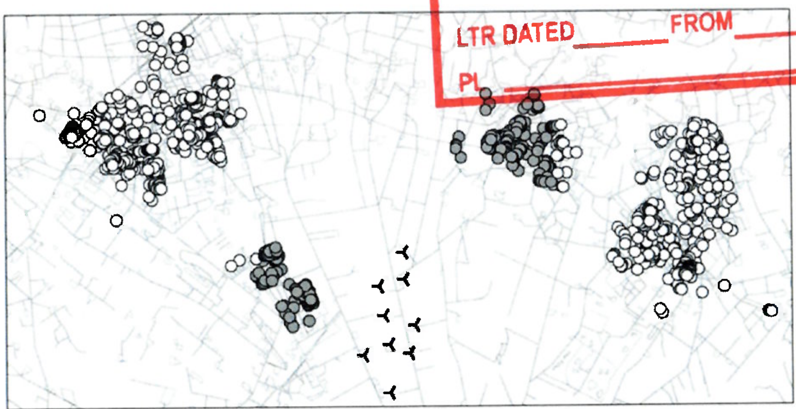

FIGURE 6

GWR model coefficients (a) and significance levels (b) for variable *Visibility (no. of visible turbines)*

In summary, the negative impact of wind farm proximity (measured by the inverse distance to the nearest turbine) that was found in the spatial fixed effects models could be confirmed, investigating the variable using the GWR method. Additionally, we found that proximity effects vary substantially across and within the cities, contrasting the estimated results of the distance dummy variables. The investigation of the local coefficients of the visibility variable revealed that visibility has no significant impact on property values.

Therefore, the results obtained in this case could not provide any validation for the relevance of applying a fixed viewshed effects model specification.

V. CONCLUSIONS

In order to investigate the impacts of wind farms on the surrounding area following the current public debates associated with siting processes in Germany, we applied a hedonic pricing model to the property market of the two neighboring cities Rheine and Neuenkirchen in the northern part of NRW. We investigated wind farm proximity by means of different spatial fixed effects model specifications, addressing spatial autocorrelation through spatially clustered omitted variables and spatial heterogeneity, and a local GWR model in order to further account for spatial heterogeneity caused by spatially varying relationships in the underlying data. As many hedonic pricing analyses investigating wind farm impacts focus on distance measures as a proxy for wind farm proximity, we also included variables capturing potential shadow flickering and visibility effects. We applied GIS techniques on the basis of high resolution geodata for the implementation of these variables.

We used four different spatial fixed effects models accounting for the underlying administrational and spatial structure of the study area, with a particular focus on a fixed viewshed effects model specification. Comparing the models, the specification with the tightest controls for spatially clustered omitted variables performed best.

According to the estimation results provided by the spatial fixed effects regressions, there is statistical evidence for a negative impact of wind farm proximity measured by the inverse distance to the nearest turbine. Various distance dummies also indicated that negative impacts are mainly limited to properties in the immediate vicinity within 1.5 km. Due to lower significance levels of the distance dummy variables, local variations of coefficients and significance levels needed further consideration. Properties that were sold after the construction of the wind farm showed lower values compared to those which were sold before, indicating a negative post-construction effect. Alternatively, the announcement of the wind farm project had no measurable influence on property prices. The results obtained for the shadow flickering variables did not allow for a clear interpretation.

The fixed viewshed effects model provided the lowest values regarding the overall model performance, although the results were largely consistent with the other models. The major insight is that absorbing potential effects of visibility, the inverse distance to the nearest turbine still remains negatively significant.

The application of the GWR revealed a more complex picture of proximity effects through the weighting of spatial relationships and local variations in the data. The negative impact of wind farm proximity that was found using spatial fixed effects could be confirmed applying the GWR method. Based on local GWR estimates, the negative effects are attributable to strong local influences of the wind farm site. Therefore, the local significance levels of wind farm distance provide evidence for a stronger negative impact in the city of Neuenkirchen than in the city of Rheine. Local coefficients and significance levels of the visibility variable revealed that visibility has no significant impact on property values. Therefore, the investigation of visibility by means of a GWR could not provide any validation for the relevance of applying a fixed viewshed effects model specification. Against this background, the results obtained by the fixed viewshed effects model remain ambiguous.

Nonetheless, further investigation of wind farm proximity and specifically visibility, also combining global and local spatial regression techniques, is needed, particularly to derive general conclusions and reliable recommendations with regard to the impact of wind farm siting in Germany. As social acceptance aspects of the siting of energy facilities become more important, especially with regard to the increasing relevance of decentralized energy supply from renewables, research on external effects of these technologies is crucial.

Future research on the impacts of wind farm proximity should essentially include the further investigation of spatial autocorrelation and spatial heterogeneity, also comparing and exploring the performance of different spatial models, such as spatial error and lag models vs. spatial fixed effects, and spatial weighting approaches. Further research incorporating local statistics, such as the GWR, alongside with established spatial models is needed, in order to underline the relevance of geographical techniques in economics.

As local authorities are increasingly aware of social acceptance problems in Germany, projects that involve civic participation in the planning process become increasingly important in order mitigate public protests. Therefore, it might be interesting to comparatively investigate wind farm projects that were planned with and without civic participation by means of the hedonic pricing approach.

Acknowledgements

We would like to thank Franz Hüsken of the "Gutachterausschuss für Grundstückswerte im Kreis Steinfurt" and Wilhelm Kaldemeyer of the Rheine city administration for granting us access to property market data for the cities of Neuenkirchen and Rheine. We are also indebted to Karin Landsberg of the Geodatenzentrum NRW for providing detailed GIS data and maps of the considered study area. Furthermore, we are grateful for helpful comments and suggestions by Ben Hoen, for student research assistance by Patrick Mittendorf, and for research funding provided by the E.ON ERC foundation (gGmbH Project No. 27-10).

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APPENDIX

TABLE A1
Statistics of the wind farm distance dummy variables

Distance dummies	Total number of transactions	Transactions after announcement	Transactions after construction
Distance 0.5 - 1 km	15	15	6
Distance 1 - 1.5 km	77	66	45
Distance 1.5 - 2 km	74	21	16
Distance 2 - 2.5 km	139	108	89
Distance 2.5 - 3 km	74	18	17
Distance 3 - 3.5 km	119	61	56
Distance 3.5 - 4 km	336	152	120
Distance 4 - 4.5 km	275	82	52
Distance 4.5 - 5 km	296	158	132

TABLE A2
Statistics of the GWR model coefficients – ln *Inverse wind farm distance*

	Minimum	25% Quartile	Median	75% Quartile	Maximum
Intercept	2.771	2.881	4.719	5.119	6.009
ln *Inverse Wind farm distance*	-.111	-.094	-.070	-.055	-.047
ln *Lot size*	.919	.948	1.056	1.080	1.087
Waterfront	-.061	.011	.037	.113	.147
Type single-family house	.115	.145	.164	.170	.184
Type duplex house	.200	.231	.260	.271	.282
Type row house	.159	.188	.194	.199	.216
Type multi-family house	.170	.235	.341	.359	.428
ln *CBD*	.001	.006	.032	.065	.082
ln *Supermarket*	-.001	.012	.074	.089	.110
ln *Commercial area*	-.066	-.041	.006	.023	.036
ln *School*	-.013	-.006	-.008	.061	.117
ln *Forestland*	-.069	-.052	-.037	-.006	.012
ln *Major road*	-.040	-.024	-.006	.005	.012
ln *Road*	.031	.042	.076	.088	.103
Street noise	-.139	-.077	-.052	-.042	-.019
ln *Railroads*	-.185	-.055	-.036	.020	.044
ln *Transmission line*	-.050	-.028	.018	.071	.189
ln *Lake*	-.045	-.039	-.012	.004	.022

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Denver 28-30 August 2013

Audible amplitude modulation - results of field measurements and investigations compared to psycho-acoustical assessment and theoretical research

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Summary

In the UK the cause of amplitude modulation (AM) and the ability to predict its occurrence is considered abstruse by many. Few have experienced or measured AM and yet conclusions are frequently made asserting that it is rare and that any action to counter its effects is limited by minimal knowledge surrounding its nature and cause. This paper aims to advance current knowledge and opinion of AM. Methods used to successfully investigate AM are confirmed. AM should be measured during evening (after sunset), night time or early morning periods. Meteorological effects, such as atmospheric stability, which lead to downward refraction resulting from changes in the sound speed gradient alter the character and level of AM measured. AM is generated by all wind turbines including single turbines. Propagation conditions, mostly affected by meteorology, and the occurrence of localised heightened noise zones determine locations that will be affected. Measurements from eleven wind farms have been presented and discussed in relation to current research and theory. Findings confirm that AM occurrence is frequent and can readily be identified in the field by measuring under suitable conditions and using appropriate equipment and settings. Audible features of AM including frequency content and periodicity vary both within and between wind farms. Noise character can differ considerably within a short time period. The constant change in AM character increases attention and cognitive appraisal and reappraisal, inhibiting acclimatisation to the sound. It is advised that those responsible for approving and enforcing wind energy development improve their understanding of the character and impact of AM. This can be achieved by attending a listening room experience which has been trialled and is discussed in this paper.

Introduction

In the UK denial continues that AM is other than rare with reliance placed on a 2007 report prepared for Defra[1] by the University of Salford which found low incidence of

[1] UK Government Department for Environment, Food & Rural Affairs

AM (Moorhouse et al, 2007). Re-analysis of the Salford data confirms many cases were missed (van den Berg, 2009). We and other independent researchers (Hoare, 2009) have also found that the Salford report understated incidence of AM. In the UK we have now identified at least seventy UK wind farms where it is known that AM is the cause of complaints. Many of the wind farms studied in the Salford report were situated in isolated locations with few residential neighbours. Examination of the sites existing in 2007 suggests that many of the wind farms included in the Salford report were unlikely to lead to AM complaints simply due to their isolated locations. As wind farms have spread to more populated parts of the UK, and as turbine hub heights have increased, incidence and complaints of AM have risen.

Few regulators and decision makers visit wind farms under the conditions likely to give rise to enhanced AM, leading to a risk of ill-informed decisions. Other important issues remain in dispute. For example, it has been argued that A weighted variations of less than 3dB are not readily recognised and do not lead to intrusion; something identified as erroneous when observing AM. In an attempt to inform such debates we have trialled a "Listening Room Experience" using data and audio gathered from field measurements[2]. The Listening Room Experience enables lay decision makers to listen to different samples of amplitude modulation varying in character and decibel level. They can then reach independent and informed conclusions regarding audibility and impact of AM. The Listening Room Experience is discussed at the end of this paper.

The following section discusses some of the current research on AM. Section 2 details appropriate procedure to identify and measure AM. Field measurements of AM are presented and discussed in Section 3 with reference to current research. Section 4 explores some psycho-acoustic factors influencing the perception of AM. The Listening Room Experience, a procedure designed to help inform decision makers, is then discussed in Section 5.

Van den Berg's research published in 2005 highlighted the major features and causes of AM. 8 years later, his findings are still either neglected, undervalued or being presented as 'new' information. It appears that the UK is seeking a simple cause and effect relationship between turbine(s) and AM which does not necessarily exist. Indeed the evidence, as discussed below, suggests that all wind development, including single turbines, will generate AM. The exact nature and level of AM that arises, along with the locations where it is prominent, is dependent on a number of contributing site specific meteorological and geographical features.

Van den Berg (2005) recognised the mechanisms generating AM, relating largely to trailing edge noise, and which is generic to all turbines. Van den Berg outlines the following features as generating or contributing to AM: atmospheric stability, near synchronicity, atmospheric absorption increasing prominence of low frequency sound and high turbine noise levels when background noise levels are low. Oerlemans and Schepers (2009) discuss trailing edge noise and swish footprints generated by turbines. They found that under cross wind conditions although the average level is lower, amplitude modulation has a greater peak to trough, up to 5dB, than upwind or downwind directions. Findings were corroborated by measurements at a distance of approximately 240m from a single turbine. Di Napoli (2009) notes the importance of weather conditions for correctly measuring wind turbine noise; measurements were specifically taken during a night time period. Di Napoli measured AM with a peak to

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[2] A number of the sound files referred to in this report and used in the Listening Room Experience are presented on our website with interactive graphs.

trough typically of 5dB and up to 12dB. Greatest peak to trough was attributed to decreases in wind speed and occurring towards the end of accelerations in wind speed and blade rotation speed. AM with a double peak was also found (page 6). The importance of measurement in the correct weather conditions and at the correct time of day is again noted in Di Napoli (2011). This study found that smaller, older turbines generated significant AM. Impact from AM was linked to synchronisation of AM pulses and low wind speeds at the immission point. Broadband noise was not found to decrease over distance as expected and in contrast to Oerlemans and Schepers (2009) least AM was measured under cross wind conditions with downwind samples at far field measurement points resulting in highest measured peak to trough level.

Bakker and Rapley (2011) do not directly discuss AM but discuss the occurrence of heightened noise zones which arise around wind farms. They found that noise levels from a single turbine can vary by 2-5dB and multiple turbines can produce noise levels varying by 6-13dB. It was observed that the specific location of equipment was extremely important as noise could vary significantly over very short distances. Cand et al (2012) conclude on review of literature that potential causes of AM relate to non uniform inlet flow likely caused by wind shear or atmospheric turbulence effects. This is further discussed in Smith et al (2012) and includes detached or stalled flow over the turbine blade as a cause of AM. Following a long term study Larsson and Öhlund (2012) describe the impact of meteorology and ground attenuation effects on AM and note its prominence at greater distances from the turbines. Synchronicity / interference between turbines is again noted as a cause of AM at greater distances. Larsson and Öhlund (2012) observed differences in noise level of 6-14dB. They conclude that AM is observed 30% of the time at 400m, 10% of the time at 1km from the nearest turbine and is most common in the evening, night time and morning (p. 5).

The influence of meteorology in causing AM is attributed less weight by Lee and Lee (2013) although the effect on propagation is noted. The discussion by Lee and Lee (2013) provides further evidence that all turbines will cause AM but states that AM is heard at long distances only in certain directions. This changes as the wind direction changes.

Lee and Lee (2013) found that where 'operating and atmospheric conditions are identical, the acoustical characteristics of wind turbine noise can be quite different with respect to the distance and direction from the wind turbine' (p. EL94). They identified mathematically that AM can be caused by all turbines and that variation in spectral content and sound energy changes with distance and angle to the wind direction. Lee and Lee (2013) did not consider atmospheric refraction the effects of which, as suggested by measurements in the above research, complicate predictions of wind turbine noise and AM. These factors may explain the different conclusions reached by Oerlemans and Schepers (2009) and Di Napoli (2011).

Lee and Lee (2013) also found that 'at long distances from the wind turbine, the amplitude modulation is hardly perceived in the upwind, downwind, and crosswind directions...Nevertheless, even at long distances the amplitude modulation is still audible in other directions provided that the background noise is low. In addition, these sounds are no longer similar to the swishing sound. They are low-frequency amplitude-modulated sounds'(p. EL98)[3]. The differences in findings appear in part

[3] In general this agrees with many of our field measurements but is not always the case.

due to atmospheric refraction and ground effects. For example changes in the wind direction can mean the long distance low frequency AM immission level changes from being generated at the top of the blade rotation to the near ground part of the blade rotation. This shifts the source noise from around 120m to around 35m above ground level for a typical turbine. The effect of atmospheric refraction is considerably different at these heights.

Although the paper by Lee and Lee (2013) discusses some important issues in relation to propagation of AM a major limitation is the neglect of refractive effects. Evidence on atmospheric refraction obtained by Wilson (2003) indicates that when atmospheric conditions lead to downward refraction of sound energy, the decibel level at receptors is greater by at least 3-4dB than when conditions lead to upward refraction. Wilson (2003) also shows that the meteorological changes from upward refraction to downward refraction relate directly to the variation in sound speed with height which in turn is influenced by wind speed gradient (wind shear), temperature gradient, temperature fluctuations and to some extent humidity especially over wet surfaces. Small changes in meteorology are predicted to lead to significant change in noise impact near the ground, reflected in the variations identified in the above research.

In summary the following assertions regarding the cause of AM and exacerbating factors can be made:

- → All turbines, including single turbines can cause AM.
- → Trailing edge is the main source of noise on a turbine causing AM.
- → Meteorology affects propagation of AM.
- → Inflow turbulence caused by meteorological / topographical air turbulence causes / exacerbates AM.
- → Synchronicity / heightened noise zones exacerbate AM at distant locations.
- → AM is found in cross wind and down wind conditions but can also occur at lower sound energy levels upwind.
- → Measurements of AM should target evening, night time and early morning periods when there is low cloud cover / high wind shear.

Measurement of AM

Determining appropriate measurement locations and observation times

It was evident from an early stage of our research that wind turbine noise levels measured at distances of 500m-1500m from the nearest turbine vary not only with meteorological conditions, such as wind direction, but with relatively small changes in location. Locating sound level meters based on daytime observations led to no more than a chance of reflecting impact after darkness. Descriptions by residents may not always be accurate and so visits at night time when there is high wind shear and / or temperature inversion is recommended to experience enhanced propagation conditions.

It is logical and supported by research (van den Berg, 2005) that atmospheric conditions leading to downward refraction of sound energy will result in higher decibel levels at distant receptors than atmospheric conditions leading to upward refraction. It is also clear from research (Wilson, 2003) that the meteorological changes from upward refraction to downward refraction relate directly to the variation in sound speed with height, which in turn is influenced by temperature and other small changes in meteorology.

In their long term study Larsson and Öhlund (2012) found variations in measured wind turbine noise at 1km of 6-14dB(A). At 400m there was difficulty separating meteorological effects from wind direction. They state that 'meteorological conditions must be taken into consideration starting at distances somewhere between 400 and 1000 m ... the enhanced AM sound is influenced by the propagation path or the interference between several wind turbines rather than changes in the emitted sound' (p.4). Larsson and Öhlund (2012) conclude that 'the occurrence of AM sound increases during evening, night and morning and then decreases during the day. This pattern follows perfectly how the temperature inversion is built up during the evening and nights and breaks up from ground when the rising sun heats the ground' (p.5)[4].

We have found variation of AM at night both temporally and in different locations, sometimes only a few metres apart. This agrees with Bakker and Rapley (2011) who identified heightened noise zones. In some cases the variation between locations is significant and in others impact is more widespread. There is a need to visit affected properties under worst case impact, often between 00:00 and 04:00 hours to identify specific locations to site instruments. Alternatively, where a resident has cogently identified affected rooms in the dwelling or garden area these may be representative; however, care is needed that the conditions monitored reflect those leading to observations by residents. There is no substitute to visiting at the times of impact.

It is important to observe and set up instrumentation when conditions lead to downward refraction of sound energy and when background noise levels are low. These conditions most often occur when there is a stable atmospheric state leading to low wind speeds near the ground. Best results have been obtained with hub height wind speeds at or above those providing maximum noise output. This requires sufficient atmospheric pressure variation (closeness of isobars). As a 'rule of thumb' if it is windy and gusting on a sunny / low cloud level day and this continues at night then significant AM can be expected. Ideally, for measurement of typical worst case noise, more distant receiver locations[5] should fall approximately within a 60 degree arc, assuming clockwise rotation of the turbines, although this will vary depending on the configuration of the turbines, topography and meteorology.

It is important to move to different localities to observe how the impact changes throughout the night, from location to location and with increasing wind shear.

Measurement parameters

Low interference from the sound level meter floor, especially when undertaking internal measurements, is critical to obtaining good data. This is best achieved using a low noise floor microphone, typically below 10dB(A). A type 1 sound level meter measuring LAeq, 1/3rd octave band Leq and measuring at least 125ms intervals,

[4] These findings concur with our own field measurements which we have conducted over the last 7 years.

[5] Those in excess of 500m.

preferably every 100ms[6], is needed. We now measure down to 0.4Hz to enable analysis of infrasound but this is a separate consideration beyond the scope of this paper. Measurements are best synchronised with good quality audio recordings ideally at 24 bit rate and 48kHz sampling rate; however, 16 bit rate may suffice. Some experimentation is often required to avoid "clipping" of the sound recordings and loss of reproducibility.

Where good quality audio recordings are obtained these can be processed using appropriate software[7] to confirm reproduction at the relevant sound levels observed in the field and for representative playback.

In our experience regulators measuring AM noise will place a sound level meter within a dwelling with a hand operated trigger for residents to record AM when it occurs. They rarely use high quality audio and do not normally possess low noise floor microphones. This results in poor quality sound reproduction where the troughs of sound energy are lost and many characteristics of the AM are masked by interference with the noise floor. Regulators often do not record data with a sufficient time interval to see temporal effects. Any spectral information, if recorded, is usually corrupted because of the noise floor of the meter. Remote data analysis undertaken by regulators can fail to identify the psycho-acoustic character of the noise. Through use of inadequate measurement parameters, compliance checks frequently understate the impact of AM and wind farm noise leading to erroneous findings.

Findings in relation to field measurements

The following charts represent a small sample of the data measured from a number of wind energy developments in and around the UK. The findings presented below aim to provoke discussion on the various causes of AM and raise important issues regarding psycho-acoustic aspects of AM perception. Measurements are presented in chronological order. In the UK wind farm noise is generally assessed external to the affected property. The majority of measurements below were recorded externally; where measurements are made within the dwelling an internal noise measurement has been noted.

Deeping St Nicholas, Lincolnshire, England

Deeping St. Nicholas Wind Farm is located within the flat fenland area of eastern England. The data shown on the chart below was measured internally, with a window partly open and just over 1000m from the nearest turbine. The wind direction placed the downwind angle for the measurements at just over 30 degrees (clockwise). This concurs with a prediction of low frequency dominance as identified by Lee and Lee (2013).

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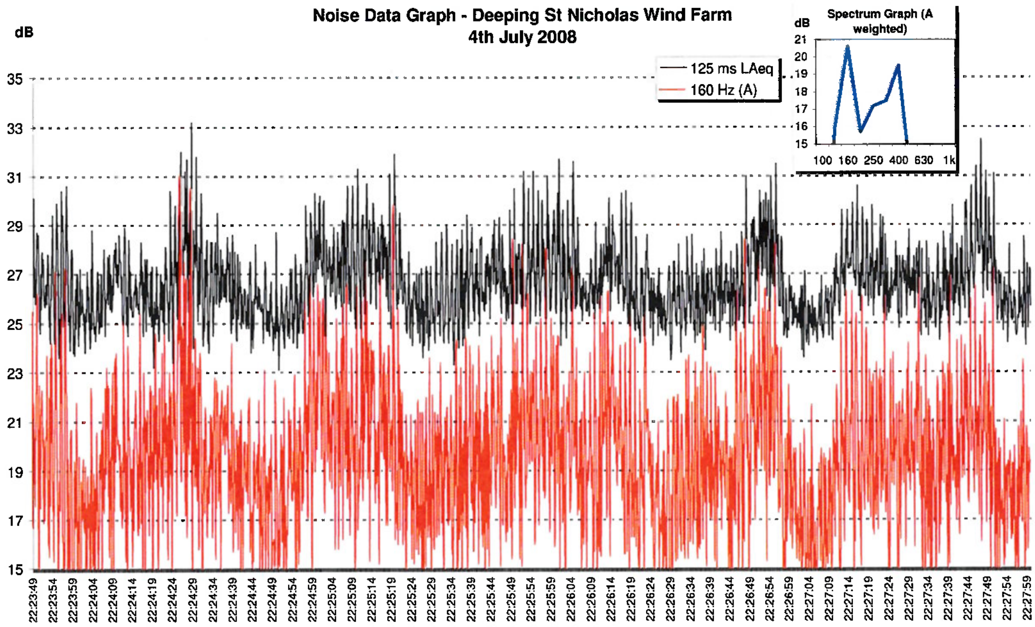
[6] We have found no benefits using shorter time periods than 100ms and the large data handling requirement becomes an impediment.

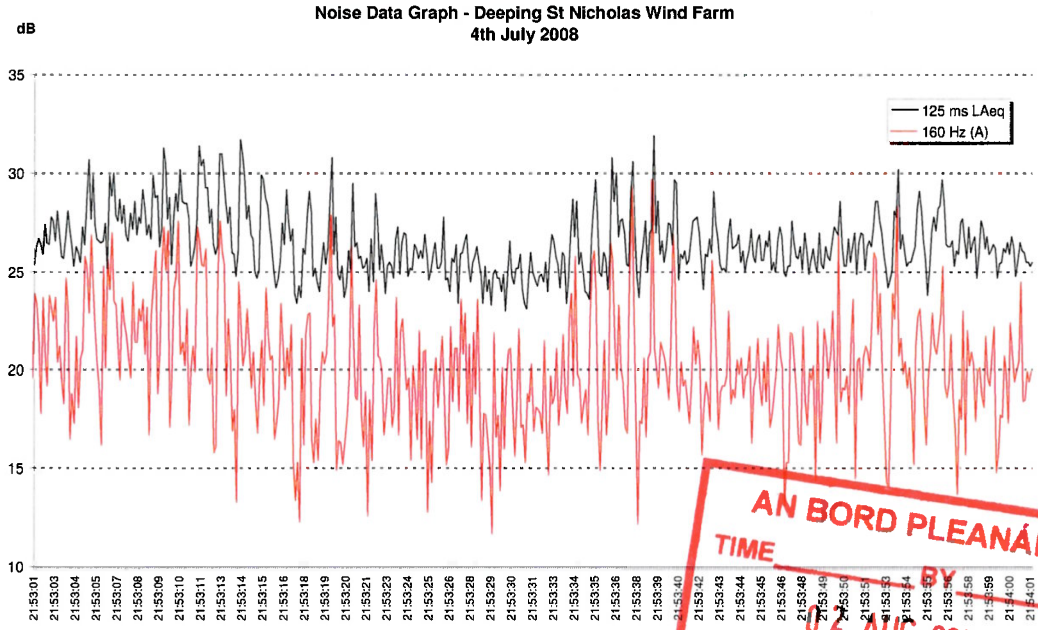
[7] For example, Spectral Plus.

As can be seen from the spectrum graph in the top right hand corner, sound energy is focused between the 125Hz and 400Hz third octave bands. The 160Hz third octave band is dominant. The A weighted AM peak to trough was typically 6dB, although modulation in the 160Hz third octave band is considerably greater. Background noise levels measured in the bedroom were below the noise floor of the meter (18dB(A)). From experience background noise levels are likely to be in the region of 12-15dB(A). All data is A weighted to allow direct comparison.



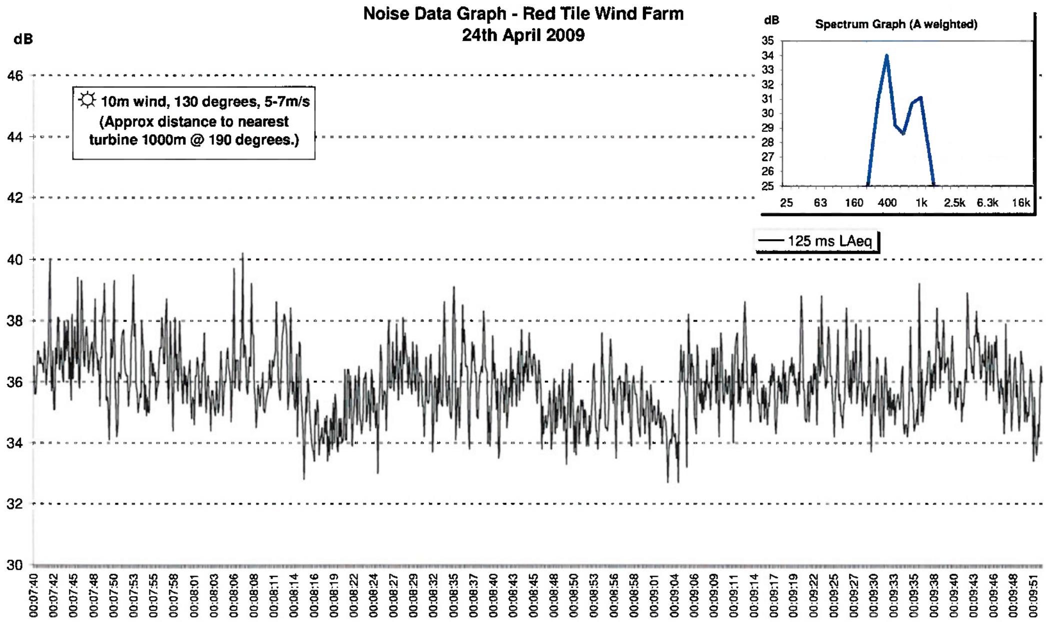
Analysis of the data from this site, as with other sites, reveals a time shift in the spectrum data. Sound energy within different third octave bands arrives at the microphone successively a fraction of a second apart. As a consequence the overall A weighted level does not fluctuate peak to trough to the same extent as the individual third octave bands fluctuate. This masks the true effects of varying sound energy in different frequency bands and supports the approach in the New Zealand Wind Farm Noise Standard (2010) and the DTI report on the measurement of low frequency noise at three UK wind farms (Hayes McKenzie Partnership Ltd, 2006) both of which look separately at observing the varying third octave band levels as well as the fluctuation in the A weighted AM. The above data also agrees with predictions by Larsson and Öhlund (2012) and Lee and Lee (2013) of greater low frequency dominance in the immission levels at increasing distance from the wind farm.

The chart below was obtained earlier the same evening and shows the extent of the third octave band fluctuations in the 160Hz third octave band. Peak to trough variations are in the region of 9-17dB. Some of the A weighted Leq peaks can be seen to be dominated by this low frequency fluctuation.



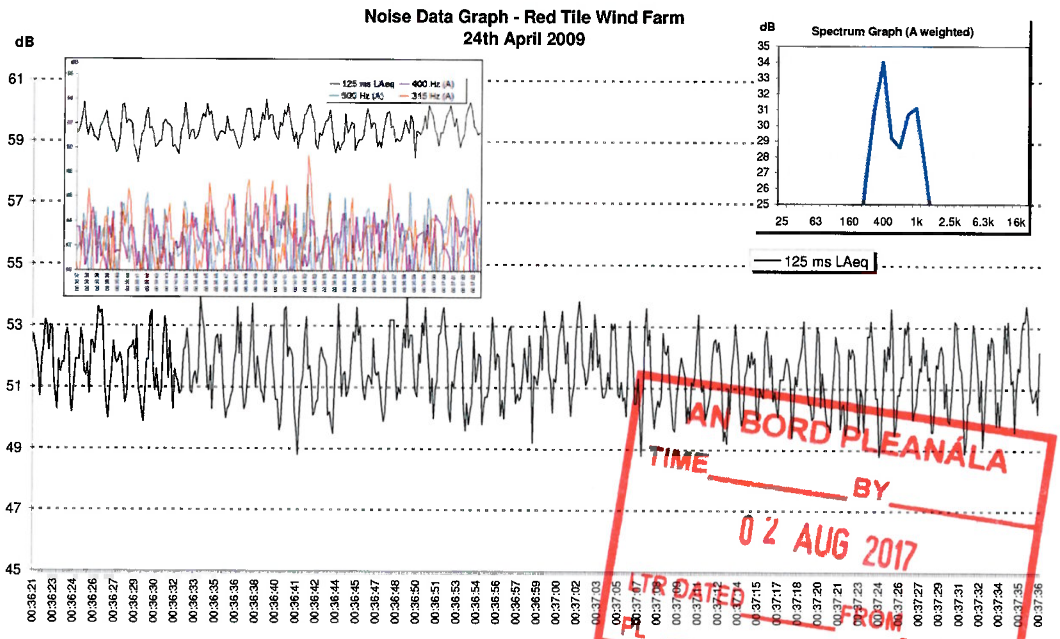
Red Tile Wind Farm, Cambridgeshire, England

Red Tile Wind Farm is located on a flat site in eastern England. Measurements were made approximately 1000m from the wind farm.



The example AM trace shown here is erratic both in peak level and shape. AM peak to trough is typically 4-5dB. Sound energy is focused in the 400Hz third octave band with some contribution from the 1kHz third octave band. This frequency content is of slightly higher frequency content than has been observed in AM measured at other wind energy developments. Although measurements were taken at a similar distance to those shown for Deeping St Nicholas Wind Farm, slightly higher frequency content is expected due to cross wind measurement conditions.

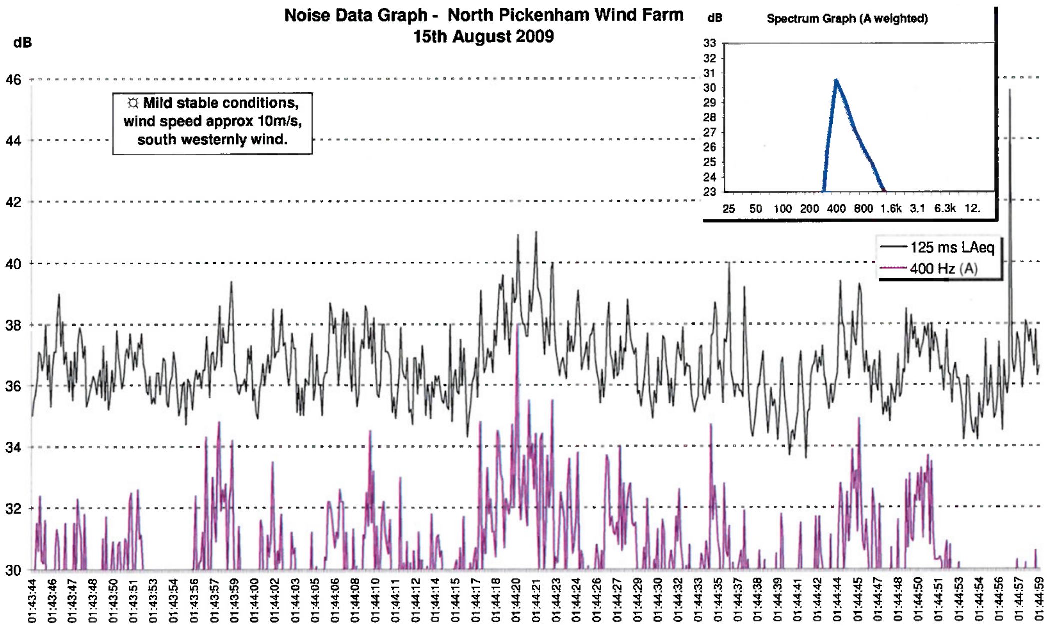
The AM in the chart below was measured slightly later in the night than the chart above and closer to the turbines. The AM is now less erratic in peak range and level.



Although the AM peak often consists of two or multiple peaks, it is constant in this character and peak to trough difference is consistently in the region of 3-4dB. Average sound energy spectral content is shown, in the top right hand graph, to be dominated by 400Hz third octave band energy; however, the top left hand graph, showing the third octave band 125ms time trace, reveals that most peaks are dominated by energy in the 315Hz or 500Hz third octave band. There is rarely any synchronisation in third octave bands and the phasing is consistently different, reflected in the multiple peak character of the AM. The AM has a sweeping tonal characteristic, which is most likely generated by the non simultaneous contribution of different third octave band sound energy to the AM peaks over time.

North Pickenham Wind Farm, Norfolk, England

AM measured from this site, approximately 1000m from the nearest turbines, is fairly erratic. The chart below shows approximately 1 minute of AM with peak to trough values typically of 4dB. The spectral content of the period is dominated by 400Hz third octave band noise. Closer inspection of the 125ms 400Hz third octave band time trace, plotted on the chart, suggests that this band does not dictate the AM peaks to the same extent as has been found at other sites. Although much of the measured noise is more broadband in nature and could be interpreted as more typical of general wind farm noise there are still lower frequency thump elements that can be heard within the data but not easily attributed to specific frequency content.

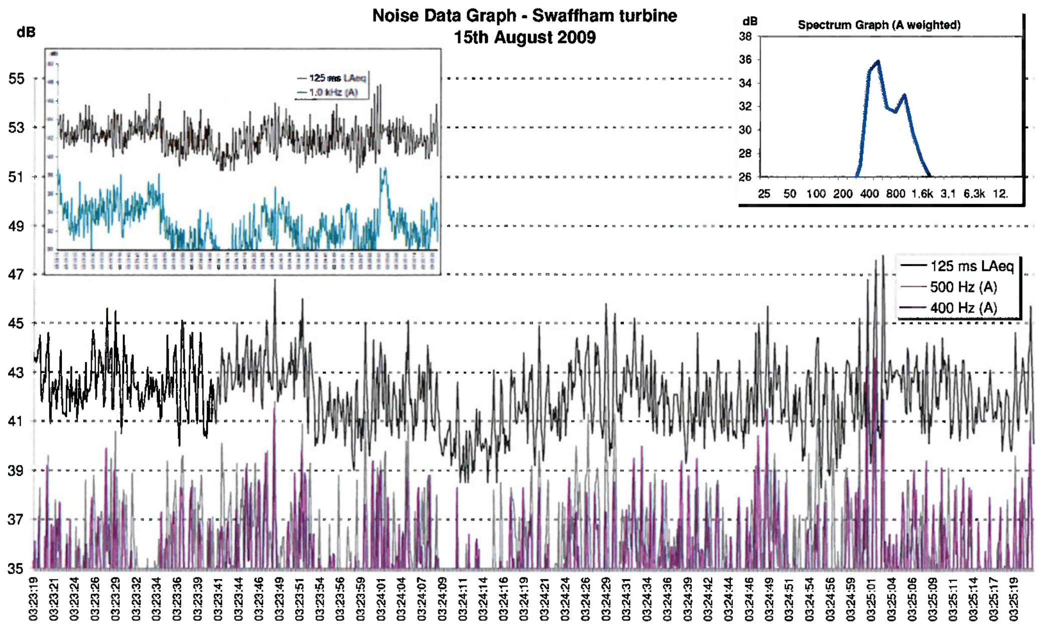


The measurement location was at varying angles to the turbines due to their geographical spread. This may be the cause of the less distinct peak to trough variations in both the A weighted 125ms trace and the individual third octave band levels. However, peak to trough variations in the 125Hz third octave band were in the region of 8-10dB. This could explain the perceived intrusion from low frequency content although it is not indicated by an A weighted analysis as dominant.

Swaffham Wind Turbine, Norfolk, England

Measurements from this single turbine were taken at a distance of approximately 320m, closer than the majority of measurements presented. The measurements were taken on the same night as those at North Pickenham Wind Farm.

AM peaks are much clearer from this single turbine compared to the multiple peak trace measured at Red Tile Wind Farm and North Pickenham Wind Farm. Dominant frequencies within the 400Hz and 500Hz third octave bands can be seen to clearly dictate specific AM peaks. AM peak to trough values were typically 4dB although differences of up to 6dB were measured.

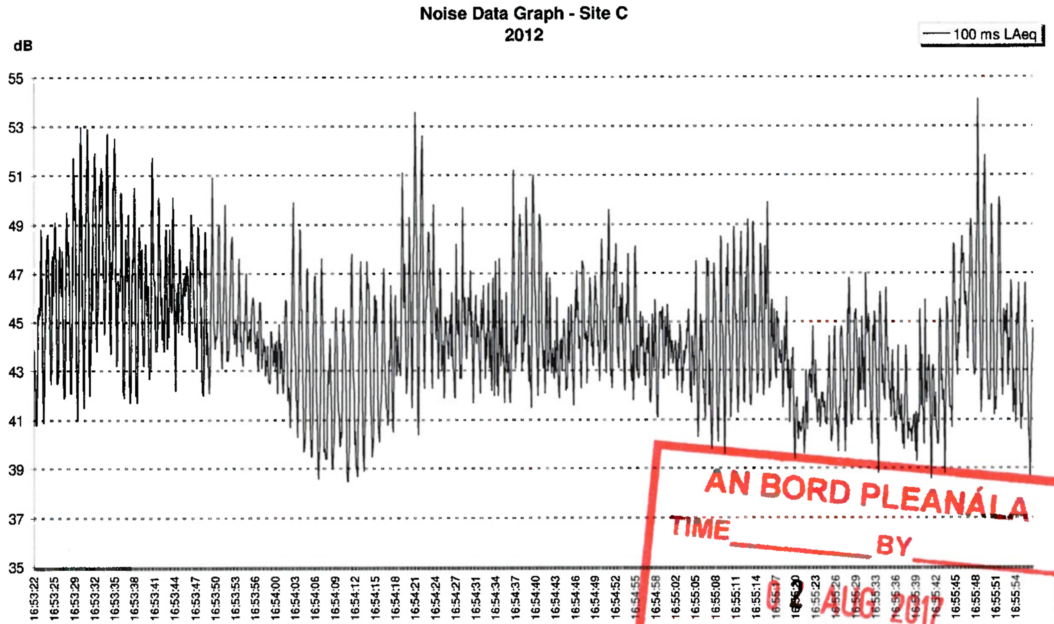


Although a peak in the spectrum graph for the period is observed in the 1kHz third octave band, see top right hand side of the above chart, it is not a major contributor to the AM. The main chart shows energy in the 400Hz and 500Hz third octave bands mapping well with the 125ms LAeq peaks. The graph on the top left hand side of the above chart shows the same period with the 1kHz 125ms third octave band time trace added. The 1kHz third octave band energy follows the main shape of the 125ms LAeq trace but does not modulate to the same extent as the 400Hz and 500Hz energy, shown in the main graph, and does not contribute significantly to AM peaks.

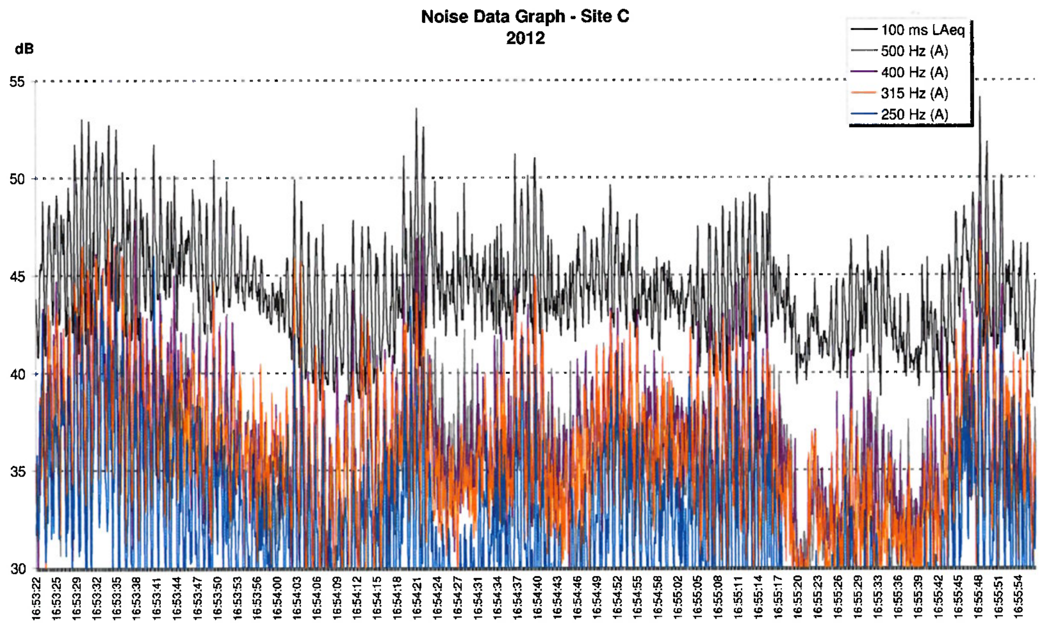
Site C, D & E

These locations remain anonymous at this stage at the request of the affected parties. The measurements were made in three different external amenity areas located in a remote rural area. AM occurs frequently at the sites. The three extracts below were measured on three separate occasions in 2012.

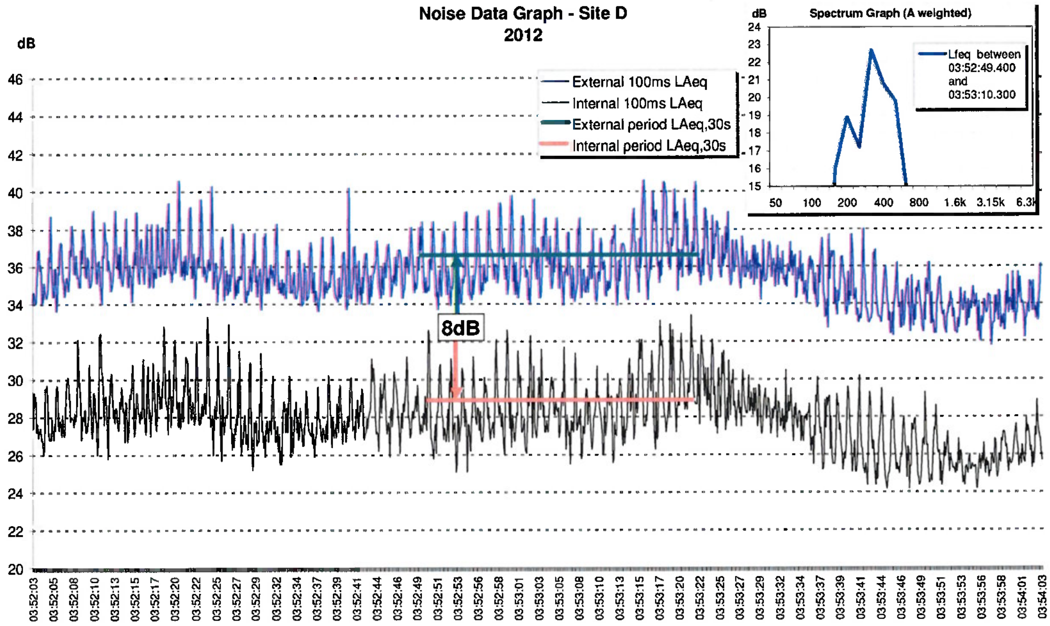
Site C is 450m from 3 turbines with AM measured in a cross wind situation. The wind turbine noise is dominating and at least 10dB above the background noise level. In contrast to other cases, significant AM was measured from this wind farm during daytime hours. AM peak to trough is regularly 8-10dB.



Peaks are determined by different frequency bands; generally noise in the 315Hz third octave band is dominant with contribution also from energy in the 500Hz, 400Hz and 250Hz third octave bands. These variations were judged to arise due to the variation in contribution from different turbines and varying degrees of synchronicity.



At site D internal (with the window partly open) and external measurements, in the garden area, were obtained and are compared in the chart below. Site D is approximately 1000m from nine turbines with several turbines almost equidistant from the residence. The wind direction during measurements resulted in the property being between a cross wind and downwind direction from the turbines.

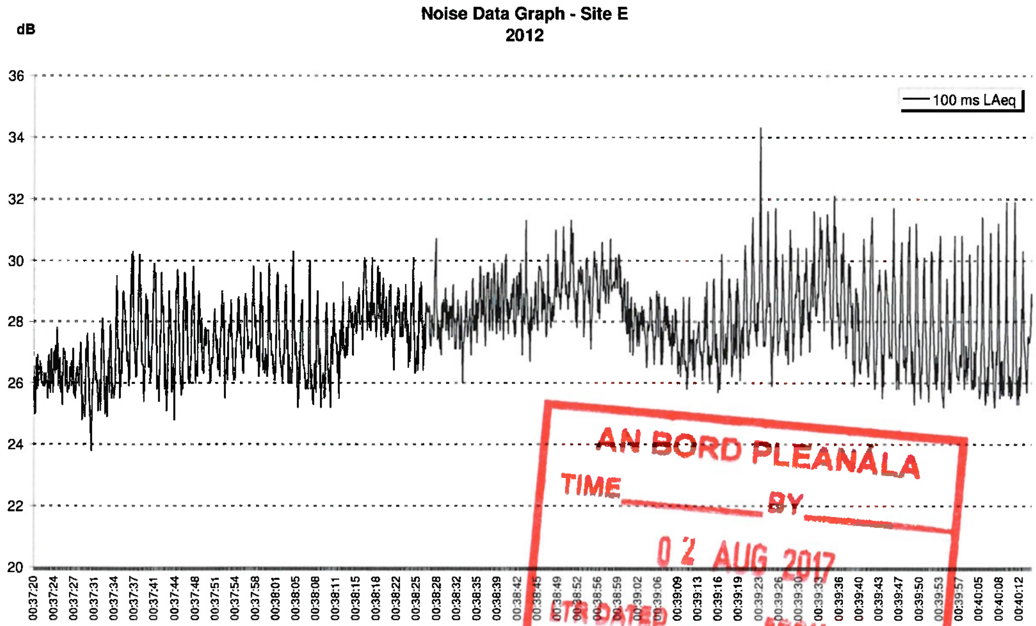


With the window partially open, reduction in noise level was approximately 8dB. Peak to trough levels externally were generally 4-6dB. Internally the peak to trough difference was approximately 1dB greater. The internal spectrum graph is shown in the top right hand corner of the chart above[8]. The 315Hz third octave band energy is dominant with significant contribution from 400Hz and 200Hz third octave band noise. Whilst the sound energy levels and peak to trough range varied slightly, prolonged periods of impact arose with little variation in the peak to trough range. The data indicated a high level of synchronicity.

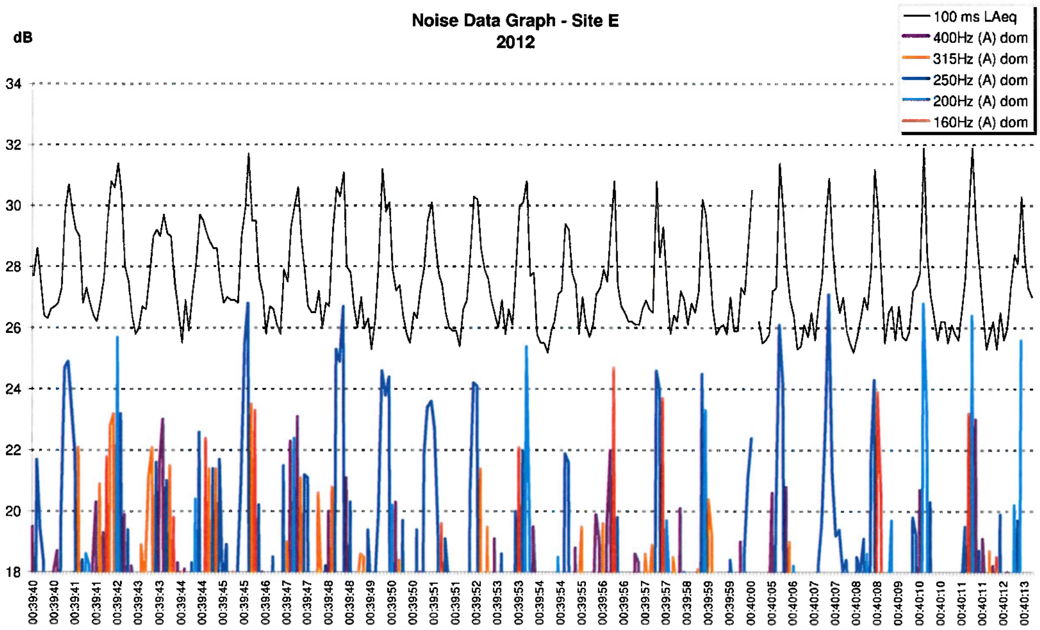
Site E is approximately 1000m from the wind farm. Measurements were made downwind of the turbines. On this occasion dominant lower frequency noise was measured internally.

[8] External spectral data was not recorded.

The chart below shows the noise trace, indicating a peak to trough range of 4-6dB. The chart shows intermittency with periods of greater peak to trough variation lasting for a few seconds and periods of diminished AM. This was found to be a common pattern observed in the measurements at this location.



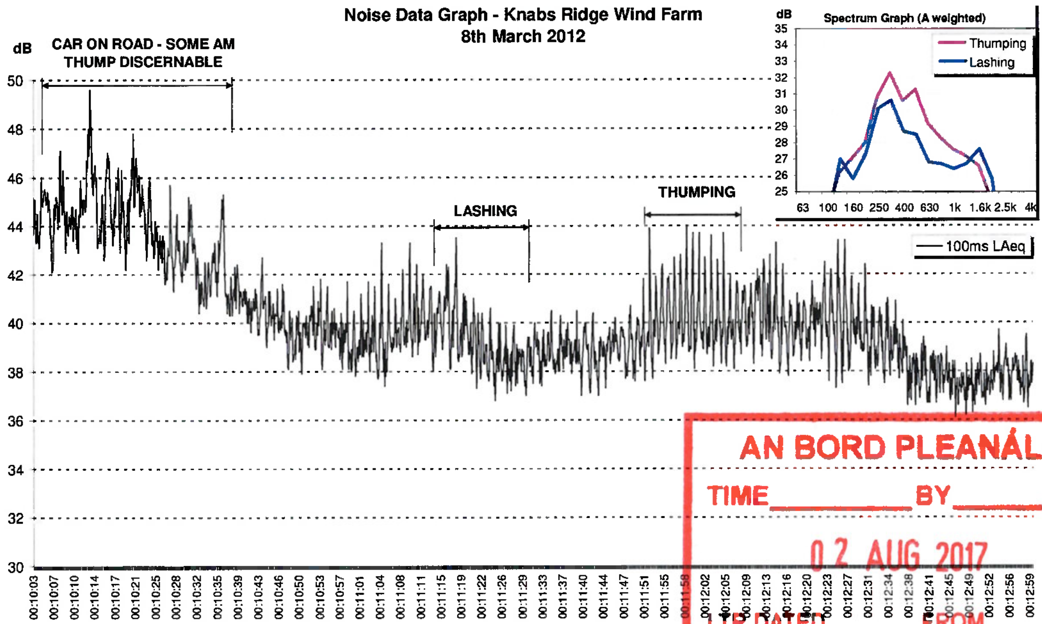
Analysis of the last 30s of the above period, shown on the chart below, demonstrates the changing dominance of low frequency noise.



The 100ms LAeq trace is shown with corresponding spectral analysis. Most AM energy was found between the 160Hz and 400Hz third octave bands. To assess the dominance of each third octave band in each AM peak, for each 100ms sample only the third octave band with the highest decibel contribution is plotted. Thus, the chart shows the most dominant third octave band at a given point in time. The last three peaks of the extract can be seen to be dominated by 200Hz third octave band noise, the fourth peak from the end is equally dominated by 250Hz and 160Hz third octave band noise and the fifth and sixth peaks from the end of the period are dominated by 250Hz third octave band noise. Not only does the variation in the peak to trough difference change but there is also a noticeable change in the character of the sound energy of the peaks; this was considered to exacerbate the effect on listeners.

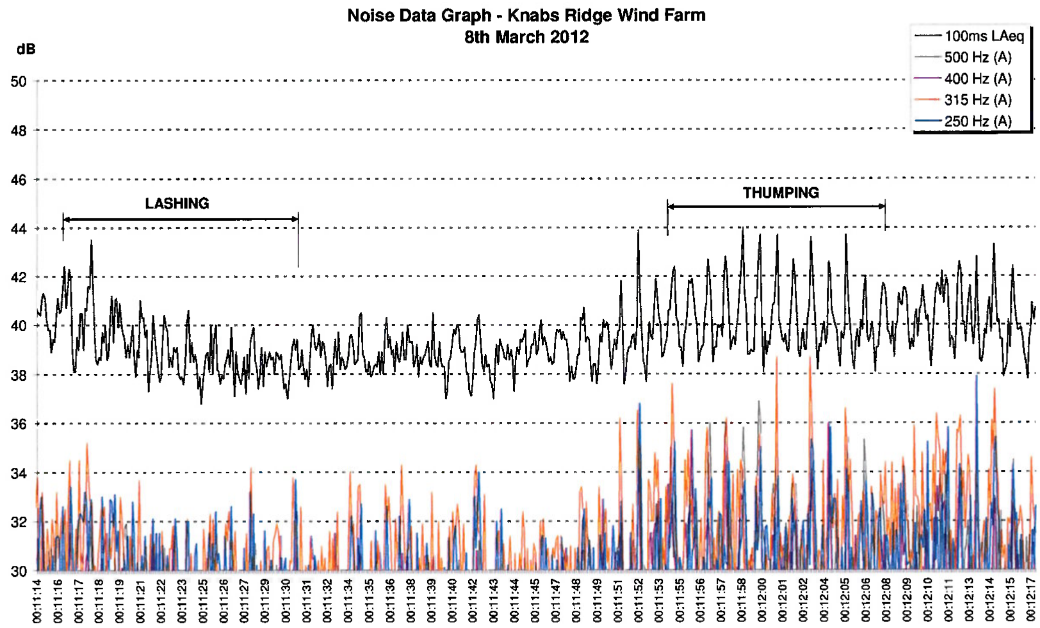
Knabs Ridge Wind Farm, North Yorkshire, England

AM from Knabs Ridge wind farm was measured on a nearby caravan site approximately 550m from the nearest turbine. At the beginning of the chart below a car passes on a nearby road. Noise from the car pass-by does not audibly mask the AM noise although it interferes with the noise trace. Two distinct types of AM can be heard and seen in this period, described as 'lashing' and 'thumping'.



The thumping AM has a clear single peak with energy focused in the 315Hz third octave band. Whereas the lashing AM sounds more high frequency dominated, there is a 125Hz third octave band component to the noise along with the main 315Hz third octave band energy and some higher frequency energy around the 1.6kHz third octave band. See the top right hand graph in the chart above.

The chart below shows that the lashing AM consists of poorly aligned peaks from several third octave bands. The thumping AM is dominated by 315Hz and 250Hz third octave band energy that is often synchronised. These characteristics are lost when examining the average spectrum graph for the period and demonstrates the need to look at the spectrum during each peak.

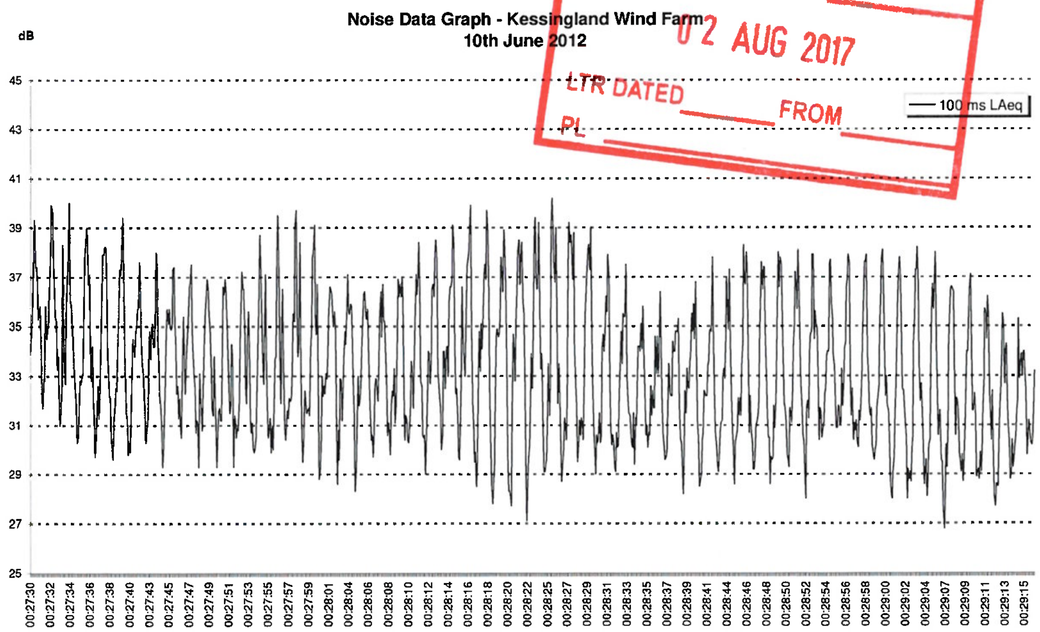


During much of the period shown on the chart above the peak to trough level is around 3dB or less, but is audibly judged as similarly intrusive to AM with higher peak to trough due to its spectral content and the manner in which it changes. In the 2006 DTI report peak to trough ranges of 2-6dB were identified as unacceptable and considered by the author as warranting a penalty[9].

Kessingland Wind Farm, Suffolk, England

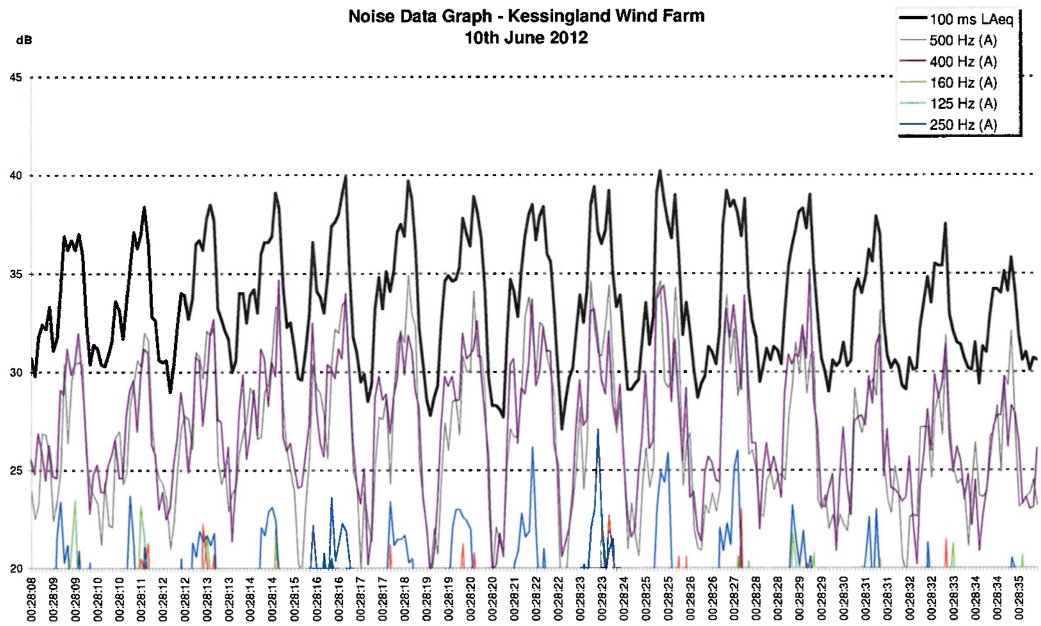
Located close to the eastern coast of the UK, AM from the two turbines at Kessingland is frequent in occurrence. The majority of the local community have been complaining and campaigning for the turbines to be turned off. Despite noise monitoring exercises being undertaken the noise issues have not yet been resolved. We have measured AM from the two Kessingland turbines on three different occasions. Whilst AM is fairly consistently present when the turbines are operating at night time, there are different features to the noise at different times. The chart below shows a period of approximately 2 minutes measured on 10th June 2012 at a distance of 550m from the nearest turbine. The typical peak to trough range is 8-10dB.

[9] The DTI report and Freedom of Information releases on the report confirm this.

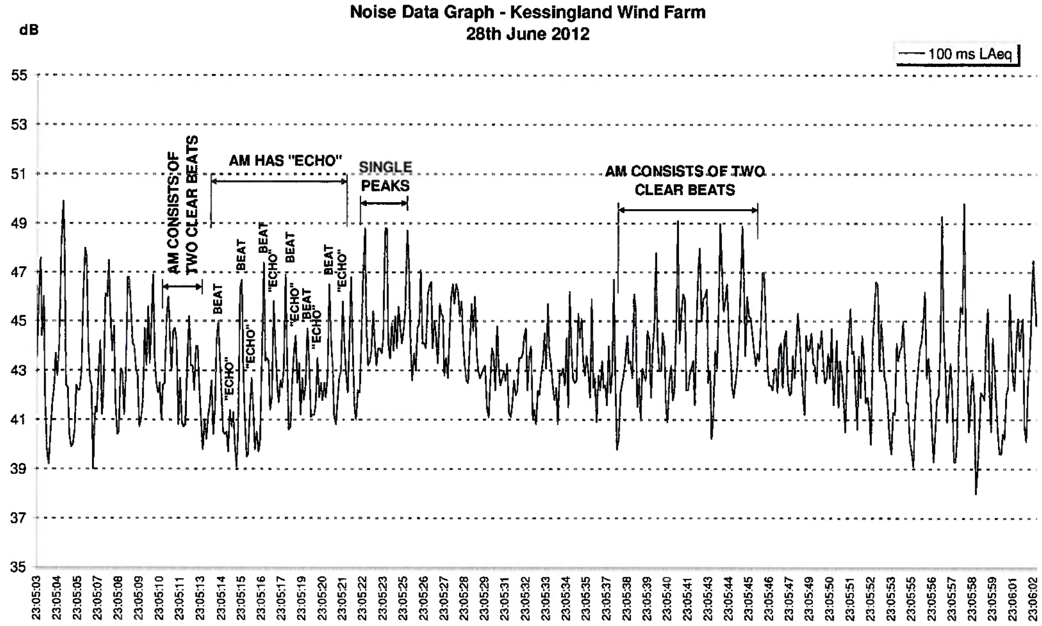


The chart above appears to show mainly one recurrent peak of noise and although audibly it is initially heard as one sound, two characteristics, a pulse and a 'swish', within the peak can be heard.

The chart below shows a sample from the middle of the above period. The expanded 100ms LAeq now demonstrates that the AM peak is in fact a double peak. The main component frequencies are within the 400Hz and 500Hz third octave bands. Lower frequency contribution is also present occasionally within the 250Hz third octave band and minimally in the 125Hz and 160Hz third octave bands. Energy within the 250Hz octave bands can be seen to contribute more within the middle of the period.



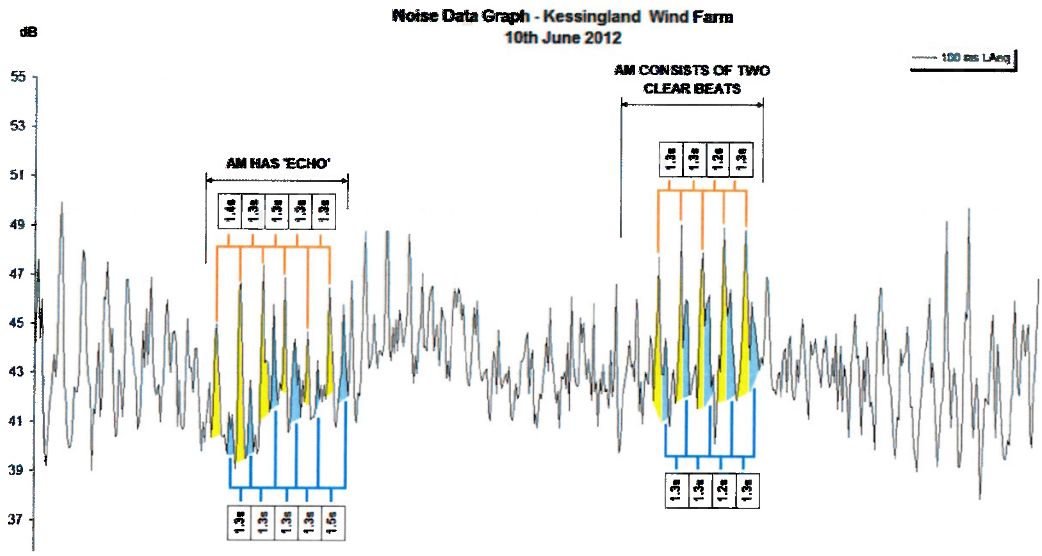
Measurements at Kessingland obtained on the 28th June 2012 were more varying in level and nature than those obtained on 10th June 2012. The chart below shows an AM trace lasting approximately 1 minute. Within this period the AM can be heard as one distinct and strong peak, a peak consisting of two beats and a beat and "echo" effect. The "echo" is not a reflection but an AM peak at a lower level[10].



As with the measurements on 10th June, the main component frequencies are within the 400Hz and 500Hz third octave bands, although some AM peaks have significant, though not dominant, 200Hz and 250Hz third octave band content which phases in and out. Comparison of the AM beat and echo sequence and the AM period consisting of two clear beats strongly indicates that the "echo" and second peak in the double peak AM have a common source. Similarly, the AM beat, from the beat and echo sequence, and first peak in the double peak AM are also likely to have a common source.

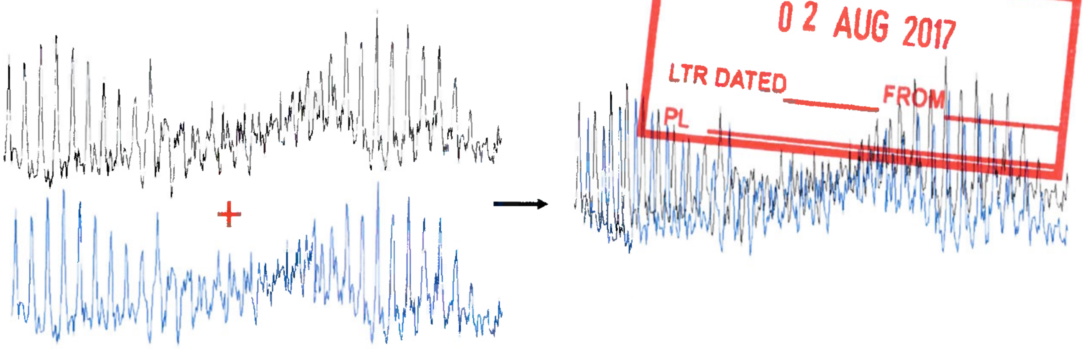
[10] The sequence of a strong pulse followed by a pulse lower in level gives the impression of an echo.

The chart below shows the time difference between the 'beats', 'echoes', first peaks of the double peak AM and second peaks of the double peak AM. There is equal periodicity observed.



The above graph suggests that the AM beat and echo and double peak characteristics could be caused by difference in phasing between the two turbines. When the two turbines are out of synchronisation the AM is heard as two separate sound events.

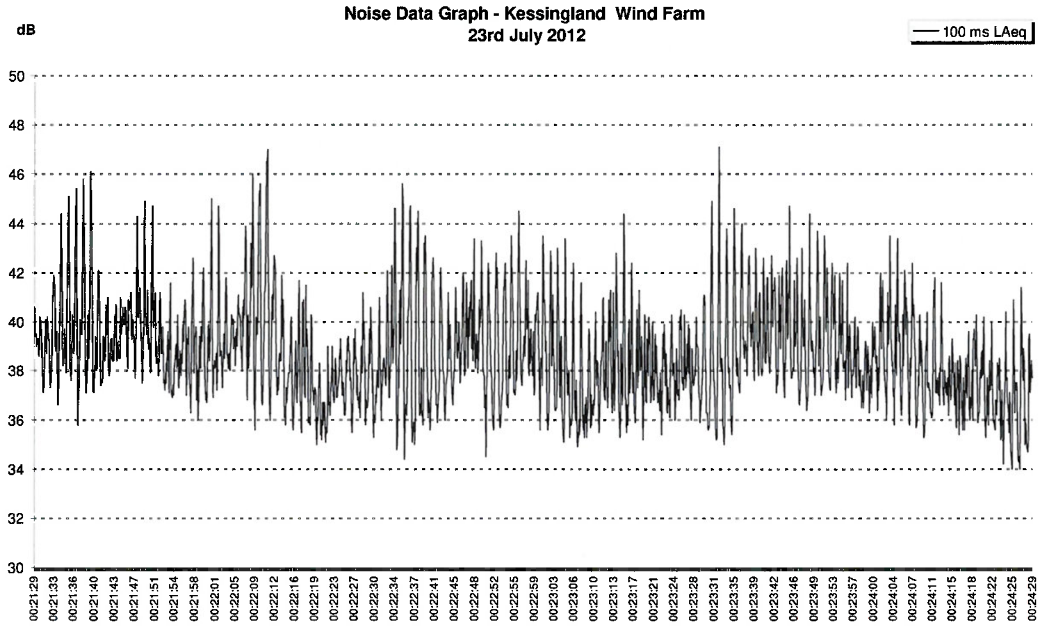
As the peaks from the two turbines move closer together in phase the peaks become merged and heard as one sound event with two pulses. This is demonstrated in the example image below where for illustration purposes it is assumed both turbines have the same sound energy emissions but one is delayed.



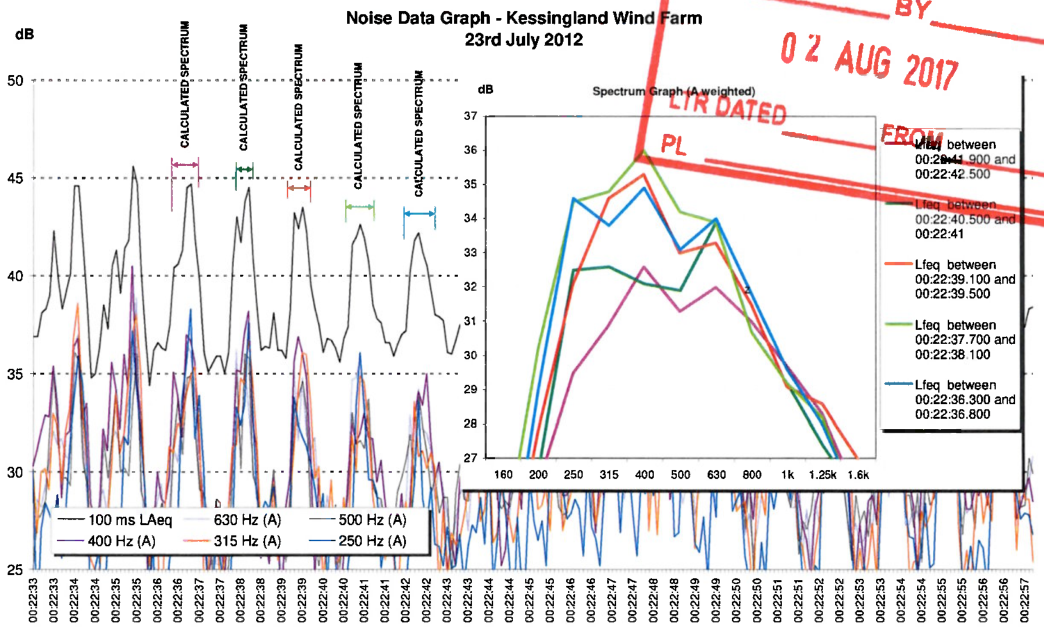
Single uniform AM peaks of greater amplitude may occur when AM from the two turbines is synchronised. These characteristics are considered to exacerbate the impact[11].

[11] This is further discussed in section 4 below on psycho-acoustic perception of AM.

The graph below shows a period of AM measured at Kessingland on 23rd July 2012 at a distance of 630m. AM is consistently present although the peak to trough level varies.



Spectral analysis of a sample of the AM peaks confirms a changing dominance in frequency content of successive AM peaks between energy in the 250Hz, 315Hz, 400Hz, 500Hz and 630Hz third octave bands.



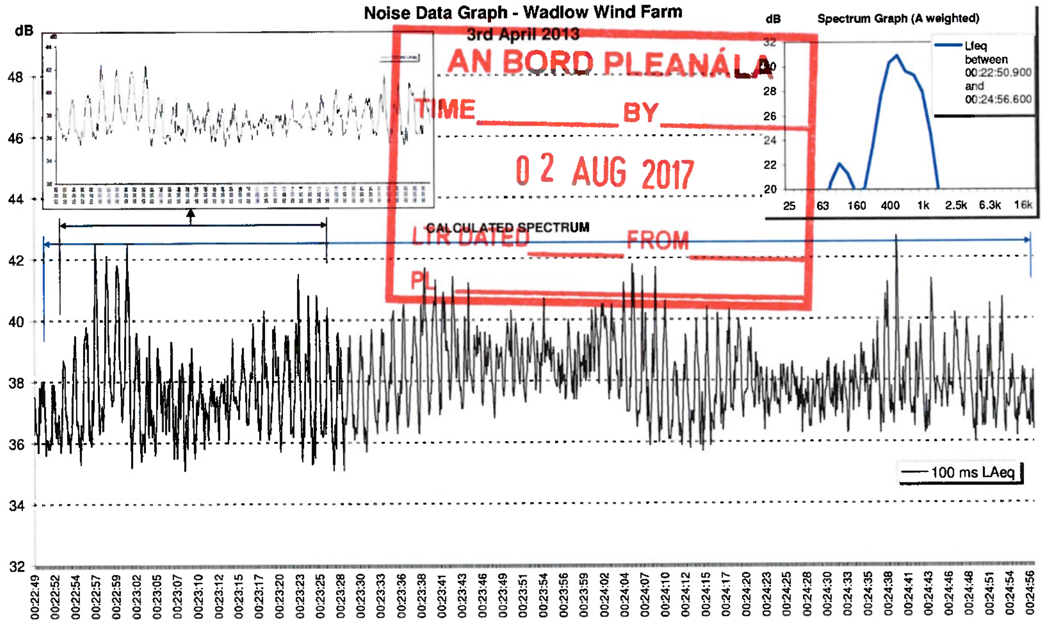
The first peak has higher frequency content in the third octave bands 400Hz and 630Hz. The second peak has some lower frequency content but is dominated by 630Hz third octave band energy. The fifth peak is equally dominated by 250Hz and

400Hz third octave band energy. Despite this sample of AM appearing to have a fairly uniform peak shape it is evident that the spectral content is complex and inconsistent resulting in noticeable changes in character. It can also be seen that where each event progresses through the rise and fall in sound energy there is a change in the dominant frequency. For example the middle peak highlighted is first dominated by 400Hz as the sound rises and 315Hz as it falls. Each peak differs in frequency content during the rise and fall in overall sound energy resulting in AM with a constantly changing character.

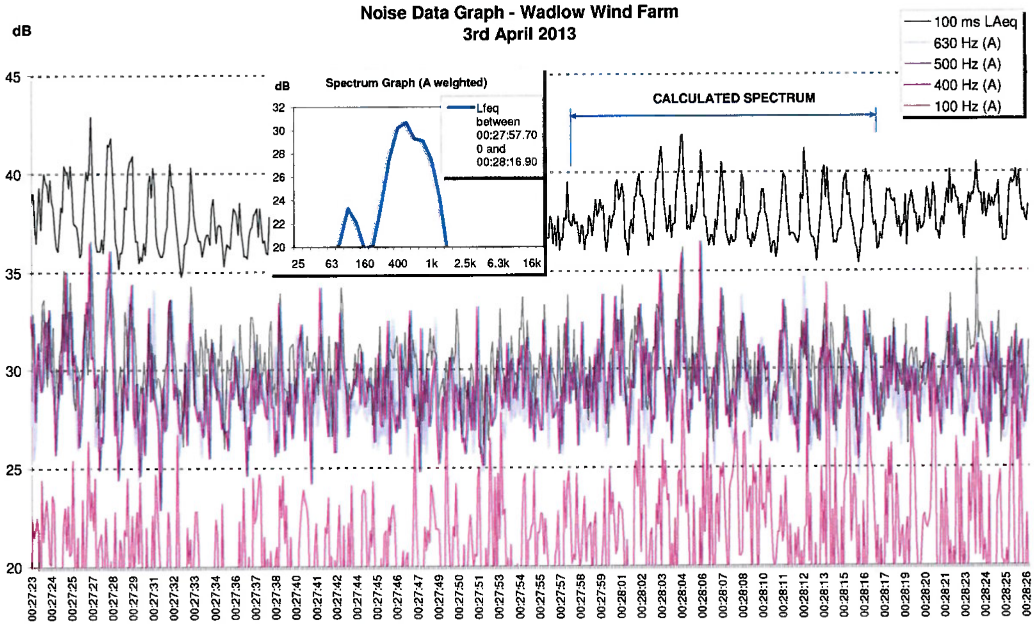
Wadlow Wind Farm, Cambridgeshire, England

Located close to the A11 road, when there is a westerly wind component the daytime noise levels in the vicinity of Wadlow Wind Farm are dominated by road traffic noise. At night time road traffic noise is minimal and there are few other sources of noise in the area. The site is located in eastern England, characterised by flat landscape. Measurements were taken approximately 1250m from the nearest turbine. The measurement location was 30 degrees clockwise from the downwind direction.

The chart below shows the 100ms noise trace for a 2 minute period. The AM peak to trough is generally 4dB with some differences of up to 6dB observed. The AM could be described as fairly clean. Peaks can be seen to phase in and out and this was the case fairly consistently for the 2 hour measurement duration. The inserted graph on the left of the chart below shows synchronicity of peaks at the beginning of the extract. Towards the end of the extract two pulses to the AM peak can be seen (and heard). The spectral content of the AM is generally dominated by energy in the 400Hz, 500Hz and 630Hz third octave bands. Sound at these frequencies generates a 'swish' or 'whoosh' sound.



On occasions a lower frequency thumping element to the AM sound is discernible with significant contribution from the 100Hz third octave band and which at times occurs as the peak subsides. Aural assessment of the sound in the field indicated that the higher frequency AM experienced arose mainly from a nearer turbine and the lower frequency AM was from a more distant turbine. The chart below shows the frequency content of a short extract of AM.

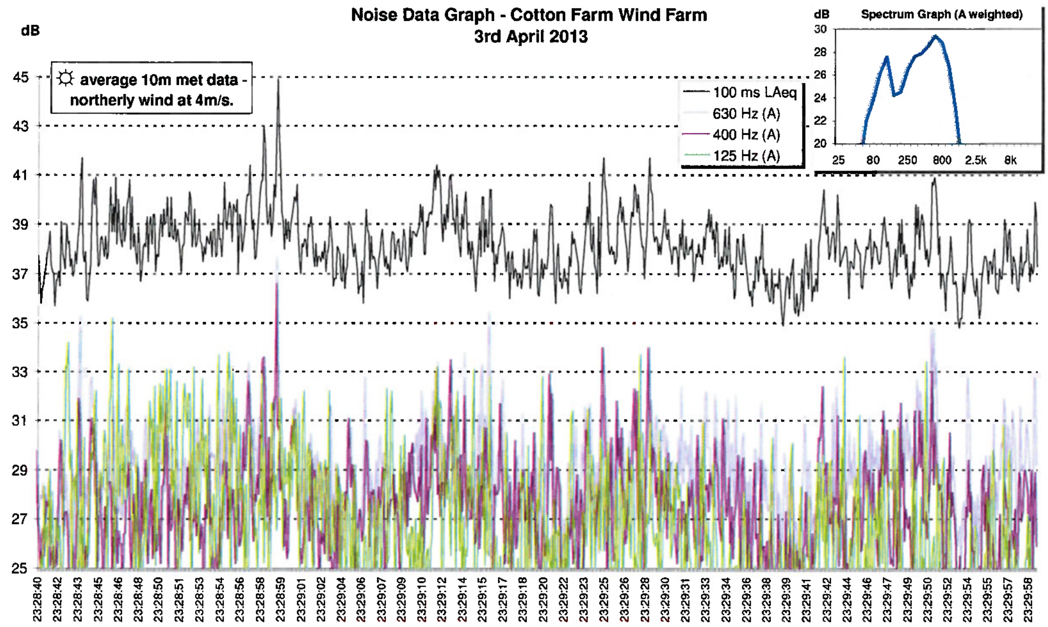


The spectrum graph for the period indicated on the chart above shows a dominant peak in the average frequency content around 500Hz; however, a secondary peak is evident within the 100Hz third octave band. With reference to the main chart and the 100ms traces for dominant third octave bands, whilst the 400Hz, 500Hz and 630Hz third octave bands modulate at a fairly consistent level and range, the 100Hz trace is more variable. Towards the end of the period the 100Hz third octave band noise can be seen to dominate certain AM peaks.

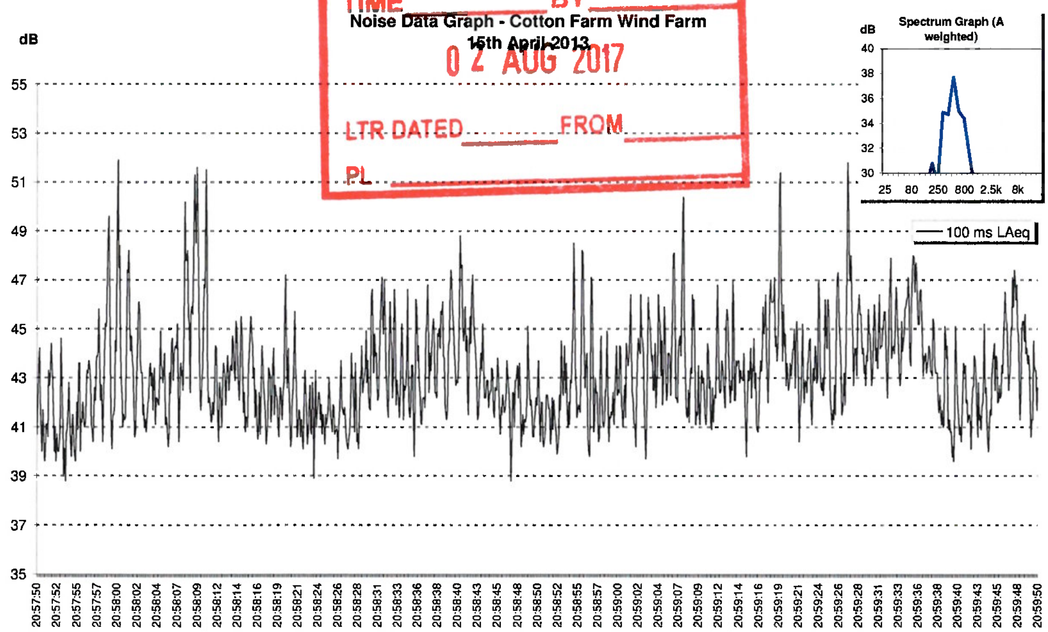
Cotton Farm Wind Farm, Cambridgeshire, England

AM has been measured from Cotton Farm on two occasions, the wind farm has only recently become operational. On 3rd April 2013 AM was measured to the west of the turbines under downwind conditions at a distance of 1200m from the nearest turbine. Temperatures during the daytime had not been particularly high, but there had been a relatively cloudless day and evening before the measurement period leading to increased wind shear. Not all turbines were operating during the measurement period. Although wind turbine noise was dominant in the area, some distant road traffic noise was also audible. The AM measured and heard did not pulsate as clearly as is the case with other measurements and results with a 'dirty' noise trace. AM peak to trough was typically 2-4dB and up to 6dB on occasions. There is a clear 125Hz third octave band component to the AM.

Frequency dominance within the peaks varied such that there were periods of 125Hz third octave band dominated peaks followed by 630Hz and 400Hz third octave band dominance. The random change in sound energy spectrum from one peak to another was a significant factor in the character of the AM. The change in sound energy character here is more distinct than the example from the Kessingland turbines examined above.



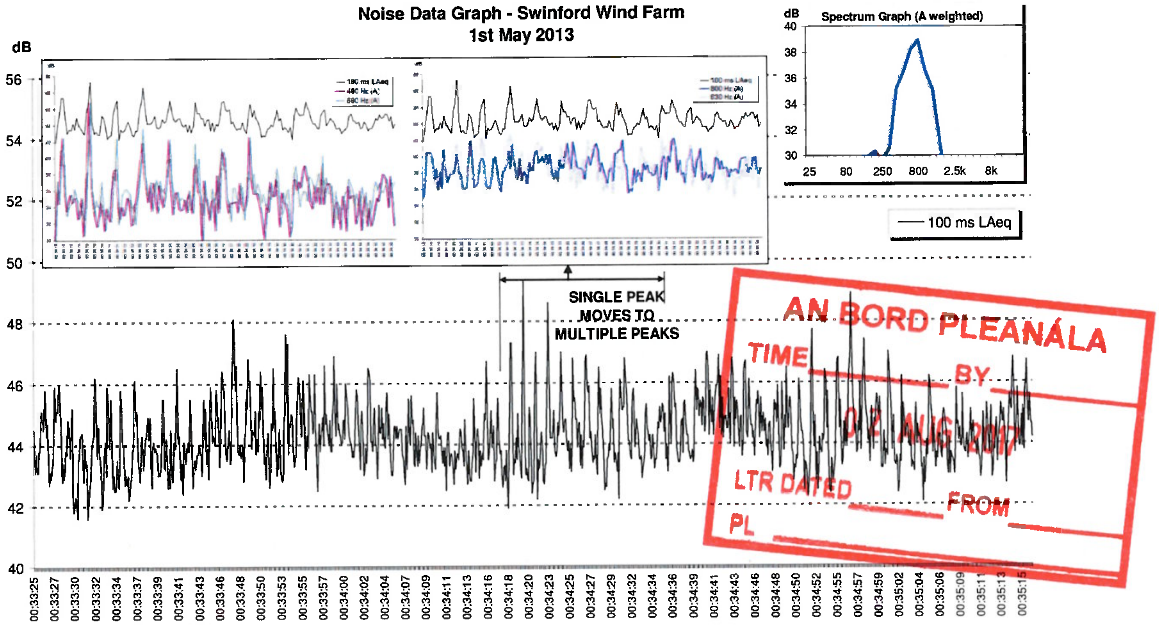
On 15th April 2013 measurements were taken to the east of the turbines at a distance of 800m from the nearest turbine.



AM was much clearer, though still erratic in occurrence, and peak to trough differences of typically 6dB and up to 8-10dB were measured. On this occasion low frequency noise was less prominent within the data and the dominant sound energy was focused around the 500Hz third octave band.

Swinford Wind Farm, Leicestershire, England

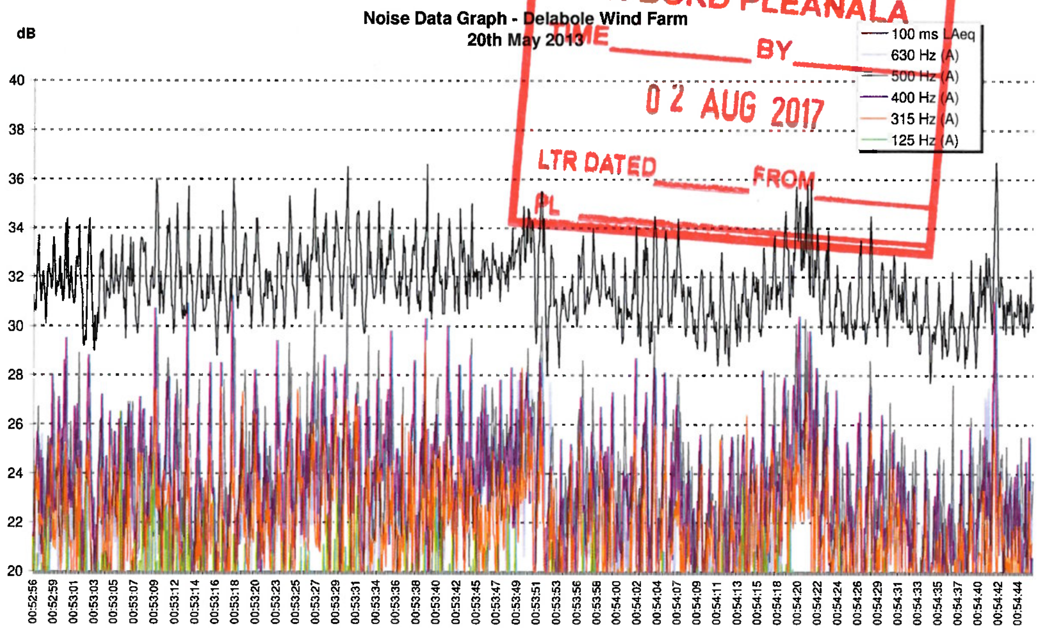
The weather conditions during the evening measurements at Swinford Wind Farm were not ideal for generating AM. There was high atmospheric pressure and wind energy speeds were continuing to fall and change direction throughout the period. The distance to the nearest turbine was approximately 750m. AM with peak to trough values typically of 3-5dB were measured and the dominant frequency content was focused in the mid frequencies around the 800Hz third octave band.



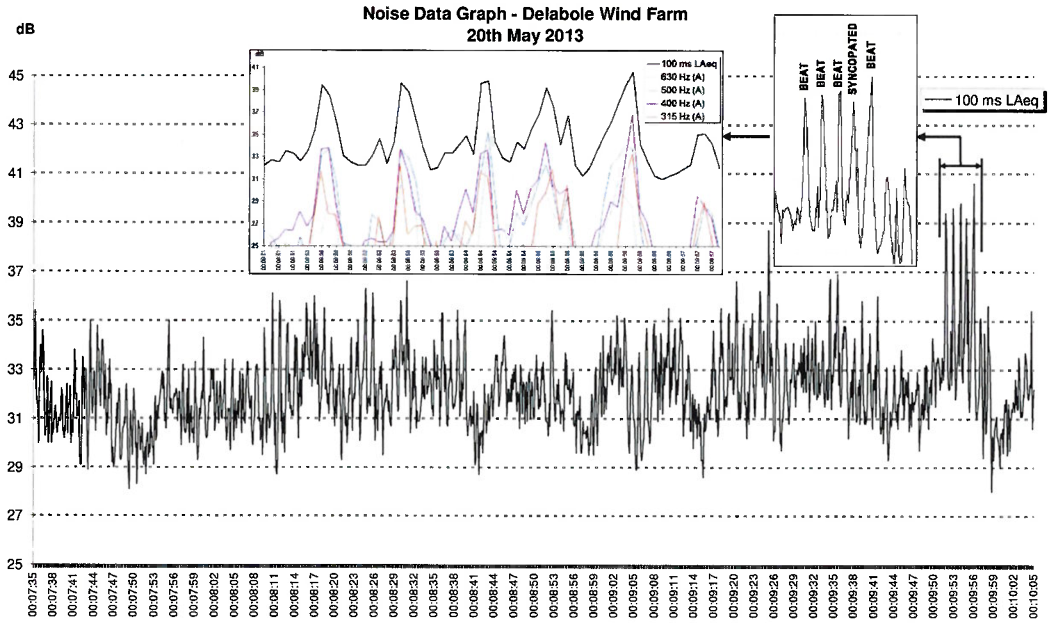
The graphs inserted in the chart above show the average spectrum on the far right hand side, and to the left a more detailed frequency analysis of the highlighted period. The period shows clear defined AM peaks which can be seen to move to less distinct AM with multiple peaks. The left hand side frequency analysis shows energy in the 400Hz and 500Hz third octave bands. The middle frequency analysis shows energy in the 630Hz and 800Hz third octave bands. The 400Hz and 500Hz third octave band energy fairly consistently peaks together, although the peaks disappear towards the end of the extract. The 630Hz and 800Hz third octave band energy peaks coincide at the beginning of the extract with the 400Hz and 500Hz third octave band energy. However, they quickly shift out of phase creating multiple less well defined peaks. Thus, the distinct peaks of AM during this period occur when dominant frequencies are synchronised. The clarity of the AM appears to be lost firstly due to phase shift in 630Hz and 800Hz third octave band energy and then towards the end of the extract due to less modulation in all four dominant third octave bands.

Delabole Wind Farm, Cornwall, England

AM from Delabole Wind Farm was measured at a caravan site approximately 400m from the nearest turbine. The measurement location was approximately 70 degrees counter clockwise to the downwind direction. Although AM was measured, weather conditions and the negative angle relative to the rotation angle were not conducive to typical worst case AM generation. Peak to trough was typically 4-6dB and as shown on the chart below dominant frequencies varied peak to peak but are mainly focused in the 315Hz, 400Hz and 500Hz third octave bands. Prevalence of 125Hz third octave band energy can be seen to vary throughout the period with most contribution at the beginning of the period.



A period from earlier on in the night presented below shows that the AM was slightly more erratic, with periods of AM of higher peak to trough differences phasing in and out.

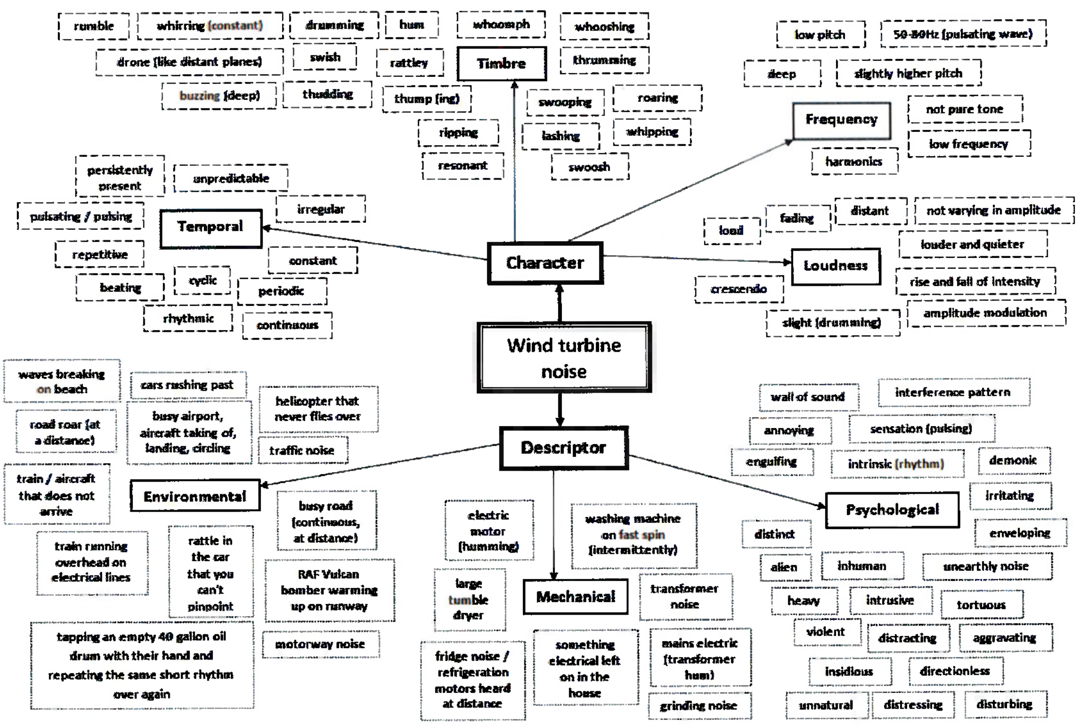


Towards the end of the period there are five AM peaks with a peak to trough difference of approximately 6dB. The peaks draw attention both due to their loudness and the rhythmic character. The first three AM beats are regular, the fourth is out of time in comparison to the first three beats and the fifth beat is perceived as in time with the original rhythm set up by the first three beats. With reference to the frequency content, it can be seen that the AM peaks that are perceived as in-time have synchronised peaks in the 315Hz, 400Hz and 500Hz third octave bands. The dominant frequencies in the syncopated beat are misaligned. This change attracts attention to the beats.

Psycho acoustical factors

Wind farm noise is widely acknowledged as more intrusive and more annoying at lower decibel levels than other types of industrial noise (Pederson & Waye, 2004). Although attitudes towards wind development have been noted as influencing perception of wind farm noise (Van den Berg, 2009) psycho acoustic factors have been little discussed or explored.

The word map below categorises some of the many terms used by affected residents to describe AM, including physical likeness of the sound and musical terms describing the character of AM.



"The assessment of sounds that vary in level and spectrum over long time periods requires continuous judgments" (Scharf, 1998, p. 1187). Whilst it is easy to provide a simplified acoustic description of AM through determination of an average decibel level, an AM peak to trough level or a dominant frequency component, such descriptors fail to relate to the auditory and psychological perception of the sound.

Indeed, rarely do the descriptions on the word map above consider an absolute overall decibel level or third octave band level and most aim to subjectively describe both the temporal and spectral character of the sound as it varies with time.

Our perception of sound will be influenced by cognition, by past experiences and associations with the sound (Hodges & Sebald, 2011). As Juslin and Västfjäll (2008) note "the perceptual system is constantly scanning the immediate environment in order to discover potentially important changes or events. Certain sound qualities are indicative of change, such as sudden or extreme sounds, sounds that change very quickly, or sounds that are the result of strong force or large size. Sounds that meet certain criteria (e.g., fast, loud, noisy, very low- or high-frequenced) will therefore produce an increased activation of the central nervous system" (p.564).

The musicologist Meyer theorised that our expectations of music (sound) govern our emotional response. Expectations of our environment and emotional response, based on sensory assessment, are a constant part of everyday mental processing. As Huron (2006) notes, accurate expectations benefit preparation for appropriate perception and action (p.3). Examining our environment for sensory changes and preparing for appropriate action requires varying and controlling our levels of attention and arousal accordingly. Emotion resulting from expectations reinforces appropriate reactions and promotes positive outcomes. For example, if something in our sensory environment changes we automatically pay more attention: our eyes focus on an object moving in the distance, a door slamming will quickly evoke a startle reaction. Although the door poses no threat, it is beneficial for survival to react as if danger were present, to become fearful and alert (Huron, 2006). Huron continues to discuss the uncertainties associated with expectations. Sounds and music can manipulate uncertainty regarding what and when certain sounds will happen, where and why sounds or music occur. These elements are manipulated by composers to illicit specific emotional reactions to music and sounds.

On a very basic auditory level, aspects of AM sound may cause heightened attention or arousal, resulting in negative emotional states and focused cognitive analysis. The internal measurement of AM at Deeping St Nicholas Wind Farm demonstrates significant low frequency contribution. Low frequency sounds are often associated with large objects or objects with a lot of energy, which in turn are often related to feelings of uneasiness due to associations with danger. The association with threat is heightened when AM gets louder and peak to trough difference increases. A sound that gets louder is often gaining energy or getting closer, again environmental factors that may be associated with potential threat.

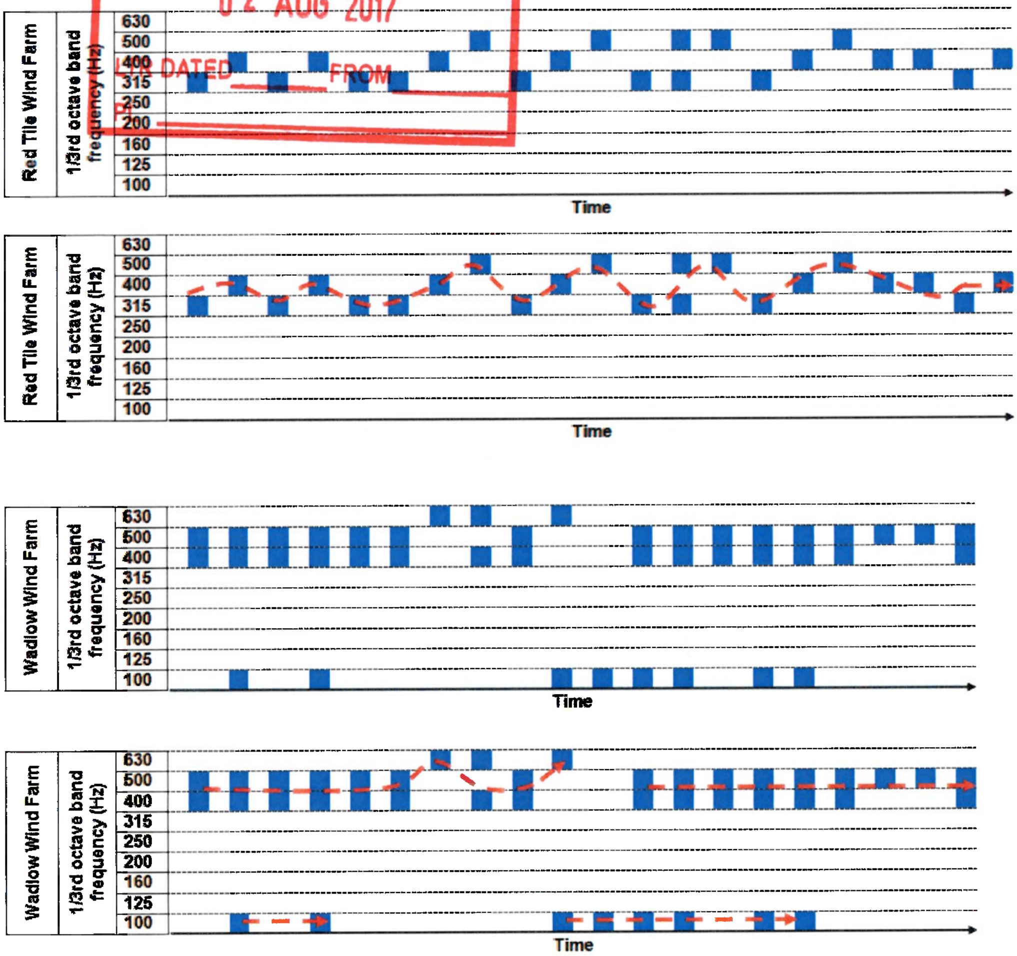
AM peak to trough is often unpredictable and higher peaks can arise suddenly and after periods of less modulation. See for example the chart for Site E. Towards the end of the period the AM fades, peak to trough is in the region of 2dB, and typical noise levels are approximately 28dB(A). Within a few seconds the sound changes to AM with peak to trough of 4-6dB and peaking above 34dB(A). The listener would likely be in a dark room without any visual clues. Arousal and attention are therefore focused on auditory clues. These changes represent a significant change to the sensory environment and as noted by Huron (2006) and Juslin & Västfjäll (2008) our body will react accordingly. This effect can also be seen in the Cotton Farm AM measured on 15th April, which displays erratic peaks in the region of 51dB(A) compared with the majority of peaks between 45dB(A) and 47dB(A). Changes in peak to trough difference are often accompanied by changes in spectral content or dominance and would add another varying factor to the auditory environment which could draw attention.

The discussion of theory and measurements can easily be related to the terms used to describe AM in the above word map. Terms such as 'distressing' and 'disturbing' may be related to fear or threat responses. 'Deep', 'heavy' and 'thudding' may be compared to musical features eliciting negative emotions[12]. Descriptors relating to our expectations of our environment include 'unpredictable' and 'train / aircraft that does not arrive' which may encourage prolonged attention.

In addition to basic mental processing and associations of sounds, our ears are also capable of highly complex analysis. Albert Bregman coined the term auditory scene analysis to describe the way in which the ear processes and organises sounds in to meaningful components as a way of understanding our environment. The ear searches the sound for clues including temporal, spectral, periodical and sequential relationships (Plack, 2005). Rises and falls in frequency may be segregated as separate streams depending on pitch proximity (Stevens & Byron, 2009). Sounds will also be grouped according to a perception of rhythm, beat or meter[13] (McAuley, 2010).

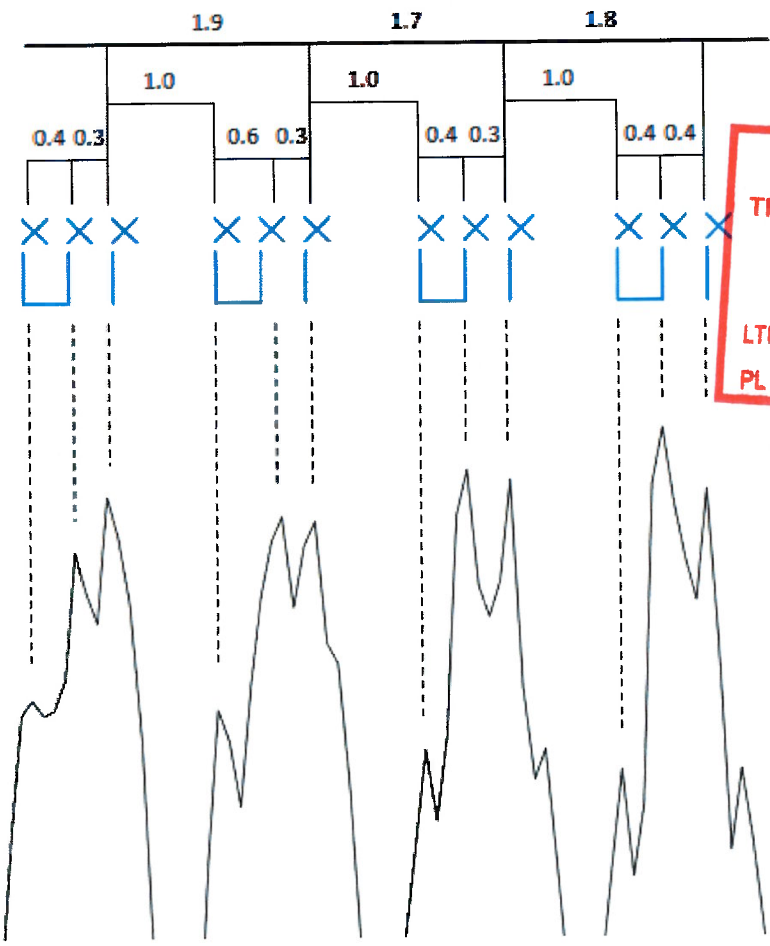
As indicated in the data presented above, AM is a complex sound consisting of varying frequencies, loudness and meter (pulses and beats). The noise data graph from Red Tile Wind Farm shows fairly equal but unsynchronised modulation of sound energy in 315Hz, 400Hz and 500Hz third octave bands. The sound energy is fairly close together in frequency (pitch) and also close together in time. The sound that is heard is sweeping and broadband. The different component frequencies have been grouped together in to a single sound stream by the brain. In contrast the noise data graph from Wadlow Wind Farm demonstrates two separate streams grouped by frequency (pitch) and to some extent time. The majority of energy is in the 400Hz and 500Hz third octave bands but, towards the end of the period some peaks are dominated by 100Hz third octave band energy. There is sufficient distance between the frequencies dominating the AM peak, and without intervening blurring frequencies, for these to be heard as two separate sounds. This is demonstrated on the image below with the red dashed lines representing the streamed sounds.

[12] Consider for example the theme tune to the film Jaws.
[13] A rhythmic element as measured by division into parts of equal time value. (http://dictionary.reference.com/browse/meter?s=t)



The discrepancies between how AM sounds from different wind farms or at different time from the same wind farm can be processed by the ear and may help to describe the disparity between descriptors in the word map above. Terms such as 'whirring (constant)' and 'repetitive' may fairly describe the AM at Red Tile Wind Farm whereas terms such as 'irregular' and 'thumping' may better describe the AM from Wadlow Wind Farm.

As well as pitch, rhythm and meter play a role in grouping sounds. Rhythmic aspects of AM regularly feature in descriptions of AM and can easily be observed in much of the data. The AM peaks at site C regularly occur at intervals of approximately 1s. In contrast the extract from Kessingland on 28th June has already been described in this paper as having a beat and 'echo' sequence' and AM consisting of two beats. The beat and 'echo' sequence is a good example of how the ear interprets sound with rhythmic hierarchies. In western music there is a preference to hear sound with meter, an alternation between strong and weak beats (Thompson & Schellenberg, 2002). As the AM often varies due to phasing differences our attention increases as we process the new rhythm or meter that results. The extract from Kessingland on 10th June shows a fairly constant period of AM with a regular periodicity of just under 2s. Each AM peak consists of a dominant double pulse; however, there is also a third weaker pulse before the main AM peak. Each pulse conforms to the meter. The weak pulses are separated by approximately 2 seconds, the first peaks are separated by approximately 2s and the second peaks are separated by approximately 2 seconds. The weak pulse and double peak AM form one rhythmical group. The timing between each group is 1s. The timing within each group, i.e. between the weak pulse and first AM peak and between the first AM peak and second AM peak, is just under half a second. Thus, a rhythmical hierarchy can be formed. See the image below which shows the time in seconds separating the constituent pulses of the AM and how this forms a rhythmic hierarchy



Although it is unlikely that on perception we will naturally develop this rhythmical hierarchy for AM, it shows that there are rhythmic relationships between the pulsing components that generate the AM trace which draw attention and have meaning.

Temporal entrainment also plays an important role in perception of sounds. Entrainment describes the interaction of two rhythmic processes combining to a common phase. Entrainment to rhythms is observed in humans from an early age (Trainor & Hannon, 2013) and there is evidence that biorhythms entrain to external rhythmic stimuli (Large & Jones, 1999, as cited in Stevens & Byron 2009; Schneck & Berger, 2006). With reference to the word map above, the description of AM as having an 'intrinsic (rhythm)' may relate to the entrainment between the AM beat and biorhythms. As noted above, the AM peaks at site C regularly occur at intervals of approximately 1s. This interval is not uncommon in the measured AM data. The timing between each AM group in the Kessingland data from 10th June is 1s and the timing within the group is approximately half a second. Fraisse (1982) (as cited in Thompson & Schellenberg, 2002) found that physiological processes, such as heart rate and walking pace, tended to occur at a rate 60-120 beats per minute. AM events occurring approximately once per second coincide with a rate of 60 beats per minute and as such AM entrainment, synchronisation between AM and our movements or heart rate etc, is likely to occur.

Information regarding a sound source can be determined by the process of localisation. This relates to the 'where' expectation discussed by Huron (2006). The ear can detect the direction from which a sound originates by comparing differences in timing and frequencies perceived by each ear (Pierce, 2001). This is a feature we have not been able at present to replicate in the Listening Room Experience (see below). The precedence effect describes the phenomenon by which we hear sound as originating from the direction where we first hear the sound, even if this changes or originates from two separate sources. As AM has been shown to regularly vary in both level, frequency content and timing, there may be difficulties in localising the source of AM due to contradicting or confusing auditory clues. With reference to the word map above this supports descriptions of AM as 'enveloping', 'wall of sound' and 'rattle in the car that you can't pinpoint'.

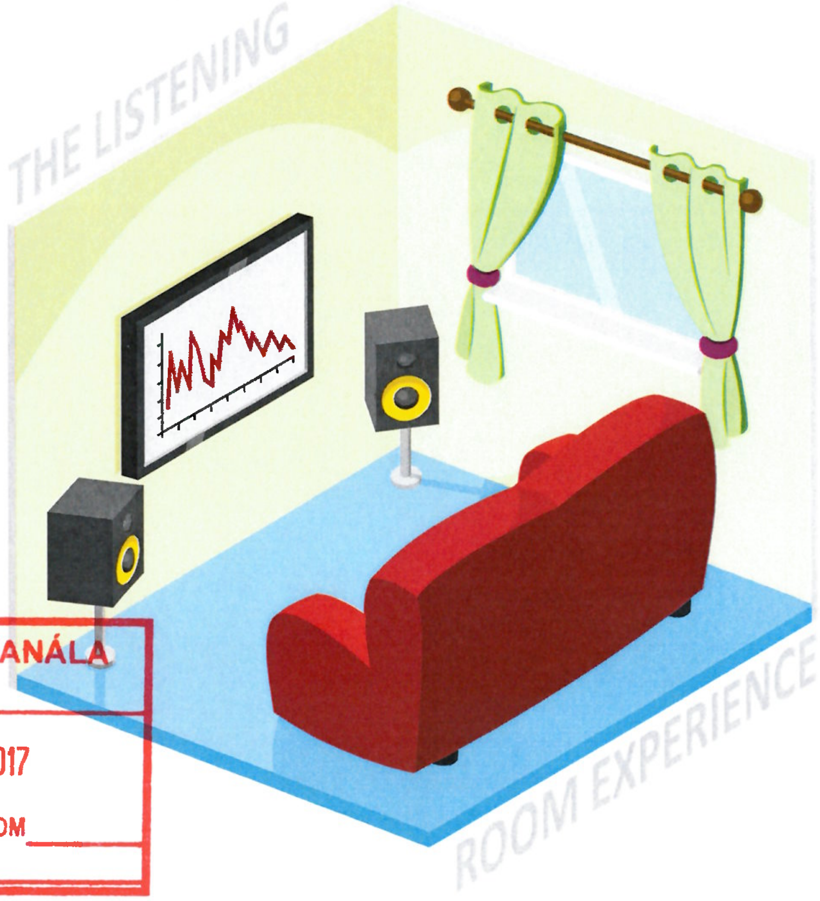
With a little consideration of the range and complexity of auditory processes used to assess our environment it is not surprising that AM evokes many different descriptors of the sound. The varying nature of AM necessitates constant reappraisal of our auditory environment and supports anecdotal evidence that AM is rarely a sound that can be pushed to the back of our consciousness. For these reasons it is considered inappropriate to try to categorise the boundary between acceptable and unacceptable AM by reference to a total or average sound energy level except when identifying circumstances where it is clearly intrusive if all other factors are equal. Instead, assessment should focus on the audible character of the noise, recognising that there are many manifestations of the sound which increase impact once discernible.

The Listening Room Experience

The Listening Room Experience is an exercise where wind farm noise is replicated as close as possible to that which is experienced in and around homes[14].

Acousticians are well aware of the problems associated with using the decibel level to convey how noise intrudes and the difficulty in deciding what levels of noise are acceptable when it exhibits varying characteristics. The lack of transparency in decibel parameters can be exploited and it is difficult for lay decision makers to appreciate the consequences of accepting or setting decibel limits, especially when two opposing acousticians present different arguments over acceptability.

[14] A typical playlist schedule is provided on our website along with some of the tracks used in the experience.



In UK courts it is normally open to either party to present the evidence of their choice. We have successfully used audio recordings on many occasions in the courts to convey the character of a noise; where defendants object it may lead the court to question why they do not want the court to hear the noise. In more recent cases we have attempted to accurately simulate the decibel levels in order to replicate the experience of the noise that the community actually experience. This is especially important for wind energy development where, as shown by our findings above, noise features such as AM have a distinct and intrusive character. Difficulty arises in the UK as planning decisions do not compel regulators to undertake a listening room experience even when one party request it.

Court room scenario

Problems also arise as the courtroom or inquiry hall is remote from the character of the bedroom, living room or garden of a rural residence. The background and ambient noise levels within a city courtroom are usually much higher than in a rural bedroom when there is a distinct lack of industrial or transport related noise sources. The state of mind of the listener is important, whilst on public display and studying technical evidence the listener is not attempting to relax in the same way as if they were in their own home. The perception of the impact clearly changes as a result.

We have sought to create a relaxed listening experience which is outside of the court room or inquiry building. Previously we have used a specialist listening room facility and a recording studio but found that it is best to run the exercise in a rural dwelling provided the background noise levels are low and unaffected by dominant manmade sources. The location should provide an environment where decision makers are not in front of the public, are sat in comfortable chairs in a living room type environment and allow relaxation perhaps even imagining trying to sleep with the noise. Experience suggests it is normally best to conduct the experience after dark, in the late evening when people are naturally preparing for the night and sleep. We consider it is important to replicate the conditions when impact arises as close as possible, especially low background noise levels. Background noise levels in rural bedrooms can typically be below 15dB(A) with windows open and below 8-10dB(A) with windows closed.[15] The room should reflect a rural bedroom / living room environment including typical reverberation times.[16]

Low-noise equipment

The use of microphones with a low noise floor to record both the source noise and background noise environment during playback is critical to ensure no artificial masking effects (usually from internal electrical interference) are present either in the recordings or at playback. Music or interview recording studios provide a good substitute for a rural living room / bedroom environment as generally they are designed to ensure background noise levels are around 15dB(A), to have low reverberation times and are normally devoid of daylight. Where such a facility is to be used, soft chairs and possibly curtains are needed to replicate a comfortable home situation as best as reasonably practicable.

The process and setup adopted

In most rooms external noise mainly enters through the window. The seating is therefore arranged in a "U" shape equidistant from and facing a window or mock window (or with one in view) and two powered monitor speakers with a flat response down to 40Hz placed either side of the window setup. A flat screen TV is used, either placed below the window or in the approximate direction for comfortable viewing. The set up enables levels at the seating to be within a couple of decibels of the actual levels experienced. Groups of 8-15 people are accommodated. For larger groups two rows of seating have been used, recognising levels are potentially slightly lower in the second row. The objective is not to perfectly replicate the sound energy levels, as this will change in different rooms and with different numbers of people but to provide a sound energy experience which is close to that experienced by wind farm neighbours.

During test playback the sound trace and spectrum are compared with the actual recordings to ensure a good standard of replication is achieved. This is also recorded during the final playback to demonstrate reasonable replication.

Each playback track is co-coordinated with an interactive graph of the decibel levels and spectrum. This software requires the audio to be converted to mp3 format so it is

[15] Many acousticians use microphones with a noise floor of 16-20dB(A). These are unsuited to recording AM inside dwellings or determining the internal background noise environment. A low noise microphone is always required.

then checked using audio processing software to ensure minimal distortion when compared to the original track.

The experience

Attendees are provided with an explanatory pack with a copy of each chart, some details about the wind farms, the piano scale to enable comparison with the spectrum and a playlist schedule. Interactive graphs are displayed on the TV screen. The experience lasts about 90 minutes and currently 16 clips are reproduced from 6 wind farms where AM has been recorded. The process is as follows:

1. External noise recordings in the vicinity of homes.
    a) Background noise is played to enable the hearing system to adjust to a low noise environment after travelling.
    b) Several late evening / early night time recorded AM incidents outside dwellings are replayed.
    c) Wind farm noise (devoid of AM) compared to periods when the wind farm was stopped for testing is played to enable comparison with turbine noise virtually devoid of character.
2. Internal noise recordings inside dwellings or simulated inside dwellings.
    a) Background noise is played again to enable the hearing system to adjust to the lower internal noise environment and provide comparison.
    b) Several recordings are played starting inside a car and then transferring inside different dwellings through the night.

Procedure adopted

The room is softly lit and this is switched off once the TV screen is switched on. Questions and commentary are kept to a minimum to enable relaxation. An interactive graph with a moving curser is displayed on the TV screen placed at the window location or where it provides for comfortable viewing. A clip between 1-3 minutes is played with minimal introduction. The clip is then replayed and the TV switched off to ensure very low light / near darkness and to remove visual stimuli. Attendees are encouraged therefore to focus merely on the sound. In our experience this replay has the most significant effect as attendees notice the different impact when not concentrating on the charts and paperwork. Clips range from those with regular 10dB peak to trough fluctuations to those smaller than 3dB and varying levels of low frequency noise. This process is repeated for the external and then the internal recordings. The final extract presents levels recorded in a bedroom where the impact had continued for about 4 hours. As before this is first played allowing study of the graphs and then repeated in darkness whilst considering if attendees could sleep. At the conclusion of the session discussion is encouraged with the lights on, without the TV screen on but the AM continuing. This has previously prompted requests to stop the noise and expressions of relief when it stops.

Use of headphones

Experience indicates the use of headphones is a poor substitute. Few headphones provide a flat response and therefore change the signature of the spectrum of the noise on playback. This distortion can change the experience significantly. Also, the recordings are monaural and therefore playback through headphones creates an unnaturally flat experience by removing time shift and directionality. Further, the mere wearing of headphones induces an artificial environment which can inhibit relaxation. Whilst the speakers do not reproduce sound binaurally, room effects and direction of the speakers gives a greater sense of reality in the sound.

Anechoic chambers

Whilst the noise floor of any anechoic chamber is normally good, the highly artificial situation in an anechoic chamber leads to an alien experience and so have not been used.

Equipment used and settings

- → Norsonic 140 Type 1 SLM.
- → 40HL Gras microphone.
- → Laptop with Adobe flash player and external sound card.
- → Rokit powered professional studio grade monitor speakers.
- → Flat screen TV (silent in operation including no high frequency tone).
- → Audio recording standard = 24 bit, 48Kz standard. 16 bit 44KHz still provides a reasonable reproduction.
- → Mp3 compression = 320 kbps for the listening room experience.

Variation in the room

In reality the rooms in which people live vary acoustically and it is unhelpful to try to set a standard for dimensions and reverberation time. The important requirement is that it is reasonably free of reverberation, which can easily be achieved by carpeting, soft furnishing and people. It is important that masking noise from ambient sources is at least 10dB(A), or as close to this difference as possible, below the reproduced source noise including the troughs in the noise data. Analysis of the background noise spectrum is recommended. The reproduced source already includes background noise. Difficulty can arise in mechanically ventilated buildings which produce significant levels of low frequency ambient noise from the mechanical plant.

Conclusions

Single wind turbines cause AM. This has been recorded by several researches and by us. It is also confirmed mathematically.

AM appears to occur in heightened noise zones, where levels are greater than at some other nearby locations. This means meter location and site observations need to reflect the appropriate conditions and careful analysis of localities at the time of AM impact is required. These zones can vary with wind direction, synchronicity and meteorology (especially wind shear) although certain locations appear to regularly experience higher noise and levels of AM than others.

Crosswind AM can arise at significant distances in excess of 400m.

A range of features in the AM are experienced. Typically AM will fluctuate with heightened peak to trough values for periods of a few seconds. The greater the atmospheric stability the less variance in the AM trace.

Under a wider range of atmospheric conditions the AM that commonly occurs has increases in peak to trough variations (fluctuating with periods of significant AM) for about 6-20 seconds which then gradually subside. In some circumstances the AM does not subside and continues with only minimal variation for periods of several hours. This appears to arise when there is a steady wind direction and wind strength as well as prolonged high wind shear.

The spectrum of the AM depends on the distance from the individual turbines but also meteorological effects, the extent of refraction, synchronisation of separate turbine emissions and the frequency content emitted in the direction of the receiver. This leads to a wide range of variations with increasing lower frequency dominance within the AM peaks at greater distances typically approaching one kilometre or more. Where there is an array of turbines you can experience different frequency AM from a nearer turbine and normally lower frequency AM from a more distant turbine either at the same time or in succession giving changes in the sound character that are highly variable and rarely the same. Some sound characteristics are commonly repeated, most likely due to the same range of recurring meteorological conditions.

Peak to trough values of overall A weighted levels at distances of 400m to over 1km can vary in excess of 10dB. This can involve sustained periods or AM varying by 10dB peak to trough but even when variation is less than 3dB the constituent frequency bands still modulate dramatically. This results in a changing noise character that is intrusive because they trigger a range of psycho-acoustic effects and associations. Individual third octave band levels will typically fluctuate far more than the A weighted levels with peak to trough values commonly in the order of 10-15dB and at times higher.

Coherence / synchronisation effects clearly arise where sound waves at particular frequencies reinforce at certain points for a short period and then diverge again. The divergence and partial coherence which changes over time leads to changing noise character increasing the noticeability, perception and impact of the AM peaks.

The complex change in spectral content over time is clearly a common feature of AM. The multitude of sound attributes results in AM that constantly changes in its noticeability and impact. Many of the characteristics do not manifest themselves within the overall A weighted variations with small peak to trough values still exhibiting significant change in noise character. It is also clear that changes in spectral content, peak to trough range and consistency will vary not just with distance and wind direction but with a complex interaction of meteorological conditions most likely including downward refraction resulting from changes in the sound speed gradient. The variations in location of impact and distance of impact from the turbines lead to changing periods of adverse noise at wind farm neighbours. These are again dependent on a complex interaction of meteorological factors.

The elements identified within AM and their psycho-acoustic characteristics show why reference to the A weighted decibel level is a poor basis for acceptability or unacceptability in a particular case. However, any measure of peak to trough variation that is identified is likely to reflect an unacceptably intrusive noise in most cases. The importance of subjective and psycho acoustic perception of AM is vastly underestimated in assessment of wind farm noise. AM displays many features that attract attention both on a basic and complex level of auditory processing.

Regulators and decision makers need to experience the effects of AM to fully understand wind farm noise impact and the limited relevance of average decibel controls in relation to the psycho-acoustical effects. As a substitute to living and experiencing wind farm noise impact at an affected dwelling, the Listening Room Experience provides a reasonable way of experiencing and understanding the impact.

Postscript

Measurements versus predicted levels

This paper has focused on the character and occurrence of AM identified in field measurements. A significant factor in the measurement of AM is the source speed gradient in the atmosphere and in particular temperature and wind shear effects leading to downward refraction.

Analysis of the sound speed gradient data in the work by Larsson & Öhlund (2012) effectively shows a 3-4dB increase in levels over those predicted when there is an increase in the sound speed with height or under high wind shear conditions. The increase in sound energy under these night time conditions has been found by a number of other researchers (van den Berg, 2005; Palmer, 2011). It follows that prediction methods ignoring the variable effect of refraction and sound speed gradients, may understate levels. Our own field measurements under stable atmospheric conditions or high wind shear conditions have similarly found levels are higher than predicted by 3-4dB(A).

Complaints of AM

Recent research Crichton et al (2013) and Chapman et al (2013) has suggested complaints arise as a result of pressure groups or because individuals are already opposed to wind farms. This is contrary to our own direct evidence where many communities and individuals either did not object to the development, positively supported the development or moved near to the wind farm in the belief that it would not adversely affect them. It also follows logic that people adversely affected may seek advice from pressure groups and it is not always clear which step occurred first.

One of the authors has experience of staying at affected locations and being woken by AM on more than one occasion though not prevented from returning to sleep either because the effects subsided or were masked by playing music. In all cases windows were kept closed.

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inter.noise 2014
MELBOURNE AUSTRALIA
16-19 NOVEMBER

Initial findings of the UK Cotton Farm Wind Farm long term community noise monitoring project.

Proceedings of INTER-NOISE 2014

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ABSTRACT

This paper provides early results of a long term study of community impact from wind farm noise and uses of the data obtained. A continuously recorded database of noise collected under different meteorological conditions has allowed detailed analysis of particular characteristics such as amplitude modulation and also the reliability of assessment methodologies for predicting and quantifying impact. Surprising outcomes are explored including upwind impact. In 2013 MAS Environmental established a permanent monitoring station to record and publish data online located 600m from the nearest turbine to correlate the impact upon the community and provide an extensive database. This paper maps the evolution of the project. Online data enables a wider study of the effect of meteorological change on noise immission in a flat eastern area of the UK. Anyone can independently observe and listen to the audible elements of the noise that people complain about. This tool aids understanding as well as predicting times of likely adverse impact. The database has enabled testing of proposed controls, particularly in relation to audible amplitude modulation and demonstrated the recent Renewables UK proposed control mechanism fails. Data obtained challenges blade stall research claims as the primary cause of far field AM and wind farm noise prediction methodologies.

Keywords: Wind farm, Community impact, data analysis, database, control mechanisms, prediction
I-INCE Classification of Subjects Numbers: 14.5.4, 63.7, 66.1, 66.2

1. INTRODUCTION and DISCUSSION

This paper outlines the Cotton Farm Wind Farm community noise monitoring project where real time sound and weather data is continuously gathered at a representative community location and provided on-line for anyone to research, evaluate and improve their understanding of wind farm noise. The Cotton Farm WF project compliments measurements made by MAS Environmental (MAS) of amplitude modulation (AM) and other elements of wind farm noise at over 18 sites.

The provision of the equipment was funded by local community donations. The community were cognisant of the likely adverse impact. MAS undertook all the research, software development, system installation, maintenance and calibration, data processing and analysis. As the funding is limited substantial potential analysis and research remains to be undertaken. In particular there is extensive complaint evidence that can be correlated with noise measurements and compared to the audio.

MAS have made some of the data available to others to test responses to AM and / or test potential control mechanisms. MAS looked at automated test processes and found none to be a suitable replacement for manual inspection of the audio. Difficulty arises as two periods of data can provide noticeably different outcomes and a procedure or algorithm designed to trigger for a certain criteria based on one particular dataset, for example with a regular or single modulation peak, may not trigger when processed using a different level and type of AM, for example an erratic or double peaked modulation.

In the same way two forms of music may have the similar energy levels or beat patterns; one form of music may not be objectionable to some at a specified level but is to others. AM is viewed by some as related to the total sound energy emitted. This paper explores our findings which differ from this view and identify it is more a response to the psycho-acoustical characteristics contained within the noise.

1.2. **Cotton Farm Wind Farm and its locality.**

Cotton Farm WF comprises 8 Senvion (formerly REpower) MM92 2.05MW turbines with a total capacity of 16.4MW located between the villages of Graveley to the east, Great Paxton to the west and Toseland to the south in Cambridgeshire UK. The nearest dwellings are approximately 600 metres. See Figure 1 below.

The permanent monitoring station was established on the outskirts of Graveley. We have now collected over 17 months data and consider the research unique as we are able to test noise level and character against community response as it occurs. Much of the data is presented online so that all can see what impact arises, experience itunderstand the regularity of impact and its degree. In particular this allows analysis of meteorological conditions related to impact.

Web link www.masenv.co.uk/~remote_data/

1.3. The Monitoring Station.

This includes a 10 metre meteorological mast recording wind speed, wind gusts, wind direction, temperature, barometric pressure, humidity and rainfall in 10 minute periods within 20m distance of the noise measurement location. Measurements are made using a Vantage Pro system. This has a small solar panel and battery and transmits data to a base station located within a nearby dwelling.

Noise is recorded in a free field location at the boundary of residential property at a height of 1.5m above ground level using a Larson Davis double skin external microphone enclosure. The microphone has a noise floor of 17dBA and is connected via a 30m cable to an internally located Larson Davis LXT sound level meter.

100ms L_{Aeq} and 1/3rd octave data is recorded along with 10 minute values and statistical parameters. Audio is also recorded which can be post processed to undertake narrow band analysis if required. Data is directly streamed to a laptop computer which processes the information and uploads via a wireless internet link using the resident's broadband connection. Data is also backed up to a hard drive and manually downloaded on a monthly basis. It is output in CSV format and converted into tables and graphs using in-house programs constructed on an Excel platform.

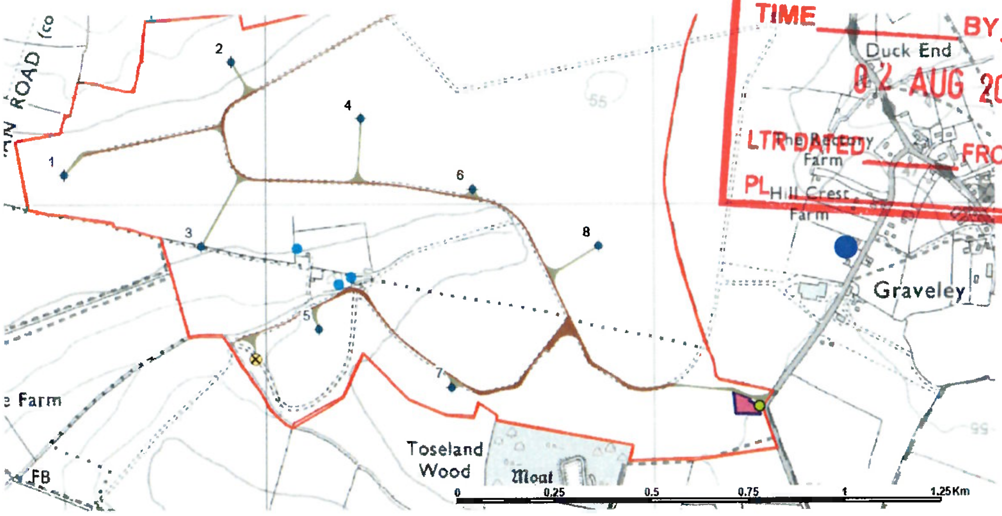


Figure 1 showing turbines & monitoring station. 1-8 = turbines & blue dot = station

Figure 2 – Pre- wind farm with dwelling to right where station now located.

Figure 3 – Post-wind farm showing anemometer (arrowed blue) & microphone location (red) in rear garden of dwelling.

Cotton Farm Wind Farm

Permanent Noise Monitoring Exercise

Continue to the data >

The aim of the long term noise monitoring exercise is to ensure that the Cotton Farm Wind Farm operates within the noise conditions set at appeal by the Inspector and to record and observe the range of noise characteristics and how it affects residents.

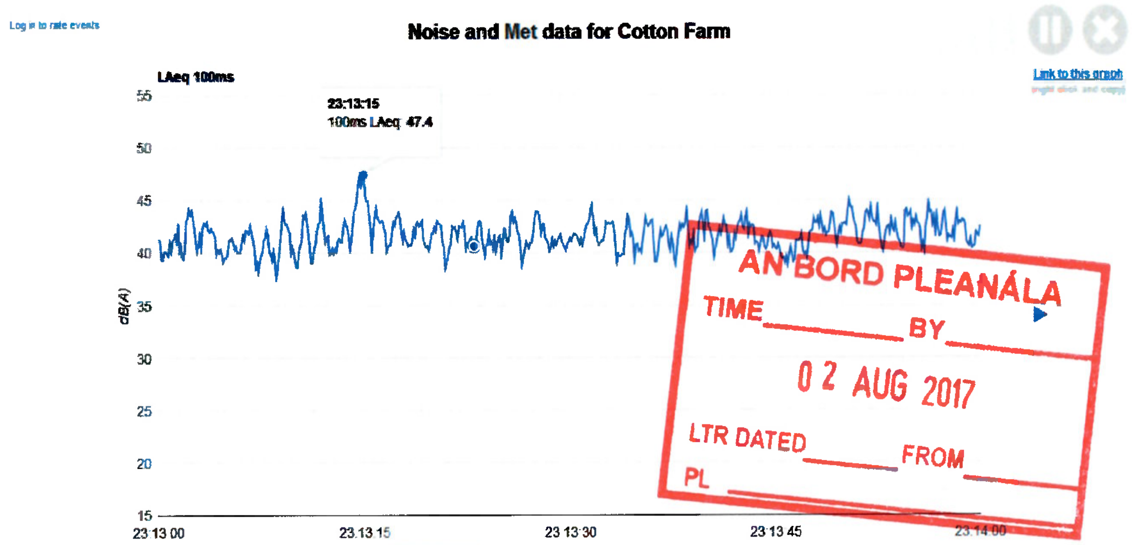
The Cotton Farm noise monitoring exercise is the first in the country to continuously monitor noise output from a nearby wind farm.

Whereas previously data associated with operational wind farms has been the undisclosed property of developers and often fails to record noise character, importantly this information will be publicly available for all to see and use.

The potential intellectual value of this research is far-reaching and will help to guide future understanding of operational wind farm noise especially as it relates to community impact.

The measurements of wind farm noise along with feedback from local residents will identify if there are periods when wind farm noise is intrusive and whether this results in a breach of limits.

Figure 4 – Start of website front page.



0	1	2	3	4	5	6	7	8	9
2014-05-06	00:20:00	11.7 °C	1.8 m/s	SE	0.00	2014-05-06	00:10:00	35.5	
2014-05-06	00.10:00	11.8 °C	1.8 m/s	SE	0.00	2014-05-06	00.00.01	37.1	
2014-05-06	00:00:00	11.9 °C	1.8 m/s	SE	0.00	2014-05-05	23:50:00	36.6	
2014-05-05	23:50:00	12.0 °C	2.2 m/s	SE	0.00	2014-05-05	23:40:01	37	
2014-05-05	23:40:00	12.2 °C	2.7 m/s	SE	0.00	2014-05-05	23:30:01	37.9	
2014-05-05	23:30:00	12.4 °C	2.7 m/s	SE	0.00	2014-05-05	23:20:01	38.3	
2014-05-05	23:20:00	12.4 °C	3.1 m/s	SE	0.00	2014-05-05	23:10:00	39.5	
2014-05-05	23:10:00	12.4 °C	3.6 m/s	SE	0.00	2014-05-05	23:00:02	38.9	
2014-05-05	23:00:00	12.4 °C	3.1 m/s	SE	0.00	2014-05-05	22:50:00	38.7	

Figure 5 – Website data page open with interactive graph at top and data tables below.

1.4. Development difficulties with the monitoring system and data uploading.

Very occasionally the sound level meter crashes and requires resetting. When this occurs individuals within the community have been trained how to reset the meter and recordings continue. Calibration is undertaken through monthly site visits when the entire equipment is checked. The meteorological mast is on a pivot and can be lowered to the ground to clean and adjust the anemometer as necessary. The microphone wind shield does not have bird spikes in order to avoid extraneous noise that some types can generate but does suffer bird pecks from time to time leading to the need to replace the outer foam screen. The Vantage Pro weather station has shown to be stable with few difficulties or problems.

The audio output on the LxT sound level meter has a hardware limited dynamic range resulting in clipping distortion during moments of high decibel level, for example during gusts of wind. This has no effect on the decibel levels calculated by the device. The audio is primarily for identification and this is not considered an impediment to analysis.

As time has progressed the site has collected a vast amount of data. In order to speed up page loading time, the site has a rating system allowing visitors to mark periods of significance. Insignificant periods are periodically removed from the site index but kept locally.

1.5. Future systems under development – low cost systems.

We are currently trialing low cost iOS platform software with an interface to a type 1 precision microphone and posting equipment ready for recording to be installed under remote video (Skype) supervision to ensure correct calibration and location. The hardware enables recording for up to 3 months without download but equally data can be automatically uploaded to "Cloud" storage for viewing and interrogation. Costs are expected around 10-20% of the existing system making it widely available. The main technical problem is obtaining a suitable external weatherproof microphone enclosure / wind shield.

Positive outcomes of the work include:

- The ability to research the actual impact arising under various meteorological conditions.
- Evidence based tests of predictions and theoretical concepts proposed for wind farm noise.[1]
- Comparison of community responses with measured sound energy values and sound character.
- Determination of contributions from extraneous noise sources.
- Immediate evidence correlating with complaints at the time of occurrence.
- Development of an online subjective rating of the AM which is moderated.[2]
- Transparency of actual impact versus decibel parameters.
- Statistical evidence of occurrence of a range of noise characteristics.
- Refinement of meteorological relationships with noise immission.[3]
- Raised awareness of the extent, frequency and duration of noise problems.
- Development of an extensive database to test metrics that are used to try to control wind farm noise characteristics such as excess amplitude modulation.
- Development of processes to differentiate wind farm noise from other sources.
- Development of simplified cost effective community monitoring procedures and equipment that can be used in other localities.

1.6. **Renewables UK (ReUK) research into Amplitude Modulation published December 2013.** (14)

The Cotton Farm WF database has been instrumental in testing the theories and ideas put forward in the ReUK research program that was itself based on smaller data sets. Whilst the ReUK research is extensive in text, it is based on limited data and field analysis. Some simple checks were able to test some of the theories put forward in their research but they are not supported by the field data suggesting false assumptions. This requires a separate paper but some findings are addressed in this paper.

2. BACKGROUND to the Cotton Farm Wind Farm project.

The Cotton Farm Wind Farm development was permitted at a public inquiry in December 2010. The local authority concluded there would not be excess noise and did not support objections based on noise. MAS concluded from investigations at a number of other sites that AM was a common and serious problem and sought its control. Additionally MAS were of the opinion the prediction methods applied, as now adopted by the UK Institute of Acoustics (IoA), understated noise impact and the pre-development assessments also overstated the background noise environment.

In the UK the positive decision of the Cotton Farm public inquiry not to control AM was used in other decisions to foster the conclusion there was not a need to control excess AM and also that the prediction methodology adopted in the UK was fit for purpose. The position on AM persists at the current time with reliance on a Salford report in 2007 which understated impact still being quoted. The Cotton Farm comments are still relied on despite extensive evidence that the inspector erred.

The government inspector in 2010 deciding the case rejected arguments for control and stated:

"I place greater weight on the results of [the Salford study] than on the research carried out by Mr Stigwood … it is simply not possible to predict in advance … statistically the odds are very much against it being a problem at Cotton Farm. I appreciate that some similarity with problem sites … but not to the extent that it can reasonably be regarded as a distinct possibility, let alone a probability"

The wind farm's acoustician[4] who gave evidence at the Inquiry stated:

"Given the very small number of occurrences of increased levels of 'blade swish' or AM, it is my view that an appropriate way to control the potential for the noise from a wind farm to contain

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1 Example findings discussed in this paper include support for Lee et al 2013 and convective amplification as a primary cause of AM and ReUK work on 'Other' AM which is contradicted by the Cotton Farm and other data.

2 Most residents/ site visitors rate the impact worse than the acousticians / researchers moderating the site.

3 The site is frequently used to judge appropriate times to visit and monitor at other sites.

4 Dr Andrew Bullmore of Hoare Lea.

increased levels of AM is by way of statutory nuisance action".[5]

MAS stated:

"the risk of AM was high and has long been under-estimated. A condition to control the noise was essential."

Post operation of the wind farm the community response is:

"A considerable number of noise complaints by residents have been made to the Environmental Health Officers. Each village appears to be affected at different times depending on the wind direction and speed ...The Action Group is also aware of residents who have been affected by turbine noise but have not formally complained"

The industry acoustician's erroneous view prevailed and has been commonly repeated and adopted by decision makers in the UK up to the current time and post work in 2013 showing AM was a common and serious problem (1). Acceptance of the need for controls is evolving in the UK but arguments that it is rare persist despite the strength of evidence globally.

2.1. Decision to continuously monitor the noise.

The local community were unhappy with the decision after funding the presentation of detailed evidence showing the need for AM control and decided to fund the installation of a permanent monitoring station. At MAS we saw this as an opportunity to expand our research and dedicated resources into the project.

Despite the Cotton Farm daily on-line data provided by MAS and continuing complaints of residents for over 17 months, no action to address the main problems have been implemented or are apparently being considered. Cotton Farm WF is owned by Greencoat UK Wind PLC a company that is invested in by UK Government.

3. RESULTS and detailed data analysis

This paper includes data analysis from the first 10 months of measurements and additional detailed analysis of a 2 month period from December 2013-January 2014. The primary focus of the research at this stage is on amplitude modulation occurrence compared to its characteristics and predictions versus actual noise levels.

3.1. Methods of data processing and analysis.

Various algorithms have been considered and produced to analyse the data and these have been compared to see how well they determine amplitude modulation including those procedures developed by ReUK which is reliant on FFT[6] analysis to determine blade passing frequency. We have also compared the method with those used by Tachibana et al, comparing the differences in the historical "fast" and "slow" processing meter settings of 125ms and 1 second respectively.

3.2. Method of data analysis adopted by MAS.

We have found the quickest and most effective method of analysis remains the processing of 100ms L_{Aeq} data into 2 minute graphs of a suitable scale. Identifying the periods unaffected by significant extraneous noise depends on the time of day and season of the year. In the UK MAS have primarily focused on 21:00-05:00 hours as an initial period for analysis when extraneous noise is infrequent. As with many processes involving complex effects, visual examination of graphical data is commonly the quickest method of identifying relevant patterns.

The original goal of the analysis was to ascertain an approximation of the occurrence of AM at the site. The approach needed to balance processing months of data quickly with the requirement to rule out any false positive indications of AM. This process resulted in scanning through 2 minute graphs looking

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5 The statutory nuisance procedure in the UK has failed every case so far and appears administratively incapable of addressing the issues and such an approach leaves communities unprotected.

6 A number of methods have been developed using the Fast Fourier Transfer approach, potentially with the hope of automating data analysis.

for clear signs of AM in each 10 minute period and verifying the absence of false positives by checking irregularities in the graph pattern using the audio recordings.

Adopting this approach means a single night period can be visually scanned in less than 10 minutes and commonly half that time. A secondary filter then is sometimes applied to identify dominant third octave bands that are also recorded every 100ms in order to assess their modulation. Where specific community complaints are recorded, these periods are scrutinised and where a clear AM trace is not obtained then spectrographs may be used or the audio checked. Spectrographs have been found particularly helpful for modulating tones or drones that span a number of frequencies or where harmonic frequencies are measured. In this manner we have been able to check long periods of data in a short period of time, before deciding what other processing might be relevant. Visual checks have also rapidly identified periods of AM impact missed by automated processes such as that proposed in the ReUK mechanism.(2)

The MAS analysis also attempted to quantify the degree of AM monitored without the need for exact peak to trough level analysis. Therefore positive periods were divided into 3 sub-categories. Any periods with clear modulation of approximately 5dB and above were indicated as positive results. Periods where the AM appeared momentary or there was any doubt over the modulation being 5dB or above for a significant amount of time, were indicated as "borderline". Periods where AM had regular peaks of 10dB were recorded as "severe". Periods were always verified by audio and categorised conservatively. Many periods were disregarded completely due to other environmental activity or extremely irregular behaviour. This will have resulted in some periods of occurrence being recorded as an absence of AM. There were times where it would appear the turbines were switched off; without confirmation these periods were included as periods with absence of AM.

3.3. **Limit of unacceptable AM.**

Scientific discussion continues over what is an appropriate trigger point of unacceptability for AM in terms of modulation depth. This is discussed further in our second paper at Internoise 2014.(3) Reliance only on modulation depth (MD) is considered a misleading approach to describing acceptability as a range of intrusive characteristics arise that do not necessarily relate to modulation depth or are not within the "A" weighted values. Impact relates also to frequency of occurrence, duration, times of impact and the consequences / effects of the intrusion.

Since 2009 MAS have used a criterion of repetitive 3dBA modulation depth impact values as an indicator there is likely to be adverse impact from AM on the basis it is clearly noticeable at these levels and changes the noise to one with character. It also means the soundscape is dominated by wind turbine noise and effectively is equivalent to an industrialised sound environment. There are no longitudinal studies of the effects on communities of AM at the boundary of acceptability and this would be impractical due to the scale of such a study and because levels at the boundary are only one component of impact.

There is repeated evidence that except in locations more distant from a wind farm where AM impact is of reduced regularity and has a smaller peak to trough range, occurrence of 3dBA modulation depth will also mean significant periods of much greater modulation depth arises for much of the time. Similarly, periods arise when modulation depth is not substantial but impact is greater. This occurs either because of the frequency content and how unusual the noise is, its rate of change or changes in pitch that are not reflected in the corresponding changes in the "A" weighted decibel levels. It is not possible therefore to segregate long term impacts according to modulation depth.

The AM immisions relating to Cotton Farm WF have some different characteristics to the AM observed at other sites for much of the time and also many common features. For example, the AM measured adjacent Cotton Farm WF could reasonably be described as erratic in nature with continuous changes in character. At many other sites prolonged periods of similar pitch and character AM can arise or AM with a different character to that found at Cotton Farm can arise. Historically it is our finding that when 3dBA modulation depth is commonly experienced communities will experience adverse impact to varying degrees.

3.4. **Use of >5dBA modulation depth data.**

In order to avoid problems of including AM that other researchers may consider acceptable or less intrusive, most analysis of excess amplitude modulation for this paper is focused on periods where peak to trough levels commonly and regularly exceed 5dBA.[7] This approach ensures arguments of extraneous noise inclusion are minimised. Our approach to data analysis is therefore considered conservative.

3.5. Data availability for research by others.

MAS have made some of the Cotton Farm WF data available to others for responsible research; however, in view of the on-going costs to the local community there is now a need to charge for data except for exceptional research projects of merit which are considered on a case by case basis.

3.6. PRELIMINARY DATA FINDINGS

Analysis of 10 months data including shut down periods is considered. This resulted in 10,030 ten minute periods analysed and included. Overall during that period 54% of nights were significantly affected by periods of AM with MD of +5dBA. A further more detailed analysis of 2 months (2/12/13-3/02/14) 56 days provided the following results:

82% of nights occurrence MD+5dBA (46 nights) of which:
30% nights occurrence of classed severe AM (17 nights)
10% nights occurrence of classed borderline MD+5dBA (6 nights)
18% nights little or no occurrence of MD+5dBA (10 nights)
4 continuous nights prolonged of severe MD+5dBA[8]

Table 1 - Cotton Farm: Total periods MD+5dBA v wind direction @ 600m

Wind Speed 10m	% of AM occurring for each wind direction (Degrees from North)															
	0	22.5	45	67.5	90	113	135	158	180	203	225	248	270	293	315	338
0		0%	8%	0%	22%	0%		25%	67%		0%				4%	
0.4	0%	4%	0%	5%	17%	17%	17%	25%	29%	15%		11%	29%	0%	11%	9%
0.9	19%	11%	10%	17%	48%	23%	28%	16%	7%	10%	23%	36%	4%	20%	0%	15%
1.3	15%	20%	28%	28%	54%	35%	39%	38%	20%	19%	20%	19%	26%	24%	6%	0%
1.8	24%	36%	35%	91%	87%	85%	60%	53%	20%	29%	19%	11%	9%	32%	15%	22%
2.2	21%	50%	23%	90%	93%	86%	65%	43%	28%	37%	39%	20%	4%	18%	56%	55%
2.7	34%	71%	30%		88%	100%	81%	66%	45%	57%	58%	28%	7%	16%	22%	53%
3.1	46%	74%			90%	95%	87%	90%	55%	64%	60%	38%	19%	18%	31%	60%
3.6	52%	78%	13%		86%	100%	89%	80%	70%	73%	86%	44%	20%	16%	42%	
4	11%	97%	50%		94%	100%	81%	93%	73%	84%	80%	88%	31%	33%	39%	
4.5	0%	100%			76%	100%	97%	85%	81%	89%	70%	63%	48%	30%	44%	
4.9	0%				50%	100%	93%	80%	64%	88%	67%	80%	30%	53%	63%	
5.4	0%					100%	87%	76%	43%	77%	73%	82%	45%	78%	11%	
5.8	0%					83%	80%	65%	41%	53%	79%		65%		7%	
6.3	0%	Cells with less than 6 records					81%	56%	14%	36%	83%	83%	63%		0%	
6.7	0%	of data (1 hour) are ignored.					29%	70%	36%	44%	78%		62%		0%	
		UPWIND						><			DOWNWIND					

[7] An added point is that the ReUK research suggests convective amplification which they call "normal" AM does not exceed 5dBA modulation depth and that this only occurs under cross wind conditions close to the turbines. Thus their theory suggests this form of AM should not be experienced other than rarely, close to the turbines and with sideways directionality. This was not the reason for comparing above 5dBA but is a coincidental benefit.

[8] Note the background noise level during this period and as influenced by the wind farm noise was 31dB L_{A90}(10 minutes) and modulation peaks were up to 50dBA.

Table 1 compares the percentage of time excess AM with a modulation depth greater than 5dBA commonly occurred for different measured 10m height wind speeds and directions. The extent of upwind AM was unexpected as was the modulation depths and overall L_{Aeq} values. Commonly decibel levels were of similar magnitude when upwind and downwind when AM was occurring.

When considered along with previous field measurements by MAS (4) the Cotton Farm data indicates a directionality pattern to AM that fits reasonably with the theory of Lee et al (5) for convective amplification. When factoring in the refraction effects, the variable pitch and shape of blades and that convective amplification is generated by different parts of the rotor disk in different directions, a pattern is produced that approximates in an illustrative form to the diagram in Figure 6 below.

The Cotton Farm WF and data for other sites confirms a directionality effect which has been tested by moving measurement locations around turbines when the wind direction is relatively steady.[9] This pattern is not entirely clear in Table 1 which is due to the array of turbines meaning the monitoring station is always at different angles to different turbines.

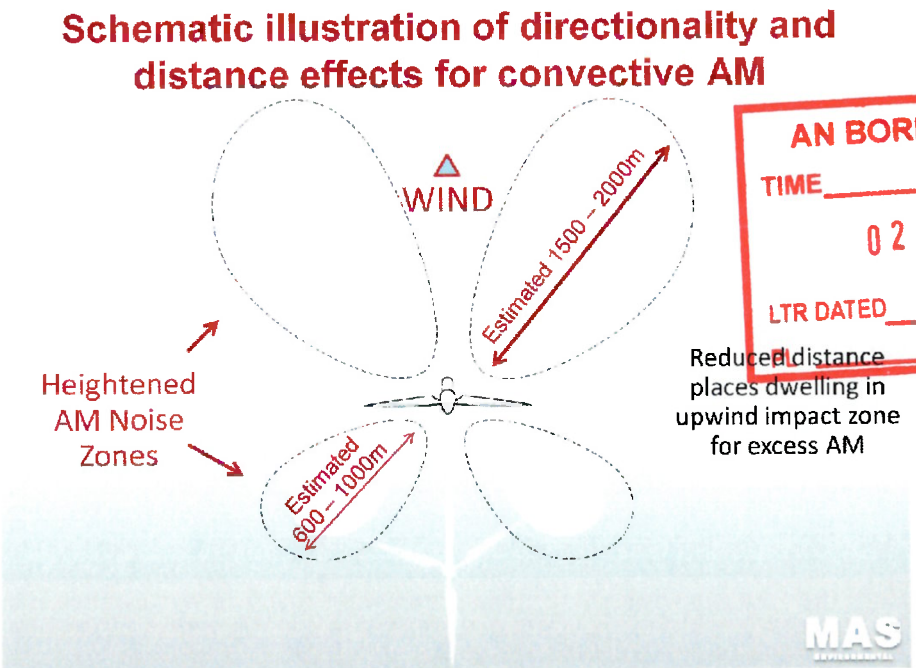

Figure 6 – Schematic representation of apparent wind turbine AM due to convective amplification.

3.7. Analysis of sound energy changes during switch off tests.

As a consequence of the community complaints, operational checks were undertaken and turbines were switched off for periods to enable measurement of the background noise contribution. These switch off tests were recorded by our continuous monitoring and provided valuable data on the changes to the sound environment. Examples are included below with some of the findings discussed. Above each main graph is an expanded section of the varying sound showing the MD and its variations.

[9] Directionality was tested at a number of sites including Delabole, Kessingland and Wadlow as well as Cotton Farm.

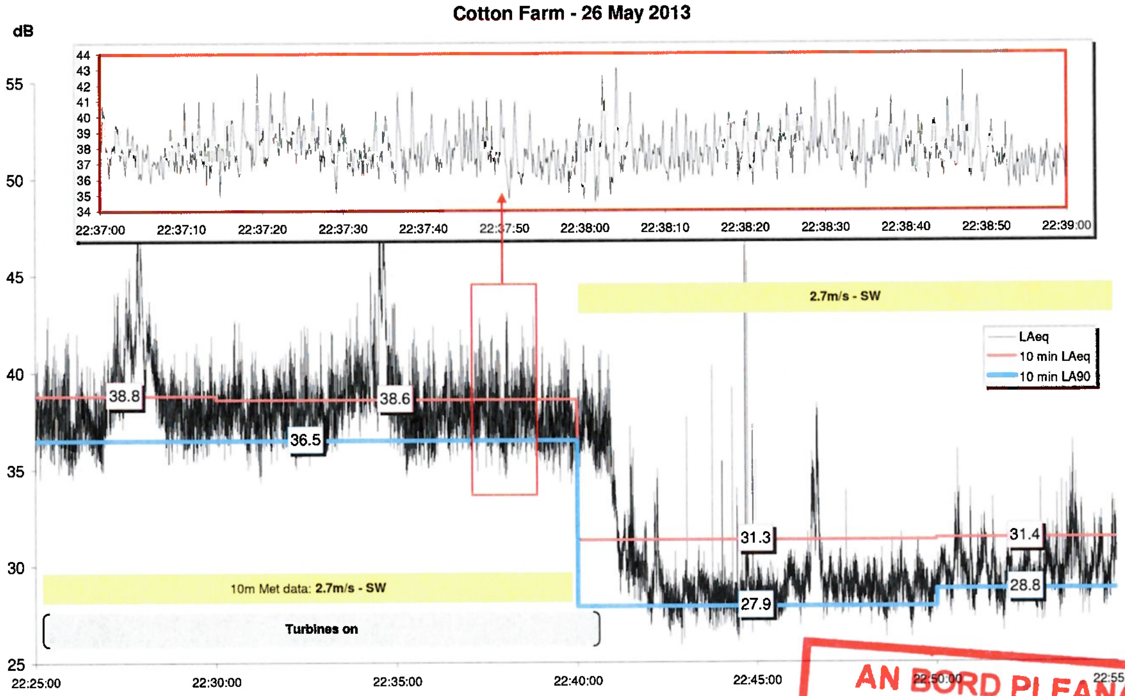

Figure 7 – Example 1 - Cotton Farm 26th May 2013 – Switch off effect

- Change in L_{A90} value = 9dB
- MD 3-6dBA and erratic in nature.
- The minimum headroom before any penalty applied to the ETSU-R-97 limits would start to curtail the noise = 7.1dB.
- This noise is not prevented by the ReUK proposed penalty.
- This noise is prevented by the Den Brook AM procedure (6).

Observations – The impact recorded was under downwind conditions. Near ground winds were low with background noise levels of 28-29dB L_{A90}. The area is relatively quiet absent the wind farm noise which increased the L_{A90} almost double that intended by ETSU-R-97. The AM impact was on top of this increase. Thus the impact from AM was not just its modulation depth, with an average value of 3-6dBA and average energy value of 39dB L_{Aeq} but other wind farm noise exceeding the background by 9dBA, with the AM greater than this and both completely dominant.

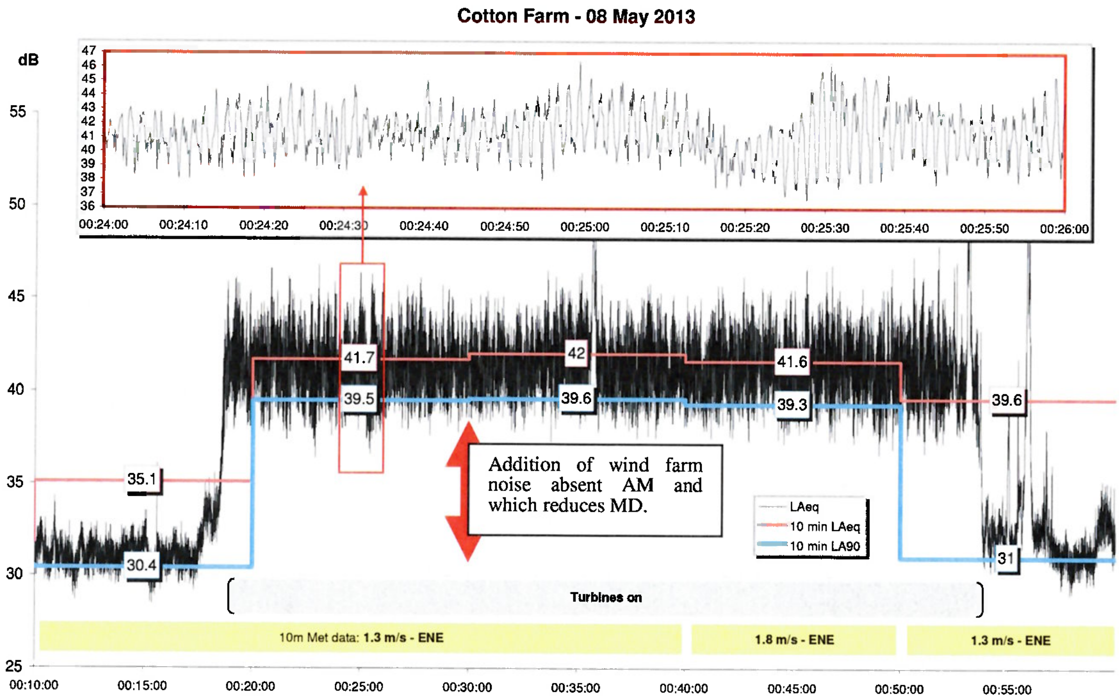

Fig 8 - Example 2 Cotton Farm 8th May 2013 – Switch on/off effect

- Change in L_{A90} value = 9dB
- MD 4-8dBA and classic in nature.
- The minimum headroom before any penalty applied to the ETSU-R-97 limits would start to curtail the noise = 4.1dB.
- This noise is not prevented by the ReUK proposed penalty.
- This noise is prevented by the Den Brook AM procedure.

Observations – The impact on this occasion occurred under upwind conditions. Note: average decibel values are higher than in example 1 and wind speeds are lower. Near ground winds were very low with background noise levels of 30dB L_{A90}. As before it shows the area would normally be relatively quiet absent the wind farm. The wind farm noise increased the L_{A90} almost double that intended by ETSU-R-97. There was a 9dBA increase in the underlying noise due to the wind farm noise. The AM impact was on top of this. Thus the AM modulation of 4-8dBA was on top of a 9-10dBA increase in levels with an overall energy value of 40dB L_{Aeq}. As previously in example 1, there is complete dominance and change in the sound environment.

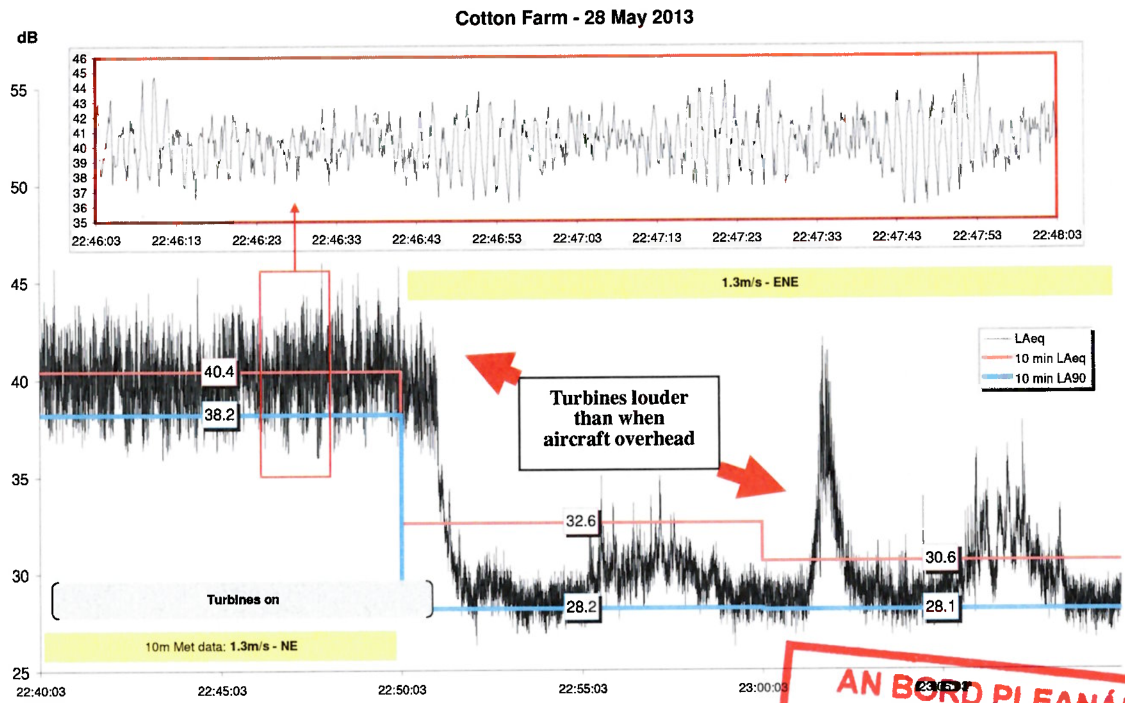

Figure 9 - Example 3 - Cotton Farm 28th May 2013 – Switch off effect

- Change in L_{A90} value = 10dBA double intended by ETSU-R-97
- MD 3-7dBA. Classic and erratic in nature.
- The minimum headroom before any penalty applied to the ETSU-R-97 limits would start to curtail the noise = 5.4dBA.
- Controlled by the ReUK proposed penalty = No
- Controlled by the Den Brook wind farm penalty = Yes

Observations – The impact on this occasion occurred under upwind conditions. Near ground winds were very low with background noise levels about 28dB L_{A90}. This shows consistently it would normally be relatively quiet absent the wind farm. The wind farm noise increased the L_{A90} double that intended by ETSU-R-97. There was a 10dBA increase in the underlying noise due to the wind farm noise. The AM impact was on top of this increase. As in the other examples the impact from AM was not just its modulation depth, with an average value 3-7dBA and overall energy value of 40dB L_{Aeq}, but its exceedance of the background noise by 10dBA. The complete dominance and change of the sound environment is particularly stark. It is notable that in this example aircraft in flight which is normally an intermittent characteristic of the sound environment would be masked by the wind farm noise.

The three examples above are typical, although under conditions of less atmospheric stability the differential between the normal sound environment absent the wind farm noise and that with it are less.

3.8. Cotton Farm – Switch on/off tests - Findings.

There was typically a 9dBA increase in the sound environment due to the turbines equating to a major change even without the presence of AM. The range identified was between 5-10dBA. The typical or most common modulation depth was in the region of 3-7dBA but at times has reached 13dBA. Excess AM was very common and an additional impact to the stark increase in sound energy and dominance of wind farm noise. The change experienced at switchover provided a good method for perceiving the difference in the soundscape caused by the wind farm noise and it is recommended such periods are used in any listening tests, where available, to enable judgment of impact.

The ReUK research approach and their proposed penalty permitted all the periods of AM experienced or tested including the periods of most extreme AM recorded from Cotton Farm WF. In most cases there was substantial headroom below the limits and none of the periods of noise causing complaint would be reduced in level or stopped. In contrast a metric built on the Japanese procedure (1) would be more effective provided it did not link to the ETSU-R-97 limits, but addressed it as standalone procedure. The Den Brook condition would prevent the impact experienced. Upwind and downwind L_{A90} values were similar at the measurement distance (600m) but the upwind AM presented different character in the noise compared to the downwind AM.

3.9. Further evaluation of AM Metrics

A procedure based on the Japanese method (1) appeared to most closely map actual impact as it varied well with variations in modulation depth. The ReUK method missed significant periods and forms of AM. The attached graph presents an example of this. This is outlined in Figure 10 below.

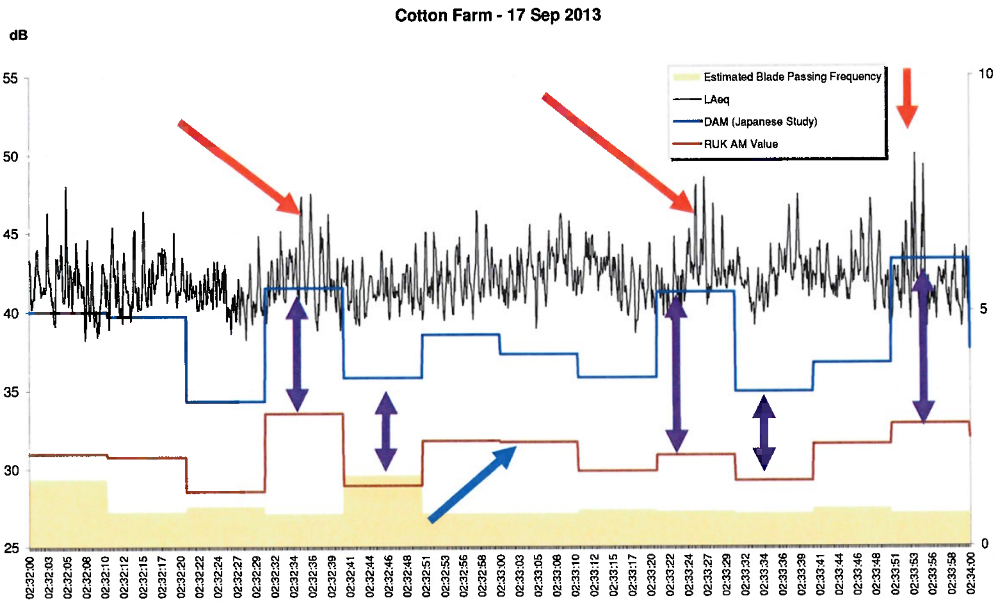

Figure 10 - Example analysis of ReUK condition versus Japanese method for 2 minute period of AM – 100ms LAeq (black), Japanese study D_{AM} (blue), ReUK AM value (brown), Calculated blade passing frequency (solid beige).

In the absence of SCADA data, the ReUK method value is based on the scenario that gives the highest figure, that which is the blade passing frequency matching the peak in modulation indicated on the graph as "Estimated Blade Passing Frequency". Even at this highest possible value, the ReUK method understates periods of increased AM and changes in noise are excessively damped. Compare the brown horizontal lines produced by the ReUK method every 10 seconds with the blue horizontal lines using the Japanese method[10]. The latter reflects the sudden changes in AM modulation depth not found with the ReUK method.

The graph shows a typical period of AM that has erratic elements of change. Three periods are identified by red arrows where the modulation depth suddenly increases, potentially due to synchronicity of the noise immissions from turbines. Not only are there differences in scale of change but the ReUK method does not always map increasing or reducing AM with an increased or reduced value. The blue arrow shows a period where one method increases its value when the other reduces. Subjectively the impact was reducing at this point.

10 The method is slightly adapted to enable comparison with the ReUK method.

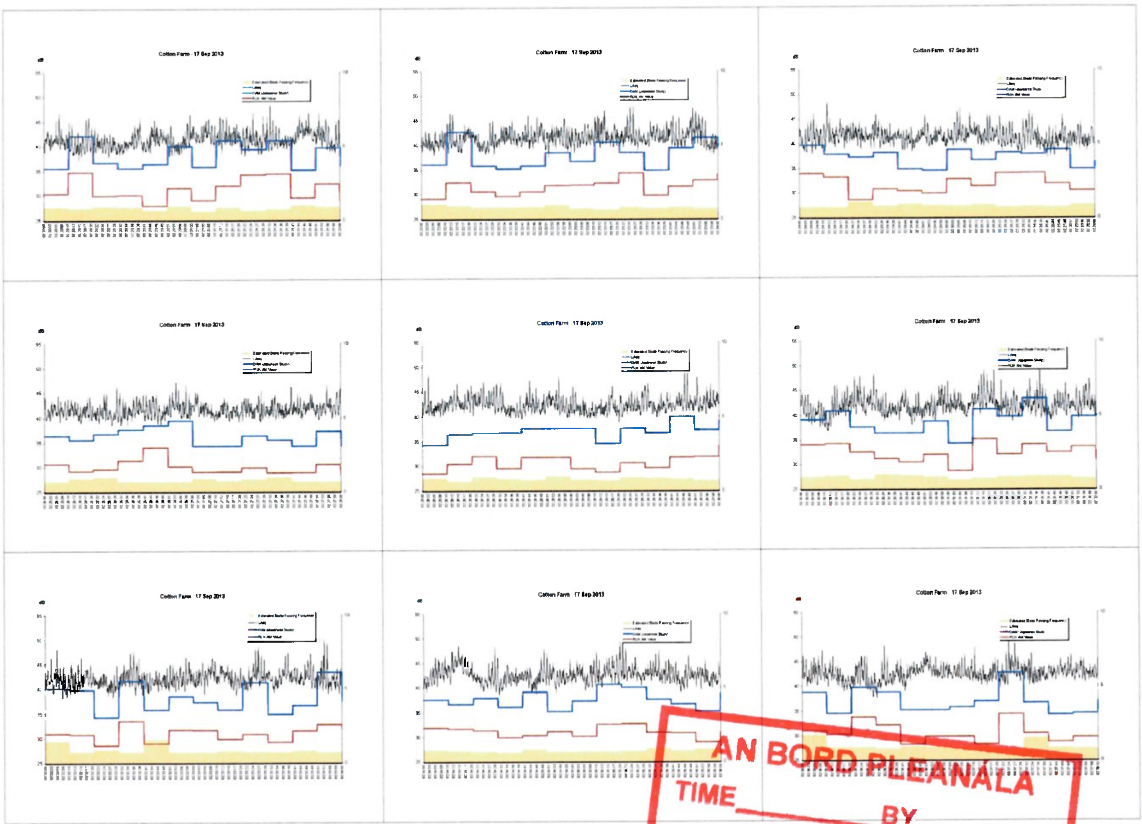

Figure 11 - Example tests.

Figure 11 – Reflects the fact extensive comparative tests have been undertaken using algorithms which consistently showed the ReUK procedure understated impact and regularly presented spurious results which did not reflect the AM experienced. This was rarely found with the Japanese procedure. Neither method can give full weight to changes in character such as changes in pitch, discontinuity and rhythm in the noise.

3.10. Summary findings from initial data analysis of the Renewables UK proposed condition.

a. Even when looking at the worst case AM recorded at night, however extreme it was permitted to continue uncontrolled by the ReUK condition. Analysis included 10 months of Cotton Farm data plus data from two other sites. The results were consistent.
b. Manipulating the data to apply the most extreme 10 seconds ever recorded as if continuous, with modulation depths up to 13dBA and an average modulation depth of 9.6dBA, it was still permitted by the ReUK method.[11]
c. There was a lack of transparency with the ReUK process preventing any ability to relate the results to actual impact.
d. Promotion of a procedure following research has led to an assumption by some that it works and it has been recommended and applied in cases. It is understood ReUK accept there are difficulties with the control.
e. The procedure remains highly technical preventing any means of easily isolating and addressing the areas where it fails.
f. The process is cumbersome and requires judgment checks at several stages. Software has been released to assist but this similarly renders the process cumbersome and open to judgment at several stages.
g. The procedure remains reliant on manual checks and notwithstanding its failure to be triggered it has rendered the process far more labour intensive than manual data checks.
h. The primary problem is the method understates modulation depth and in any event cannot assess other character.

[11] In this example the ReUK procedure produced an AM value of 6.5dB (3.1dB lower than actual) and applied a penalty of 3.8dB adjusting the limit to 38.5dBA. This still left headroom of 0.7dB before any reduction was required. Even then it would only require a reduction in overall level and not the modulation depth.

i. The procedure ignores harmonic noise at blade passing frequency which has varying significance depending on the type and character of AM being checked.
j. The procedure's error rate changes depending whether wind farm noise is dominated by one turbine at a location or contributed to by several turbines producing noise of similar magnitude. It falls substantially short of any level of obvious protection and is partly based on the erroneous idea principles for benign anonymous noise are transferable to noise with psycho-acoustic character.
k. Averaging effects of the ReUK approach indicate modulation depths of 10-13dBA result in a penalty of less than 4dBA.
l. Work by the UK Renewable Energy Foundation similarly found significant errors with the ReUK approach[i] and effectively recommended the Den Brook condition. (7)

3.11. Analysis of some ReUK general findings using Cotton Farm data.

The key conclusions in the ReUK report of interest to this research are the suggestions that:

- "Normal" AM (convective amplification) has a maximum value of 5dBA MD close to the turbines and occurs mainly in a crosswind situation.
- AM greater than 5dBA is caused by what ReUK term "Other" AM which they mainly attribute to "blade stall" effects.
- "Blade stall" is an infrequent condition and possibly rare but when it occurs it has quaquaversal emission such that it will impact equally in all directions, subject to wind refraction.
- AM impact increases with increasing energy level (L_{Aeq}) and not modulation depth increase.

Whilst the ReUK study provides some useful work helping progress, the Cotton Farm data and other data sets suggest some erroneous conclusions. In particular the common incidence of AM found at Cotton Farm WF and in various studies including the previous MAS paper (4) does not fit with the ReUk finding that AM above 5dBA modulation depth is infrequent. The directionality found in data is also contrary to the ReUK work which considers OAM as omnidirectional. [12] The Cotton Farm data and other study suggests most AM impact is convective amplification and this is not limited to 5dBA in a cross wind direction. In these circumstances the ReUK study of "blade stall" assists with one possible mechanism adding to the occurrence of AM but erroneously concludes this is the main cause of impact and that overall it is infrequent.

Complaints of AM appear to relate more to the audibility of specific intrusive characteristics and not its average energy level as implied in the ReUK study. The Cotton Farm data shows the tests undertaken in the ReUK study do not reflect what noise impact is received at community locations. Disregarding the short periods of exposure used in the ReUK study, their comparison was made by elevating the sound energy of AM in an otherwise quiet environment rather than testing it in context with the actual effects found in communities.[13]

The Cotton Farm data shows that higher sound energy AM (increased L_{Aeq}) occurs on top of the increased characterless wind farm noise that serves to mask the troughs in the AM reducing its MD. Comparatively the addition to impact from AM on top of the reasonably steady wind farm noise is relatively the same even when the average sound energy is greater. This addition is shown by the red arrow in Figure 8 above. It is likely this context change with the emerging AM fluctuations on top of the overall wind farm noise is a cumulative effect which generates the community responses and not its average energy level in isolation which would be much lower absent other wind farm noise contribution.

Complainants appear to object as much when AM is low in level and without it the environment would be tranquil. The evidence also suggests increased low frequency content can arise when average energy levels are lower and this change in character is a further factor to be considered but which was excluded in the ReUK response tests. Testing of response to noise in very short bursts in a laboratory is unrepresentative of human response in the field, especially when impact response commonly relates to weeks and months of impact and in some cases it is a matter of years. In our study (4) we found significant response differences to wind turbine AM listening experiences when they were conducted in an office compared to a home environment and when conducted daytime compared to late evenings. We also concluded exposure for a period in excess of an hour was typically required to elicit an appropriate reaction. Critically we considered it important to use actual AM with background noise such as bird calls to place it in context and so create a realistic environment. Changes in characteristics over time are also a common

[12] Closer examination of the ReUK field work enables alternative explanation for a number of their findings.

[13] 20 second bursts of artificially generated AM were used.

AM feature that was not tested by ReUK but are found with actual field data.[14]

3.12. **Predicted wind farm noise versus measured levels - ISO9613-2 based predictions.**

Data from Cotton Farm indicates procedures adopted in the UK to predict wind farm noise understate decibel levels at far field locations. In the UK prediction methods rely on a modified ISO9613-2 procedure developed primarily from research by Bullmore et al in 2009 (8) and latterly by research in 2011 by Cooper and Evans (9). A number of spot checks by MAS previously found actual levels under high wind shear conditions higher than those predicted by Bullmore et al. Concern also arises as the predictions rely on averaging, but compliance under ETSU-R-97 requires selection of specific circumstances of complaint. These conditions, normally relating to high wind shear, were not factored into the Bullmore et al study.

MAS has separately concluded the research did not sufficiently support its conclusions long before the Cotton Farm project commenced due to anomalies within the work; however, Cotton Farm WF's predicted noise was decided on the basis of the current ISO9613-2 method following the Bulmore et al work. It is considered the work by Cooper and Evans (9) indicates higher levels than the adopted UK method as when differences in use of L_{A90} and height are accounted for to compare the UK methodology, for flat sites, it suggests the UK method understates values up to 2dBA.

Criticisms arose over the Bullmore et al (8) research due to the high level of filtering of the data that was not transparent and not all the reported data supported its conclusions. Requests by others to obtain the data to enable peer review were refused and this remains the position to date (10). A request by MAS to review the data of the Cooper and Evans study was similarly refused in 2013.

The data expert who requested the Bullmore et al data reverse engineered some of the published information and concluded downwind angles were incorrectly reported in the study (10). The sites used in that study remain anonymous but their descriptions have enabled their identification. No response has been received from the authors. In these circumstances and in light of the findings from Cotton Farm WF reported below and at other sites, it is concluded little weight should be given to that research and additional study is required.

Long term Cotton Farm WF measurements compared to predictions are presented in Figure 12 below.[15] Compare the purple predicted level for the turbines actually installed with the grey circles showing wind farm noise and the green line showing the average wind farm noise for a standardised wind speed. The values indicate average levels were typically 3-4 dBA higher than those predicted and during periods of worst impact levels were of the order of 5-9dBA higher than predicted. More than 85% of the calculated wind farm noise levels exceeded the predicted values.[16]

[14] The lead researcher has confirmed acceptance their analysis understates likely responses when presenting the evidence at an IoA seminar March 2014.

[15] The measurements reported in this section were obtained independently from the operator's acousticians to avoid any dispute as to the findings based on 10m height wind measurements and they relate to standardised wind speeds.

[16] After deducting background noise contribution.

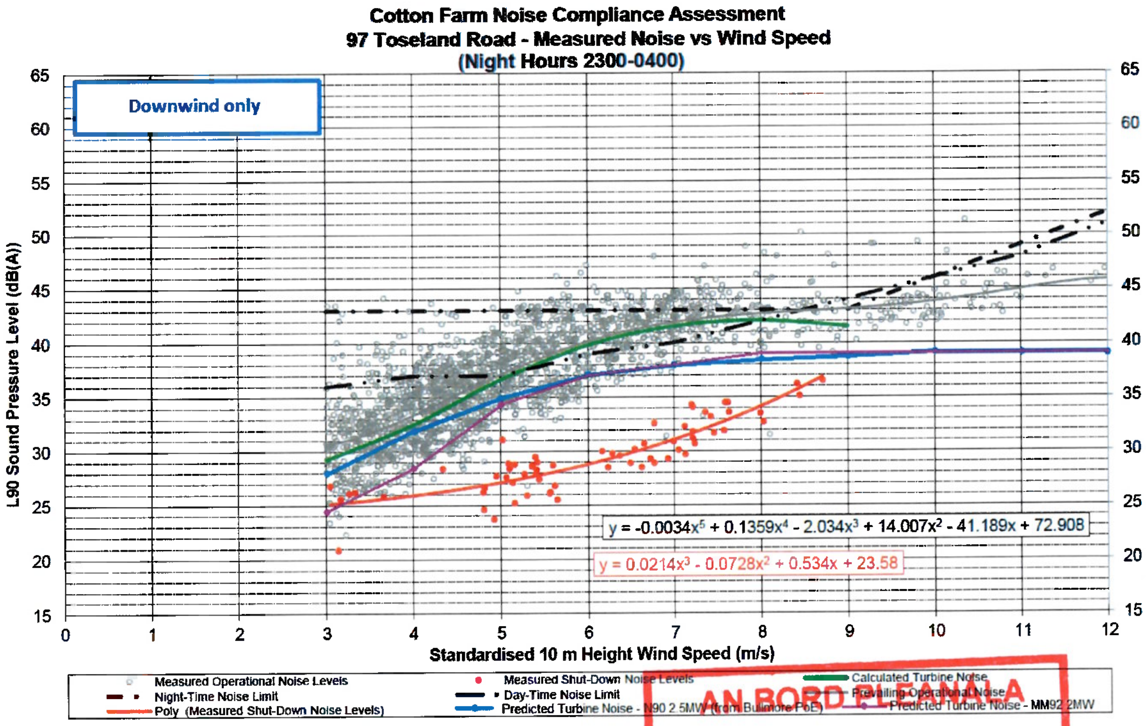

Figure 12 - Predicted turbine L_{A90} v actual L_{A90}

The findings in relation to Cotton Farm WF data compared to predictions are also supported by data obtained at the Swaffham II turbine, an Enercon E66. The data was collected by MAS and reported at the Shidham public inquiry (10). In that case predicted levels using the ISO9613-2 procedure adopted in the UK understated levels by on average 5.7dBA. No explanation has been provided for this significant exceedance. Similar exceedances have been found by others (11).

It is concluded the typical individual complaint event caused by wind turbine noise, which occurs under high wind shear conditions, may be of the order of 5-8dBA higher than the predicted noise for those conditions. This outcome is contrary to the intent of ETSU-R-97, which was designed to limit exceedance of the background noise as measured using the L_{A90} index to 7dB L_{Aeq}. It is concluded the increase in impact compared to historical wind farms in the UK arises as a result of the adoption of hub height wind speeds standardised to 10 metres rather than comparison with measured wind speeds at 10 metres as originally identified in ETSU-R-97 and this follows published research by MAS and others comparing the two methods (12) (13). The adoption of what is effectively hub height wind speeds as found in the UK IoA Good Practice Guide 2013 is a deliberate change effectively increasing the level of noise permitted near residential property through change of procedure. It is considered this is partly the reason for an increase in problems and complaints in the UK and especially excess AM problems as they now impact dwellings under upwind as well as downwind conditions partly because separation distances are reduced. Propagated levels increase with wind shear increase and they exceed the UK predicted levels by large margin.

MAS are unaware of any cases where predictions have overstated impact once adjusted for the turbine operational mode, complaint conditions and appropriate wind direction. It is concluded a review of the procedure is warranted. It is of note that had the higher sound energy levels identified post development of the Cotton Farm WF been predicted it is likely the development would have been recommended for refusal on noise grounds.

4.0. SUMMARY FINDINGS - What the Cotton Farm WF data shows

a. Far field AM follows predictions of convective amplification most of the time.

b. Far field AM with a modulation depth of 5dBA and higher is very common. It is not infrequent as suggested by ReUK and is not found mainly under cross wind as they state but at downwind angles. It is not normally experienced directly downwind of a turbine.[17] The spread of turbines in a wind farm usually means a receptor is at an appropriate downwind angle to be affected by convective amplification for a wide range of wind directions.
c. Convective amplification AM theory as explained by Lee et al 2013 (5) is supported and the concept that modulation depth can be much greater than 5dBA at distant receptors is also supported by the measurements.
d. "Other" AM, primarily related to blade stall, in the ReUK research December 2013 is not the primary cause of far field impact, albeit important, but an extra mechanism leading to impact.
e. Findings of ReUK of increasing impact with increasing average noise (L_{Aeq}) fail to address context / ambient change and therefore rely on incorrect assumption.
f. Excess audible amplitude modulation is the primary characteristic causing complaint. Where tonal noise also arises it sometimes also modulates.[18] Impact appears less related to average sound energy but its relative loudness considered in context and other wind farm noise contributions that are cumulative and separately its characteristics.[19]
g. AM exhibits a range of features and characteristics that constantly vary and are different from site to site and under different meteorological conditions.
h. AM impact can be as great under upwind conditions at distances of 600m as it is under downwind conditions.
i. Upwind and downwind AM characteristics differ.
j. Predictions using ISO9613-2 understate sound energy levels when applied using the procedure as set out in the UK IoA Good Practice Guide 2013. This finding is also supported by independent evidence. The understated average level is typically 3-5dBA at 600m and under certain conditions is much greater. This outcome follows similar findings at a range of other sites including the Swaffham II wind turbine where detailed comparisons were made with the turbine operational data.
k. AM impact occurs under a wide range of wind directions as illustrated in terms of distance and direction resulting in heightened noise zones. The actual spread of these zones can be complicated by the spread of turbines producing overlapping zones.
l. AM with regular peak to trough greater than 5dB occurred more than 54% of the time at 600m from the nearest turbine.
m. During a 2 month period 82% of nights experienced AM with modulation depth in excess of 5dBA and up to 13dBA. Severe AM occurred for 30% of nights, four of them consecutively.
n. At a distance of 600m, in the case of Cotton Farm WF AM in excess of 5dBA modulation depth occurred more commonly under upwind angles than downwind angles but both incidences were high.
o. Incidence of objection to the noise appears to increase with time with increasing awareness and an apparent sensitisation over time.

4.1. Additional findings indicated by the Cotton Farm data and its analysis

p. Propagated levels increase with wind shear increase and exceed those predicted by the IoA adopted prediction method by a significant margin. These increased values follow the science and what has been found by some other researchers.
q. As wind shear increases masking noise reduces (WT and non-WT) leading to greater context differences and impact as a result.
r. As masking noise reduces modulation depth increases. This is logical as the troughs in the noise are no longer masked. This indicates any proposed control based on LA90 values reduce protection as modulation depth increases.
s. Modulation depth is mainly limited by other wind turbine noise and not the background noise in an environment.
t. Switch off tests should be closely monitored and provide a good method of measuring the true change in a sound environment.
u. There are a wide range of characteristics where subtle differences change the impact. It can be highly erratic, repetitively similar or with repetitive changes. Variations can occur rapidly. Character change moment by moment is a significant factor. These are all significant factors in the intrusiveness of the noise.
v. Community monitoring is a valuable assessment tool empowering the community, can be achieved at reasonable cost and operated by the community in many cases.

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[17] Zero degrees to the wind direction or 90 degrees to the angle of the turbine where there is no yaw error.

[18] This is thought to be due to the noise radiating from specific blades.

[19] Relative loudness was not examined in the ReUK study.

w. The occurrence of when and where AM will impact is reasonably predictable depending on the particular circumstances relating to a site.
x. The defining factor as to the level of impact is meteorology and the extent of upward or downward atmospheric refraction. Small changes can lead to large differences in effects.
y. Nearby locations can experience wholly different noise levels and character depending whether they are in a heightened noise zone.
z. Complaints are unrelated to individual attitudes to wind farms and have arisen due to actual impact and not perceived impact.

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inter.noise 2014
MELBOURNE AUSTRALIA
16-19 NOVEMBER

The noise characteristics of 'compliant' wind farms that adversely affect its neighbours

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ABSTRACT

In the UK many wind farms cause complaints of noise despite complying with control limits. Problems relate to reliance on the L_{A90} index, failure to consider or apply ratings on the context of the sound characteristics and actual human responses due to complex characteristics. In general in the UK low frequency and very low frequency sound effects are either ignored or denied. The complex interrelationship of features within this noise and difficulties in quantifying and qualifying noise impact and inappropriate comparison with other sources of noise renders the effects difficult to investigate or quantify with contradictory outcomes possible using the same data sets. Claim and counterclaim of health and adverse effects complicate the analysis. This paper explores some of the interrelating characteristics of wind farm noise measured and observed in the field that appear to influence complaints made by communities. Cumulative effects occurring in environments normally dominated by natural sounds and both audible and inaudible elements remain alien sounds which are not habituated to. It appears that sensitisation arises. The physical reason for the failure to appropriately identify modulating noise effects and in particular low frequency modulating noise problems are explored.

Keywords: Wind farm, Complaint, Noise character I-INCE Classification of Subjects Numbers: 14.5.4, 63.7, 66.1, 66.2

1. INTRODUCTION

Human reaction to noise is influenced by a large number of objective and subjective factors. Perception and interpretation of these factors is highly individual and individual differences can be difficult to account for in any metric aimed at assessing the general population. As a result, analysis tends to focus on physical, easily measurable properties of sound. Subjective assessment of noise character is often neglected. The majority of guidance relates to noise that is considered benign and anonymous and does not contain specific character features. Where character is considered this tends to be limited to a simplistic, objective assessment of tonality and / or impulsivity.

In the UK noise nuisance assessment establishes whether a state of affairs exists where there are periods of intrusive noise that are unreasonable and excessive to the extent that they affect the use of enjoyment of a property in a material way. It requires a broader assessment approach that includes consideration of loudness, time of occurrence, duration, character of the noise, character of the area, message imparted by the noise, variation in noise over time, spectral content of the noise, frequency of occurrence, regularity / predictability of the noise, respite from the noise, length / duration of respite, how easily the noise can be avoided, impact of the noise on basic needs such as sleep or communication, the necessity of the noise in relation to greater society etc. That all these factors are deemed important for considering whether a noise constitutes a nuisance highlights the complexity of noise perception and impact, and arguably the oversimplification of these factors at the planning stage.

Noise assessment at the planning stage reduces assessment of acceptability to decibel levels and limits. In wind farm assessment in the UK, acceptability is for the most part judged against absolute limits or relative limits with an absolute lower threshold. Development can always be permitted if these lower thresholds are met, regardless of noise character or character of the area.

As wind farm noise is typically predicted at lower decibel levels than other industrial noise sources, comparisons are often made in noise impact assessments to 'contextualise' the level of impact being permitted. A wind turbine noise level of 35dB(A) is frequently asserted as equivalent to the noise level in a library or a quiet whisper (1). The 43dB L_{A90} UK night time limit is often compared to the noise level generated by a fridge (2). These comparisons and the focus on decibel levels can present a highly misleading impression of noise impact to the lay person.

An experienced acoustician always questions the noise levels and comparisons quoted, but this may not be obvious to a less experienced reader. A commonly quoted example in the media is that of the impact of military sonar on whales. "Sonar systems... generate slow-rolling sound waves topping out at around 235 decibels; the world's loudest rock bands top out at only 130" (3). Are the quoted figures sound power levels or sound pressure levels? At what distance were the noises measured? Are the figures A weighted? Do the figures account for the effect of propagation (speed of sound in water / air)? What is the frequency content? Is the noise level quoted a short term, average or maximum level? These same questions are relevant for assessment of wind turbine noise. A wind turbine may generate a noise level of 35dB(A) in average propagation conditions, but what about turbulent wind conditions and high wind shear? Is the noise constant or does it vary? What is the frequency content of the sound and does the dominant frequency vary? Is 35dB(A) the average level and does the sound vary significantly from this overall level? These questions are integral to perception and assessment of noise impact.

Perception of noise is complex and many factors influencing perception can be overlooked or oversimplified at the planning stage by reliance on absolute decibel limits and objective parameters. Inappropriate comparisons such as those given above are not only erroneous but the dogmatic oversimplification of wind farm noise assessment undermines the integrity of the acoustics profession. This paper investigates noise character and how these characteristics might contribute to the perception of wind farm noise. It compares detailed analysis of wind farm noise excerpts with other assessment metrics. It looks for explanation of why so many wind farms found to be compliant with noise limits generate significant complaints.

2. METHODOLOGY

2.1 Brief review of relevant UK guidance

UK wind farm noise is assessed using the guidance ETSU-R-97 (4). Wind farm noise is measured and assessed using the L_{A90} index of 10 minute periods. The guidance acknowledges a mid frequency 'swish' component to wind farm noise, 2-3dB(A) modulation around 800-1000Hz, but notes that as distance increases from the turbine this noise will decrease and masking of the background noise will therefore reduce any subjective impact (p.12). Tonality is noted in ETSU-R-97 as the main cause of noise complaints. In the event of complaints of tonal noise a maximum penalty of 5dB can be applied. The noise limits set in ETSU-R-97 therefore relate only to anonymous noise. Tonality is accounted for by penalty and amplitude modulation (AM) / blade swish is expected to reduce with distance to the point that it is not clearly discernible at residential dwellings. There is no further consideration of noise character.

Perhaps the most commonly used standard in the UK is British Standard 4142 'Method for rating industrial noise affecting mixed residential and industrial areas'(5). The standard is currently under review but the approach to noise impact assessment is similar both in the current and draft version of the standard. The background noise level, L_{A90}, is measured in the absence of the noise source. The noise source is measured, accounting for exclusion of extraneous noise, or calculated. A penalty is applied to the noise source for noise character, tonality, irregularity or any other feature that attracts attention. Currently the maximum penalty is 5dB but in the draft version this could be augmented with separate penalties for tonality and impulsivity. The background noise level is deducted from the source noise level plus any relevant penalty to give a complaint prediction level. If this complaint prediction level is around 5dB, noise impact is considered of marginal significance. If the complaint prediction level is 10dB or more then noise impact is considered likely to result in complaints. The important difference between this approach and that of other noise guidance is that it compares the source noise level to the background noise level occurring at the time of impact; it is not an average background noise level and there is no lower threshold of acceptability. BS4142 has proved to be a very successful and reliable judgment of noise impact.

2.2 Other objective assessments of noise character

International standards arguably consider noise character in greater detail than the UK's ETSU-R-97. The New Zealand Standard (NZS) 6808:2010 also measures wind farm noise using the

L_{A90} parameter but takes account of character under 'special audible characteristics' (6). It notes that wind farms should be designed so that no special audible characteristics arise, but where they do a maximum penalty of 6dB can be applied. This penalty is the maximum penalty to be applied regardless of the number of characteristics, e.g. tonality, amplitude modulation, impulsivity etc. The New South Wales draft wind farm guidance measures noise using the L_{Aeq} parameter and similarly to the NZS a maximum 5dB penalty is applied for the presence of tonality, low frequency noise or amplitude modulation (7). Danish guidance measures turbine noise using the L_{Aeq} parameter and has a separate limit for low frequency noise; tonal penalties are also applicable (8).

As with ETSU-R-97, international guidance tends to relate noise impact to absolute decibel levels, affording a maximum reduction of 5-6dB for noise character. Of note, amplitude modulation is recognised internationally as an adverse noise characteristic of wind farm noise, in the UK this is still a matter of debate. It is the authors' experience that amplitude modulation is the main cause of noise complaints from large wind farms in the UK.

At the end of December 2013 Renewable UK, a UK wind industry body, published the findings of research in to the cause and effects of amplitude modulation (9). Despite concluding that amplitude modulation was infrequent, attached to the main publication was a template noise condition for control of amplitude modulation. The current notion is that a maximum penalty of 5dB would be applied to the noise limit of a wind farm where amplitude modulation was found. The effectiveness and workability of the condition is still a matter of debate. Many working for the wind industry are still unwilling to accept controls on amplitude modulation, relying on assertions that it is a rare occurrence at a minority of wind farms.

Other methods for assessing wind farm noise character, specifically amplitude modulation, have been pursued independent of penalties and noise limits. A large study funded by the Japanese Ministry of the Environment resulted in three papers published in August / September 2013 (10) (11) (12). Recognising that amplitude modulation is a common feature of wind farm noise that causes serious annoyance, a method to evaluate the magnitude of AM was derived, D_{AM}. The onset of fluctuation sensation was confirmed at around 2dB modulation depth, equivalent to a D_{AM} of 1.7dB. Perceived noisiness increased as AM depth increased.

The Nordtest method is designed to assess the prominence of impulsive sounds and also proposes an adjustment criterion for the measured L_{Aeq} of an impulsive noise (13). This method was adopted by DiNapoli to investigate complaints from a single turbine in Finland (14). The Nordtest method derives a prominence value 'P' from the onset rate of the modulation peak and the difference in level between peak and trough. A graduated adjustment K_i based on the prominence, P, can be made to the L_{Aeq}. The standard also notes that when $K_i>3$ this can be used as support for application of a 5dB penalty made from subjective assessment of noise character.

In the UK another metric for establishing reasonable / unreasonable AM has been widely debated. The method is detailed in the 'Den Brook AM condition' but essentially looks for a regular rise and fall in sound energy of 3dB (15). Sound energy levels investigated must be greater than 28dB L_{Aeq},1 min. If wind turbine noise modulates regularly by 3dB or more, at average levels more than 28dB L_{Aeq}, it can be deemed 'greater than expected' and considered unreasonable.

There are many other metrics proposed for assessing AM modulation depth. Review of the different methods to assess AM is outside the scope of this paper, which aims to look at some of the ways in which AM can be assessed and whether these methods can appropriately addresses the character of wind farm noise.

2.3 Subjective assessment of noise character

The importance of psycho acoustical factors in perception and assessment of wind farm noise was discussed in greater detail in a previous paper by the authors (16). In brief, the perceptual environment is constantly appraised and reappraised. Sensory information is judged against previous experiences and expectations. Much of this sensory information is ignored but there are other aspects that are either voluntarily or involuntarily focused upon. In relation to sound it is often sudden or unexpected sounds that attract attention, for example a door slamming. However, attention can also be drawn to subtle changes in our sound environment as well described in the extract below (17).

> *Suppose you hear the sound of a refrigerator pump – a series of noise bursts of a certain duration, spectral distribution, onset, offset envelope, location in space, cycle time, and so on. If the sound is not painfully loud, people will tend to lose awareness of it rather quickly, but they will tend to be conscious of the noise again as soon as any parameter of*

> *the sound changes: The noise can become louder or softer, the time between the noise bursts can change, the intensity envelope can change, or the noise bursts can just stop. Any of these changes will trigger a new OR [orientating reflex], just as we may become aware of the noisy refrigerator as soon as the noise stops.*

The capabilities of our hearing system are well exemplified by our ability to analyse music, even by the untrained listener. We can listen to a piece of music and ascertain the basic rhythm, regular 1, 2, 3, 4 counts or a dance, for example a waltz which counts 1, 2, 3, 1, 2, 3. We can make a judgement of the tempo, whether the music is fast or slow, and whether the tempo varies (accelerate / decelerate). Musical descriptors can be used to portray a message, emotion or character. The loudness of the music is a simple judgement and often conveys the energy of the music. Something that is loud or has sudden differences in loudness often represents lots of energy. The frequency content of music, differences of pitch, are also commonly used to convey a message. In Prokofiev's Peter and the Wolf the flute and oboe, higher frequency woodwind instruments, represent the bird and the duck as smaller docile animals. The hunters and the wolf are characterised by the timpani / bass drum and the French horns. These are lower frequency instruments with a harsher sound and represent more dangerous characters.

Simple messages portrayed by music can be extended to messages conveyed by noise. Many of the features used in music to attract attention, variance in loudness and pitch, may also explain why some noise is considered benign and other noise more annoying or difficult to habituate to. A more musical analysis of noise can highlight different aspects of sounds that are easily distinguished by the auditory system and colour our perception of the environment. Approaching analysis of noise with character from a musical perspective might enable better understanding of wind farm noise annoyance.

2.4 Assessment approach

The remainder of this paper presents several examples of wind farm noise that have been found to comply with the noise limits set according to UK guidance. The excerpts presented are judged 'compliant' and in many cases complaints and enforcement action has been dismissed as a result of this compliance. The character of the noise will be discussed and analysed from a musical perspective, exploring the interrelating features and how these might be perceived. Different assessment metrics described above have also been applied to the extracts. Where necessary a description of how metrics have been calculated is provided in footnotes accompanying the results table for each example. A prominence (P) value has been determined according to the Nordtest method for three representative modulation peaks in each example, these are marked 'P1', 'P2' and 'P3' in the figures and tables.

3. FINDINGS

3.1 Swaffham II - 30th September 2013 - 1 x 1.8MW turbine

The graph below shows clear amplitude modulation noise. With the exception of some insect noise (around 12.5kHz) the wind turbine noise is the only and dominant noise source. The noise level varies in loudness throughout the extract. The shape of the noise trace varies in waves but without regularity.

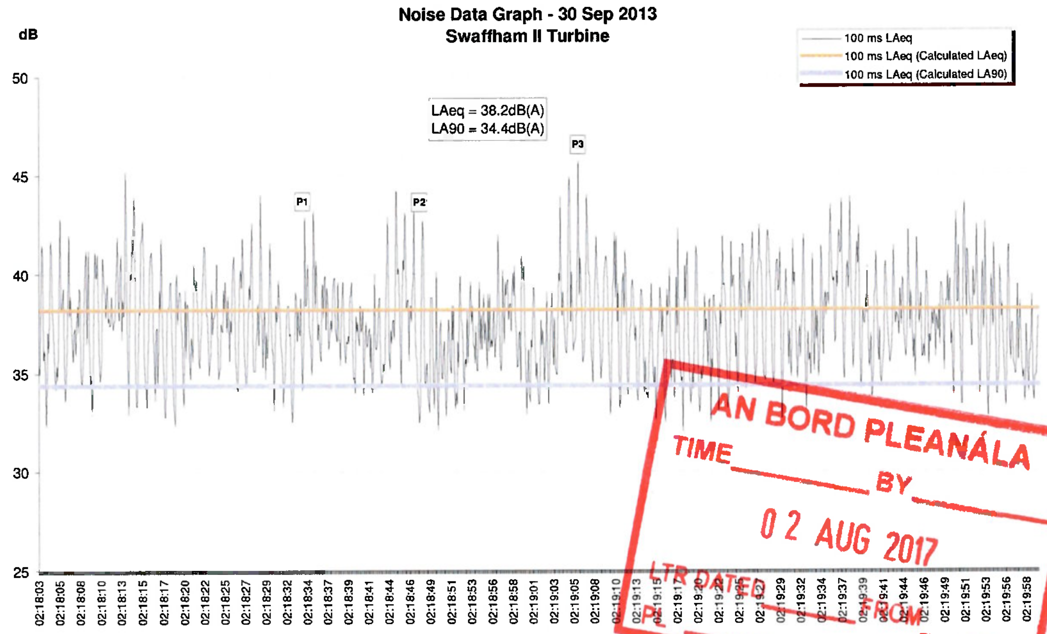

Figure 1: Swaffham II turbine - 30th September 2013

Increases and decreases in noise level and modulation peaks are followed by sudden reductions in noise level and modulation strength. The variances in loudness and clarity of modulation peaks can be compared to someone twisting the volume control on a music player or a radio station coming in and out of frequency range. The dynamics of the piece are very erratic and convey an image of something that has significant potential energy but is also highly changeable and unpredictable. Figure 2 below shows how the first minute of the above extract could be marked musically.

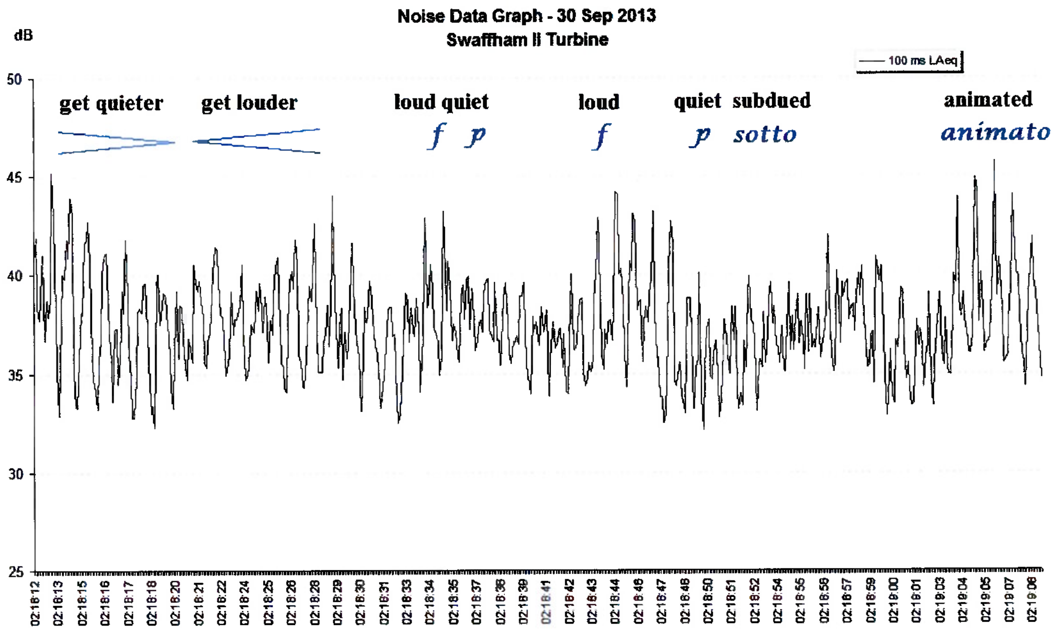

Figure 2: Musical description of first minute of figure 1

Where the listener is not in control of sudden or unpredictable change these changes are often ill perceived. The constant variance in clarity and loudness in the above extract could therefore attract attention and be perceived as annoying or unpleasant.

The character of the modulation also varies throughout the extract. Both the shape and the rhythm of the modulation varies. At the beginning of the extract there is a single defined beat, the third modulation splits in to two and a double beat is heard in place of the single defined beat. The first 20s of the extract is shown below with the rhythmic element imposed at the top of the graph, ♩ indicates a single beat and ♫ a double beat. The varying beat is likely to attract and hold attention. The lack of pattern and regularity is likely to be perceived as annoying as patterns and expectations are broken and as the beat is difficult to ignore.

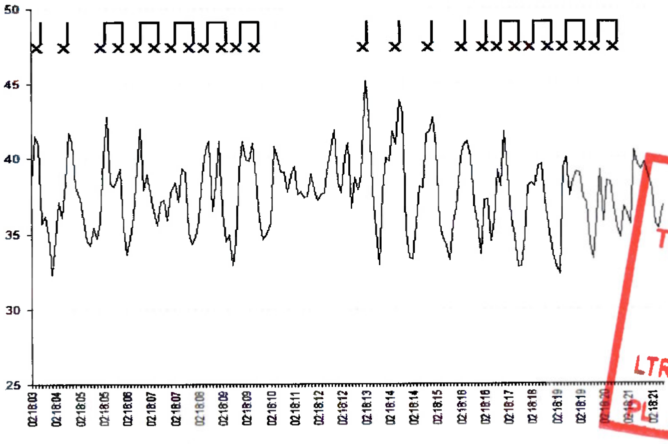

Figure 3: Extract of figure 1, variance of rhythm / beats shown

The table below assesses the example shown in figure 1 against five of the criteria discussed above.

Table 1: Assessment of turbine noise from Swaffham II turbine

Method	Criterion	Calculation	Result
ReUK / ETSU	5dB penalty to L_{A90}[1]	$34.4^2 + 5 = 39.4$dB L_{A90}	Compliant with ETSU-R-97 43dB lower night time noise limit
BS4142	L_{Aeq} (+5dB) - L_{A90}	$(37.9^3 + 5) - 34.3^4 = 8.6$dB	Complaints likely (see footnote)
Japanese D_{AM}	Fluctuation sensation when greater than 1.7D_{AM}	ΔL_{A5} (3.3) - ΔL_{A95} (-4.4)	7.7D_{AM}
Nordtest	Prominence, P	P=3log(onset rate/[dB/s]) + 2log (level difference /[dB])	P1 = 6.3 P2 = 6.5 P3 = 6.0
Den Brook	Regular 3dB modulation >28dB L_{Aeq}	$L_{Aeq} = 38.2$ Peak to trough range 4-11dB, regularly above 3dB	Greater than expected AM

[1] It is assumed in each assessment that the maximum 5dB penalty would be applied. Separate long term tests have demonstrated this is not the case and at most even in extreme cases of AM it is likely a 3dB penalty would be applicable (see reference 19).

[2] The 10 minute period including figure 1 is contaminated by nearby road traffic noise. This 2 minute period is representative of the turbine noise during the 10 minute period in the absence of road traffic noise.

[3] This is based on a 5 minute period, which includes the 2 minute period shown in figure 1. All noise during this 5 minute period is dominated by wind farm noise.

[4] Strictly this should be the background noise level in the absence of wind farm noise. In this case the turbine was operational throughout the measurements and a true background noise level could not be determined. As a best case the L_{A90} for the measurement period is used, background noise levels would be lower in the absence of wind turbine noise and the true complaint prediction level much higher.

3.2 Kessingland turbines - 10 June 2012 - 2 x 2.05MW turbines

The noise data graph below is taken from two turbines at Kessingland. The beginning and end of the extract show clearly defined modulating noise which also has a strong rhythmic element. Modulation is still apparent in the middle of the extract but has a less clearly defined, muddied modulation sound similar to a tumble dryer noise, a descriptor often used by residents to describe the noise character of wind farm noise. The noise in the middle of the extract is more continuous and undulating compared to the defined modulation that fades in and out (at the end and beginning of the extract) as if the turbines were moving in and out of synchronisation with each other. That the noise is less variable during the middle period and its likeness to a common noise source (tumble dryer) could suggest that this middle period is less intrusive, more easily habituated to. However, the change in noise character to a strongly rhythmic, irregular noise just after half way through the period creates a stark and noticeable change that draws attention. A listeners attention might wander from the wind farm noise as it becomes less prominent and more subdued but refocus on the noise when the strong modulation returns.

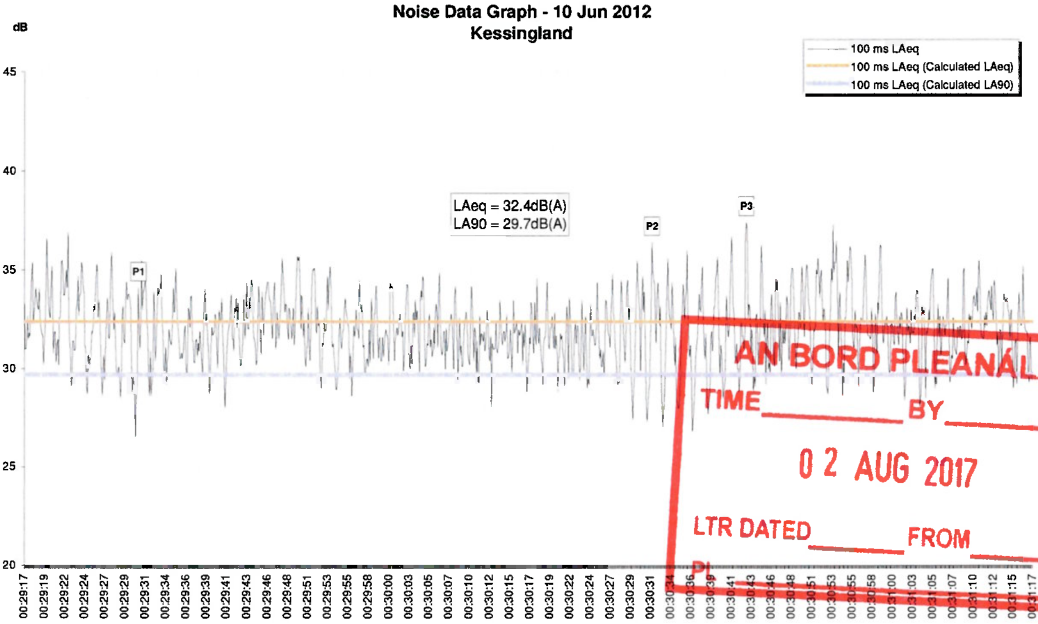

Figure 4: Kessingland turbines - 10th June 2012

The frequency content of the noise also varies throughout the extract. The dominant frequencies are centred around the 315Hz, 400Hz and 500Hz third octave bands. The dominance of these frequencies are constantly changing and increases and decreases in loudness are not necessarily perfectly synchronised, thus creating a 'Mexican wave' type effect through the third octave bands. Some of the dominant frequencies of the modulation peaks are labelled on figure 5 below to demonstrate the variability. There is also variable low frequency content, indicated by the 125Hz and 100Hz third octave band content in figure 5 below. Periods of lower frequency rumble are particularly noticeable during the middle section of the extract, though there are no obvious difference in low frequency content compared to the beginning or end of the extract. The increase in low frequency content contributes to the changeable character of the noise. Subjectively the noise varies between a whoosh, swish and tumble dryer type noise. The range of different and varying pitches adds body to the sound and creates a broader multi-dimensional sound, for example the difference between a strong quartet and the string section of an orchestra. This feature could be attributed to descriptions from affected residents that they feel surrounded by the noise.

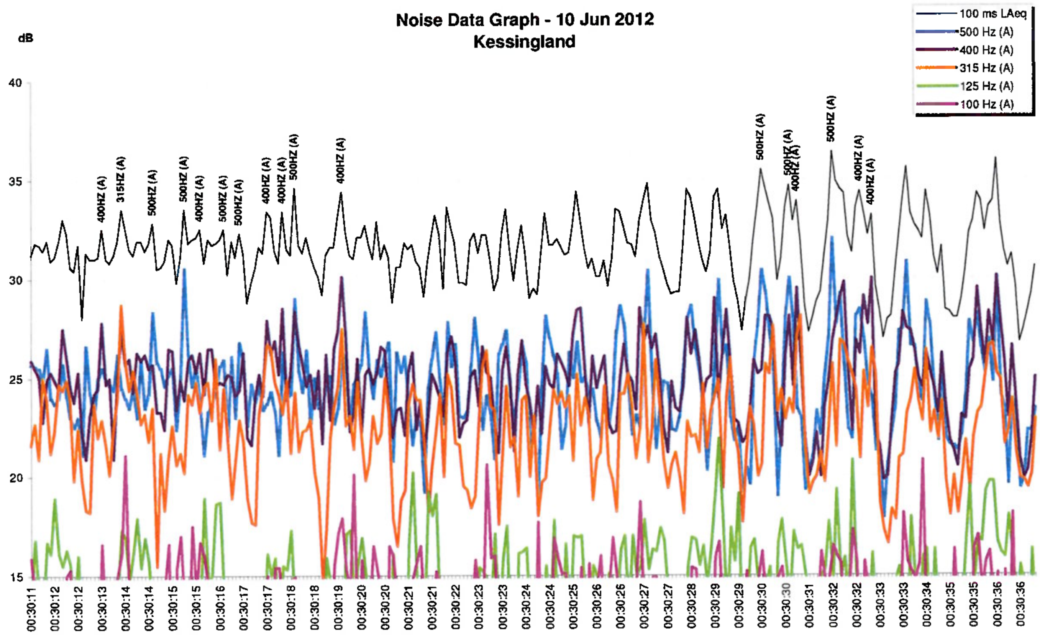

Figure 5: Kessingland turbines - 10th June 2012, frequency analysis and dominant frequencies

As noted above there are very strong rhythmic qualities to the turbine noise. This is shown in figure 6 and 7 below. In western music there is a preference to hear sound with meter, an alternation between strong and weak beats. Entrainment describes the interaction of two rhythmic processes combining to a common phase. Human entrainment to rhythms is observed from an early age (18). The emphasis of strong and weak beats in the excerpt below changes within the modulation peak and creates two distinct rhythms in the extract.

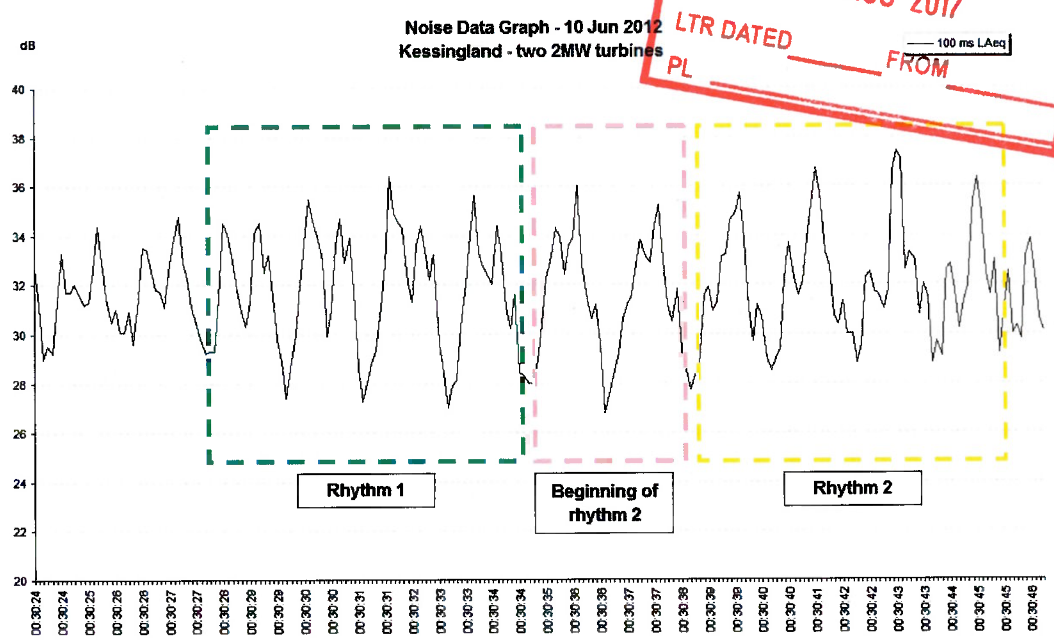

Figure 6: Extract from figure 3, strong rhythmic elements

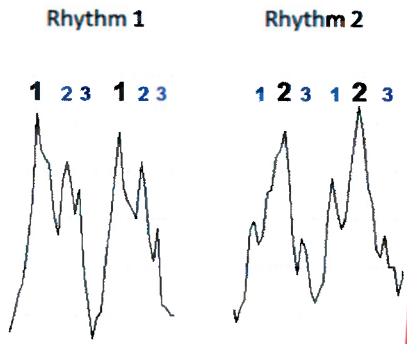

Figure 7: Dominant rhythms in figure 6

Whilst rhythmic attributes of noise are not uncommon the rhythm is usually regular, constant and predictable, in this case it is randomly variable. This could create a subjectively unpleasant noise character as the noise lacks pattern or symmetry and so is not consistent with expectations. The changes in rhythm and / or the attempt to try and look for a rhythmic pattern could make this character feature annoying, intrusive or difficult to ignore.

Numerous complaints have been received from the turbines at Kessingland. Despite the Council admitting that the noise is a statutory noise nuisance they refuse to take action against the turbines.

The table below assesses the extract shown in figure 4 against five of the criteria discussed above.

Table 2: Assessment of turbine noise from Kessingland turbines

Method	Criterion	Calculation	Result
ReUK / ETSU	5dB penalty to L_{A90}	29.7[5] + 5 = 34.7dB L_{A90}	Compliant with ETSU-R-97 43dB lower night time noise limit (**NB** also compliant with simplified 35dB L_{A90} ETSU limit)
BS4142	L_{Aeq} (+5dB) - L_{A90}	(32.4[6] + 5) - 26.2[7] = 11.2dB	Complaints likely (see footnote)
Japanese D_{AM}	Fluctuation sensation when greater than 1.7D_{AM}	ΔL_{A5} (2.2) - ΔL_{A95} (-2.8)	5.0D_{AM}
Nordtest	Prominence, P	P=3log(onset rate/[dB/s]) + 2log (level difference /[dB])	P1 = 6.0 P2 = 5.6 P3 = 5.8
Den Brook	Regular 3dB modulation >28dB L_{Aeq}	L_{Aeq} = 32.4 Peak to trough range 4-9dB, regularly above 3dB	Greater than expected AM

[5] This is based on a 2 minute period. It is assumed the 2 minute period continued in a similar manner for 10 minutes. The four minute L_{A90} covering this extract was 29.8dB, at the beginning and end of the four minute extract the noise trace is affected by road traffic noise.

[6] This is based on a 2 minute period. It is assumed the 2 minute period continued in a similar manner for 5 minutes. The four minute L_{Aeq} covering this extract has an L_{Aeq} of 33.2dB, at the beginning and end of the four minute extract the noise trace is affected by road traffic noise.

[7] The turbine was operational throughout the measurement period. The L_{A90} is taken from a five minute period approximately 20 minutes prior to extract shown in figure 4 when the turbines are still operational but at a slightly lower level. True background noise levels would be lower in the absence of wind turbine noise and the likelihood of complaints higher.

3.3 Site F - 31 December 2013 - 1 x 275kW turbine

Site F remains anonymous due to potential nuisance action. It is a single 275kW turbine that operates in two different gears. The extract below, figure 8, is a 10 minute period which shows the operation of the turbine in the lower gear at the start of the period, a change up to the higher gear in the first third of the period and change back down to the lower gear just after half way through the period.

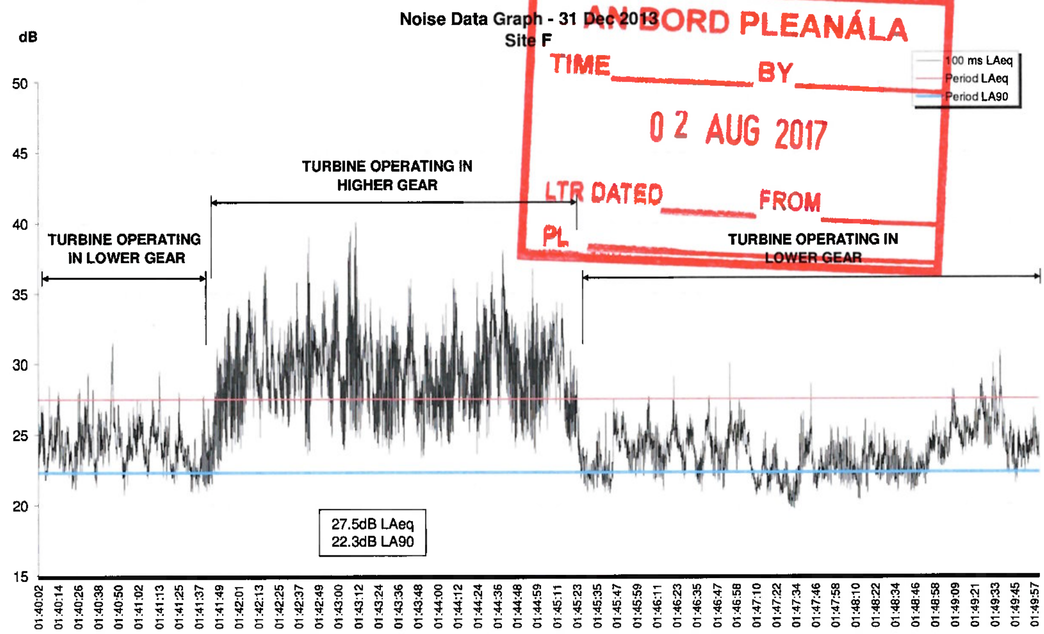

Figure 8: Site F - 31 December 2013

The turbine noise is highly tonal and an element of tonality is always present when the turbine is operating. When operating in the lower gear the turbine produces a humming noise which is mid frequency in pitch though there is also a quieter higher frequency tonal whine. In the higher gear mode the tonality of the turbine is much stronger and is better described as a dominant high pitched whine. The turbine also generates AM. In the lower gear blade swish modulates at a reasonable pace and has a more subdued character. The modulation of noise is much greater in the higher gear and this is caused both by variances in the tonality but also by a harsh whipping / scraping blade swish noise. The operation of the turbine in the higher mode generates a much harsher sound resulting from a combination of a highly tonal high pitched whine and violent (whipping / scraping) modulating blade noise. Noise generated by the turbine in the higher gear is likely to be perceived as unpleasant and disturbing due to the harsh characteristics. These characteristics are unlikely to be accustomed to because of the constant variability both in noise level and character and also due to frequent unpredictable gear changes.

Periods of tonal 'resonance' also occur in the data. This is when the tonal noise generated by the turbine becomes louder and more dominant, for example when resonance is reached from running a finger round the rim of a wine glass. The noise is comparable to the sound of a distant train passing. The similarity and dissimilarity to an existing environmental noise source could create a negative reaction to the sound. Whilst the turbine noise sounds familiar it does not behave as expected, tonal resonances return without warning, they do not appear and disappear as would be expected if the noise was caused by a distant train. This aspect of the noise is also likely to draw attention back to the noise.

Figure 9 below shows an excerpt from figure 8 as the turbine changes from the lower gear operation to the higher gear operation. There is an increase in loudness, modulation, tonality and blade swish noise as described above. Inset in the left hand corner of figure 9 is an A weighted frequency analysis of the lower and higher gear operation of the turbine shown in figure 9. It confirms the mid frequency and higher frequency tonality of the lower gear operation (blue trace at 01:40:53.600) and the strong higher frequency tonality of the higher gear operation (red trace at 01:41:48). Changes in gear occur throughout entire night time periods. They occur often but with no predictability or regularity.

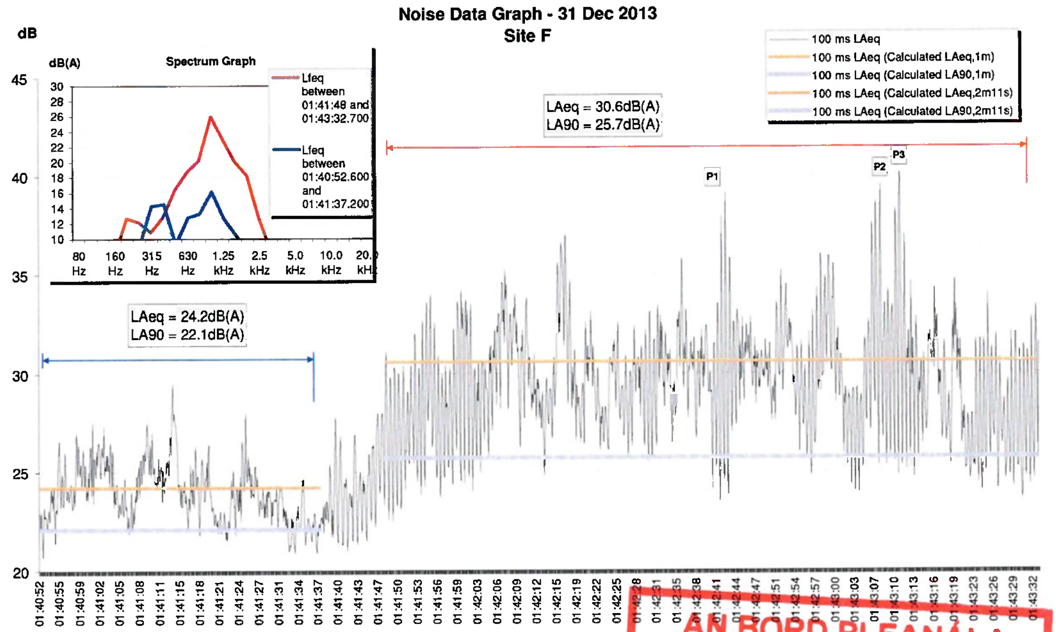

Figure 9: Site F - 31 December 2013, extract showing character and frequency content

The table below assesses the noise from the turbine at site F against five of the criteria discussed above. The D_{AM}, Nordtest and Den Brook assessment are based on the period shown in figure 9 above, 3 minutes in length.

Table 3: Assessment of turbine noise from site F turbine

Method	Criterion	Calculation	Result
ReUK / ETSU	5dB penalty to L_{A90}	10 minute period: 22.3. + 5 = 27.3dB L_{A90} High gear operation only[8]: 25.8 + 5 = 30.8dB L_{A90}	Compliant with ETSU-R-97 43dB lower night time noise limit (**and** simplified 35dB L_{A90} ETSU limit)
BS4142	L_{Aeq} (+5dB) - L_{A90}	(29.3[9] + 5) - 23.0[10] = 11.3dB	Complaints likely
Japanese D_{AM}	Fluctuation sensation when greater than 1.7D_{AM}	ΔL_{A5} (2.5) - ΔL_{A95} (-3.9)	6.4D_{AM}
Nordtest	Prominence, P	P=3log(onset rate/[dB/s]) + 2log (level difference /[dB])	P1 = 7.4 P2 = 7.0 P3 = 7.5
Den Brook	Regular 3dB modulation >28dB L_{Aeq}	L_{Aeq} = 24.2 / 30.6 Peak to trough range 3-15dB, regularly above 3dB	Greater than expected AM caused by higher gear only

8 Worst case assumption that the higher gear operation, see figure 9, occurs for an entire 10 minute period.

9 Based on a 5 minute period which includes the lower and higher gear operation shown in figure 9. Strictly BS4142 cuts off at a rated level of 35dB(A); however, it also advises that the principles are generally applicable and as the elevated period of noise gives a rating above 35dB it is considered appropriate for use in this case.

10 The L_{A90} is taken from the same 5 minute period as the L_{Aeq}; it is determined by the lower gear turbine noise, background noise in the absence of turbine noise would be lower and complaint prediction levels higher than indicated in the table.

3.4 Cotton Farm Wind Farm - 3rd February 2014 - 8 x 2.05MW turbines

MAS have set up a permanent monitoring station with significant help from local residents to measure community noise levels from the Cotton Farm Wind Farm. Residents complain of a loud 'whoomp' / 'whoosh' noise, which is prevalent in much of the data. The excerpt below is taken from a night time period entirely dominated by wind farm noise. Whilst the noise trace is consistently affected by AM, the shape of the noise trace does not vary in a wave-like shape to the same extent as the examples above. For example, a flat line can be drawn underneath the troughs of the data whereas the excerpts above follow waves of increases and decreases in the trough level. The number of turbines at Cotton Farm is much greater than the above examples and this flat lower level is likely the 'general' wind farm noise level[11]. The noise is far from characterless and significant variation is still observed and heard.

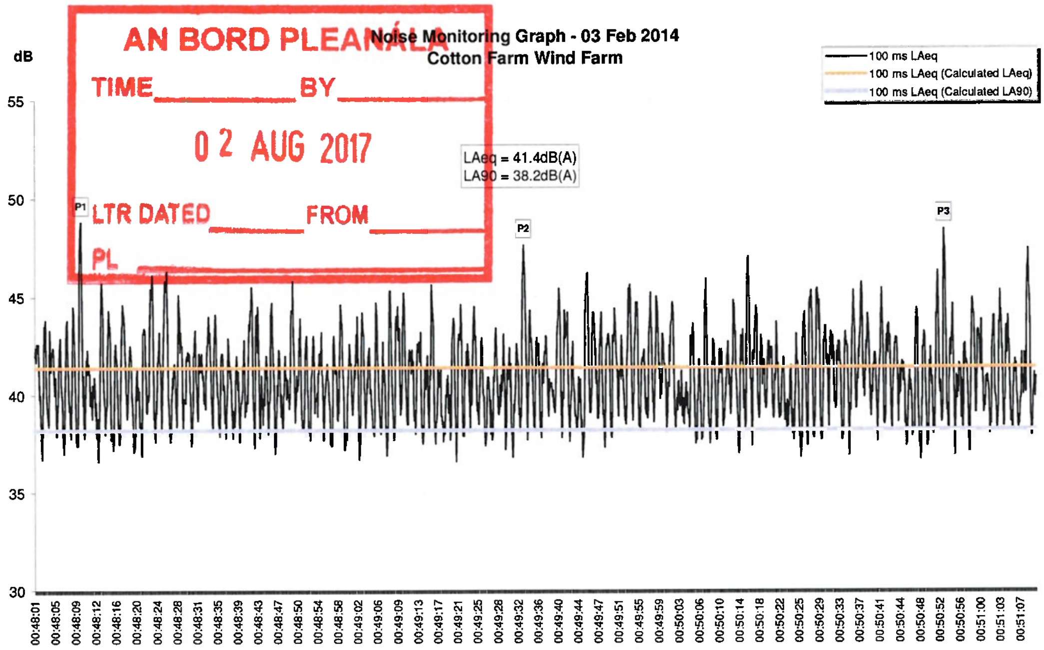

Figure 10: Cotton Farm Wind Farm - 3rd February 2014

The character of the noise at Cotton Farm is quite different to the above examples. Modulation is slower paced but has a 'big' 'roar' like sound and lower pitched in character. The main variable in the noise trace is the constant change in loudness. When there are higher modulation peaks this generates an unexpected element to the noise as the noise level continues to rise above that expected, more noise for longer.

Figure 10 below shows the first minute of figure 9 above. Changes in loudness and modulation depth continue without regularity throughout the extract. As with the first example of wind turbine noise at Swaffham the dynamics of the noise are highly variable. The beginnings of patterns can be observed in the data, increases in loudness (crescendo) and decreases in loudness (diminuendo) are marked on the figure.

[11] This has been separately confirmed by switch off tests where the turbines were stopped and is reported by the authors in a separate paper (19).

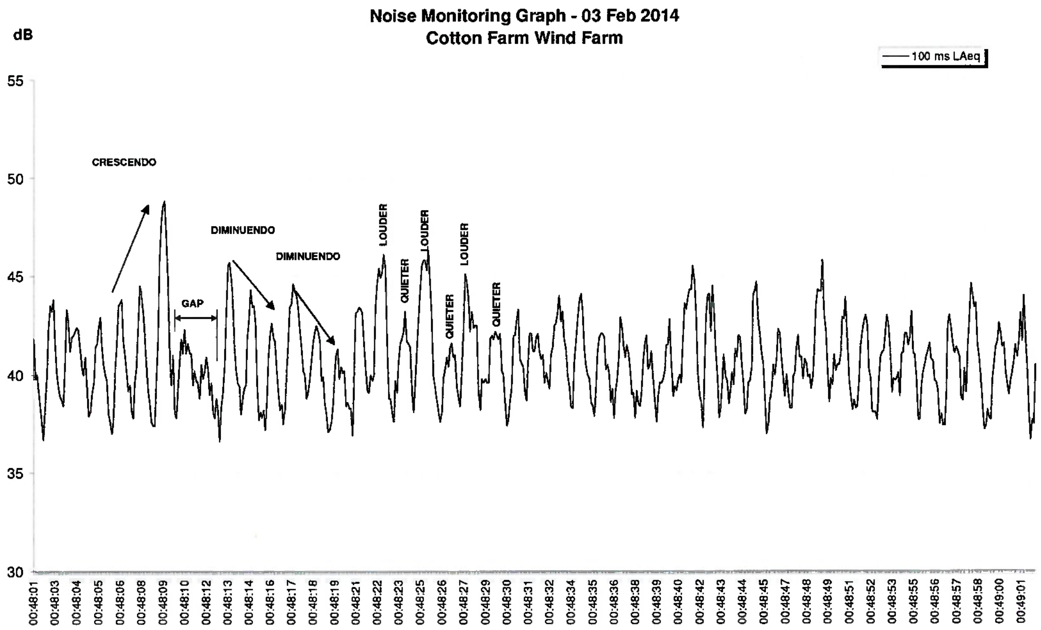

Figure 11: Extract of figure 9 showing patterns and changes in loudness

Figure 12 below demonstrates the varying frequency content of the wind farm noise. Most of the modulation is broadband and mid frequency, perhaps causing the 'big' sound, though a definite lower frequency rumble is also present. As with Kessingland, this could cause residents to feel 'surrounded' by the noise. Some peaks have a definite lower pitched / frequency 'whoomph' character, see for example the end of the period peaks 2 (blue) and 4 (black) evaluated in figure 12 below. The spectrum graph inset in figure 12 shows the presence of the rumble at around 100Hz, more 400Hz content in peaks 2 and 4 ('whoomph'), and more 630Hz noise in peaks 1 (red) and 3 (green).

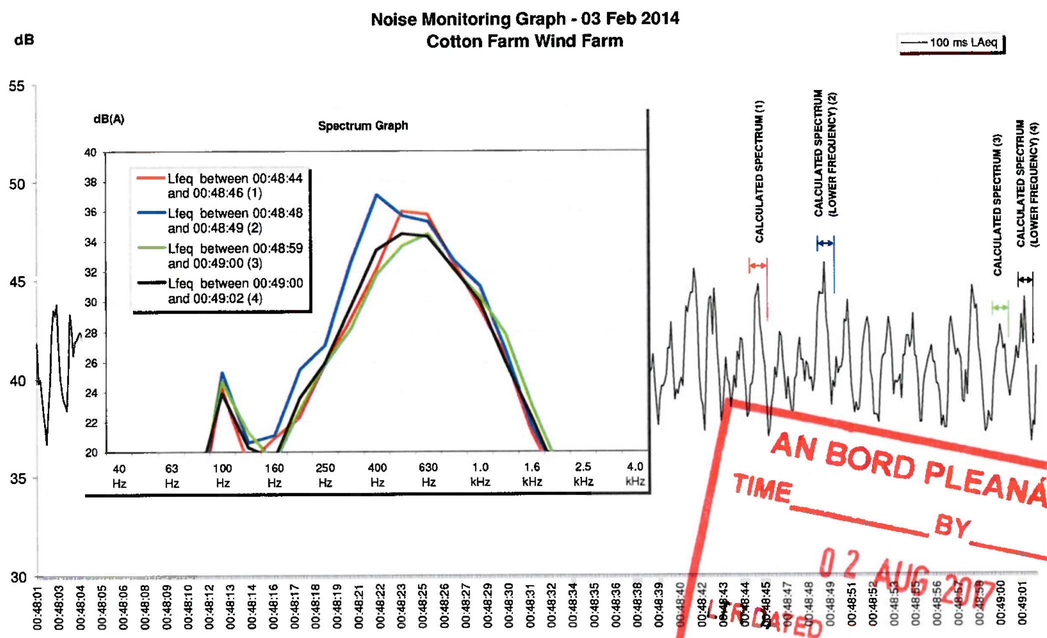

Figure 12: Extract of figure 9 showing differences in frequency content (pitch)

The table below assesses the noise from the turbine at Cotton Farm against five of the criteria discussed above. The ReUK / ETSU-R-97 assessment is based on the 10 minute period from which figure 10 is taken. The BS4142 assessment is based on background noise levels measured prior to the erection of the wind farm. The 10m height wind speed measured at the monitoring location (Toseland Road, Gravely) during the above noise measurements, figures 10 - 12, was 4m/s. The prevailing background noise level at 4m/s as measured at the application stage at 97 Toseland Road was 27dB(A).

Table 4: Assessment of turbine noise from Cotton Farm Wind Farm

Method	Criterion	Calculation	Result
ReUK / ETSU	5dB penalty to L_{A90}	10 minute period: 38.8. + 5 = 43.8dB L_{A90}	0.8dB breach of 43dB L_{A90} limit. At most de-minimis breach: unactionable.
BS4142	L_{Aeq} (+5dB) - L_{A90}	(41.4[12] + 5) - 27.0 = 19.4dB	Complaints likely - significantly exceeds onset point of complaints (+10dB)
Japanese D_{AM}	Fluctuation sensation when greater than 1.7D_{AM}	ΔL_{A5} (2.3) - ΔL_{A95} (-3.5)	5.8D_{AM}
Nordtest	Prominence, P	P=3log(onset rate/[dB/s]) + 2log (level difference /[dB])	P1 = 6.0 P2 = 5.6 P3 = 6.1
Den Brook	Regular 3dB modulation >28dB L_{Aeq}	L_{Aeq} = 41.4 Peak to trough range 4-11dB, regularly above 3dB	Greater than expected AM

[12] The 5 minute L_{Aeq}, which includes the extract shown in figure 10, was 41.8dB L_{Aeq}.

NOTE: Whilst the ReUK / ETSU approach does indicate a breach, the current approach to application of this metric is to average this result with a longitudinal study of noise impact. The averaging effect combined with a minor exceedance results in easy compliance. It is also noted that this assessment assumes that the maximum 5dB penalty would be applicable whereas research has shown this is unlikely to be the case (19).

3.5 Summary

The table below summarises the assessments of the four examples above.

Table 5: Summary of assessments at four examples

Method	Swaffham II	Kessingland	Site F	Cotton Farm
Subjective	Waves of noise, erratic dynamics, highly changeable / unpredictable, changeable modulation beats / rhythm	Strongly rhythmic, changes between defined modulation (swish / whoosh) and muddied tumble dryer sound, unpredictable patterns, 'big' sound, changes in pitch	Highly variable, highly tonal, subdued modulation, hum, violent whipping / scraping modulation, harsh, whine, resonance (distant train), highly changeable	Constant lower level of noise (constant din), 'big' sound, 'roar' like, lower pitch rumble, variable dynamics and pitch
ReUK / ETSU	Compliant	Compliant	Compliant	Borderline
BS4142	Complaints likely (8.6dB +)	Complaints likely (11.2dB +)	Complaints likely (11.3dB +)	Complaints likely (19.4dB)
Japanese D_{AM}	7.7 D_{AM}	5.0 D_{AM}	6.4 D_{AM}	5.8 D_{AM}
Nordtest	P = 6.3 / 6.5 / 6.0	P = 6.0 / 5.6 / 5.8	P = 7.4 / 7.0 / 7.5	P = 6.0 / 5.1 / 6.1
Den Brook	Greater than expected AM (4-11dB)[13]	Greater than expected AM (4-9dB)	Greater than expected AM (3-15dB)	Greater than expected AM (4-11dB)
dB $L_{Aeq,T}$	38.2	32.4	27.5 (24.2 / 30.6)	41.4
dB $L_{A90,T}$	34.4	29.7	22.3 (22.1 / 25.7)	38.2

4. DISCUSSION

This paper looks primarily at the character of wind farm noise and how this relates to assessment of impact, particularly where noise has been found compliant with limits but causes complaints. The above analysis raises many questions that relate to this assessment as outlined below.

4.1 Is it appropriate to compare wind farm noise levels to other noise source levels?

As noted in the introduction, wind farm noise levels are often compared to other noise sources, the noise level in a quiet library or the noise level of a fridge. WHO guidelines are similarly often quoted. Assessors commonly state that as noise is below either 40dB $L_{night,outisde}$ (lowest observed effect level) or 30dB $L_{night,outisde}$ (no observed effects level) the noise cannot be considered an adverse impact (20). With reference to the summary table above, the noise levels from the four examples evaluated are similar to the noise level that might be measured in a quiet library / office or the noise of a refrigerator hum in the kitchen. The majority of levels are below an $L_{night,outisde}$ of 40dB and some below 30dB $L_{night,outisde}$. Are these comparisons fair?

The noise in a quiet library will typically be dictated by heating and ventilation units. A steady,

[13] Modulation level, peak to trough.

broadband generally anonymous noise. As there is little variance in this type of noise it is easily pushed to the back of consciousness. There may be intermittent noises from those using the library, footsteps, page turning, coughing. These tend to be single, isolated events. They do not occur frequently and in many cases they are predictable with visual and audible cues that inform that the noise will happen, when it will happen and when it will cease. In contrast, and as demonstrated above, wind farm noise is constant but highly changeable and variable, without predictability or regularity. At night time, inside the dwelling and when trying to sleep there are no visual cues for wind farm noise. Audible cues can often be misleading, for example periods of lower modulation and lower wind farm noise levels indicate that the noise is going away, but quieter periods are often followed by increases in noise / modulation or sudden louder modulation peaks, see the above examples.

The noise level of a fridge might also be similar to wind farm noise level, but as with the library it is entirely different in character. The noise from a fridge might have a tonal element, but this is unlikely to modulate to the extent that wind farm noise tonality modulates, particularly in third octave band analysis. The noise from a fridge is often constant and regular with limited variation or change. It is also important to consider the context of each noise in the surrounding environment. A fridge, presumably located in the kitchen, is likely to be the least dominant noise source in this location. Other noises will either mask the fridge noise or attract attention away from the noise. Fridge noise is similar to other noises likely to be found in a kitchen, it is not unexpected or alien and usually within the control of the occupant. Wind farm noise is typically the dominant noise source where there are no other dominant man made or industrial noises. Particularly at night time there are few other sources that could either mask or divert attention from the wind farm noise. Wind farm noise is typically obtrusive in what is otherwise a quiet rural environment, dominated by wildlife sounds which are entirely different in character to that of wind farm noise.

Whilst the average L_{Aeq} or L_{A90} level of wind farm noise might be similar to the average L_{Aeq} or L_{A90} level of noise from a fridge or in a quiet library, this is demonstrably the end of any likeness.

It is clear from review of the WHO night time noise guidelines that the vast majority of research upon which effect levels are based relates to transportation noise. Can transportation noise be fairly compared to wind farm noise? As above, the character of the noises are entirely different. Studies have already shown that wind farm noise is perceived as more annoying (21). Transportation noise is predictable and much less variable. It does not contain changing rhythmic or tonal features. Transportation noise is typically found in urban areas, wind farms are more often located in quiet rural environments.

The focus on decibel level again draws focus away from the noise character and noise context. Such comparisons are at best tenuous and the appropriateness of such comparisons is seriously questioned.

4.2 Is a single figure parameter appropriate for assessing impact? Would multiple parameters be more appropriate?

The L_{Aeq} of the excerpt from Cotton Wind Farm is 41.4dB and the L_{A90} 38.2dB. This is considerably louder than the excerpt of the two turbines at Kessingland, 32.4 dB L_{Aeq} and 29.7dB L_{A90}. The noise at Kessingland should supposedly be half as loud as that from the Cotton Farm Wind Farm. Does this mean that those complaining of noise from Kessingland have half the right to complain, or half as strong a case as those complaining of noise from Cotton Farm? Would the Cotton Farm residents accept twice as much of the Kessingland noise before they complained?

Whilst there is clearly a significant difference in decibel level between the two sites, assessment based on different metrics leads to different conclusions on acceptability than review of decibel level alone. The prominence rating, P, of modulation peaks is very similar both at Cotton Farm and at Kessingland, P = 6.0 / 5.1 / 6.1 and P = 6.0 / 5.6 / 5.8 respectively. The noise modulates with a similar peak to trough range, 4-11dB and 4-9dB, both would be considered to generate unreasonable, greater than expected amplitude modulation. The D_{AM} rating of the noise from Cotton Farm and Kessingland, 5.8 D_{AM} and 5.0 D_{AM} respectively, is also not dissimilar. These metrics suggest that impact of noise character from Cotton Farm and Kessingland is comparable.

Review of decibel levels suggests Kessingland impact to be considerably more tolerable than Cotton Farm impact. Review of prominence, P, modulation peak to trough level and D_{AM} rating suggest that impact is comparable at both locations. Detailed examination of the noise character might again change the decision.

Noise from Cotton Farm wind farm and from the Kessingland turbines is highly variable in dynamic and there are unpredictable changes in peak to trough level. However, the Cotton Farm modulation is a single modulation peak with one beat or modulation pulse per peak and this is generally consistent throughout the data. The Kessingland modulation is highly rhythmic and randomly alternates between different rhythms throughout the extract. There are often two or three beats or pulses within each modulation peak. Subjectively the Kessingland noise might be considered more likely to attract attention, more difficult to ignore and potentially more annoying.

Where noise has character a single number parameter cannot adequately describe impact. Even if multiple parameters are used this can often result in conflicting conclusions of impact. There are situations and character features which, as demonstrated by the rhythmic quality of the Kessingland turbines, would be entirely neglected from assessment even if using multiple assessment parameters.

4.3 Do noise readings reflect human perception?

It is asserted above that a single noise level cannot adequately assess the impact of noise character. Description of noise using multiple parameters can also be contradictory. Does even a detailed assessment of noise character presented by noise readings accurately reflect human perception?

The four examples above were recorded external to the dwelling. The above assessment metrics also relate to externally recorded noise levels. How is impact perceived internally? Complaints of wind farm noise are commonly received at night time and residents often complain of sleep disturbance. To reflect this in noise measurements there is a strong argument to require internal noise measurements. Notwithstanding the potential difficulties of access, there are also difficulties with instrumentation. Most type 1 / class 1 sound level meters have a noise floor of around 18-20dB(A). Specialist low noise microphones are needed to accurately measure internal noise levels, which in rural areas can be as low as 12dB(A).

The accuracy of A weighting to reflect the human hearing sensitivity might also be questioned, particularly in very low noise environments or where noise, especially low frequency noise, is close to perception thresholds. There may be internal room effects that further influence the perception of noise, but how could such a variable be accounted for in a general assessment of impact?

Self reported health effects can also prove problematic when assessing noise solely using recorded noise levels. Residents affected by wind farm noise often report ear pressure effects or liken impact to other hearing impairments such as tinnitus or ringing; they often question whether they are hearing, feeling or imagining the noise. These reports can lead assessors to dismiss impact as a hearing defect rather than a feature or symptom of the wind farm noise. This is particularly the case where there are no obvious identifiable causes in the data, where low frequency noise levels are below thresholds or where low frequency noise is at lower levels than other sources of environmental low frequency noise. The middle section of figure 5, Kessingland, has a lower pitched character but there are no obvious changes in the third octave band frequency data. In many cases residents leave their homes either temporarily or permanently to find respite elsewhere, action that does not suggest imagined effects.

Rather than question the reliability of those reporting annoyance and health effects assessors should perhaps be questioning the reliability of the data to accurately portray what is being heard by those affected.

4.4 Can short term assessments of noise level and character represent long term impact?

The above examples review only short periods of wind farm noise. The examples are generally representative of the noise generated at each site and can give an indication of the main character features, but they do not represent the duration of impact and how character manifests for longer periods (to which residents are subjected). Can short term analysis fairly reflect what the resident is exposed to on a daily basis and / or the reaction and perception of the noise after long term exposure?

It is highly likely that residents will become sensitised to noise when they hear it and are affected by it on a day to day basis. Residents will be able to pick out the source noise where those assessing it, who are not as familiar with the noise, may struggle to do so. Similarly, the resident will be acclimatised to the background noise levels in the area whereas the assessor may not be familiar with the typical noise sources in the area or simply used to louder, busier environments. Is this assessors judgement therefore fair and representative of what the resident experiences?

4.5 Should character be considered as a single feature of noise or do different features interrelate and cumulatively impact perception?

The four examples examined above contain a number of noise features that contribute to distinct noise character. Should each feature be considered in isolation and then assessed cumulatively, should each feature be considered in isolation and assessed independently or should all features be combined in a single 'character' assessment? For example, does the modulation of the Cotton Farm noise make it immediately unacceptable? Would it be equally unacceptable if there was only low frequency noise and no modulation? Does the addition of low frequency noise to the modulation make the modulation more intrusive and is this more or less intrusive than adding a rhythmic component such as that found in the Kessingland data?

At site F there is a very strong tonal character and significant amplitude modulation, but the character features are different depending on the operating gear. As such there is not a single feature of noise that describes both operating modes of the turbine. How could these differences be accounted for as a single character feature? Complaints from the resident affected by site F focus mainly on tonal noise. Perhaps reported annoyance focuses on the tonal noise as it is more prevalent, it is perceived as always present compared to the variable presence of amplitude modulation noise. Should annoyance from amplitude modulation therefore attract less of a penalty than the tonal noise? Alternatively, does the amplitude modulation noise simply draw the residents attention back to the tonal turbine noise? Perhaps in the absence of amplitude modulation noise the tonal noise would be more easily forgotten? In this case the amplitude modulation noise is the driver of annoyance and so would perhaps warrant a harsher penalty than the tonal noise. Can the two features be separated? Perhaps the intrusiveness of the tonal noise is heightened when it 'resonates', which most often occurs in conjunction with periods of erratic and violent blade swish noise. Is the tonal noise more or less annoying in the presence of amplitude modulation noise? How can these complex interactions be accounted for as a single feature of noise impact?

Very little is known about how different character features interrelate and are perceived by those affected. Assessment is problematic as each case is so variable both in terms of the noise, see for example the different character features of the four examples above, and in terms of individual differences of residents affected.

4.6 Should wind farm noise character be assessed separately or as part of a total noise dose?

Many international guidelines for assessment of wind farm noise propose a penalty for prominent character features that is applied to the overall noise limit. The assessment of the four examples above shows wind farm noise with highly discernible character features that have resulted in noise complaints but comply with noise limits even with the maximum afforded penalty deducted from the noise limit. This demonstrates that the current penalty approach is ineffective.

The average L_{Aeq} level or L_{A90} rarely represent the high variability of the noise within the extract and as such do not fairly represent noise character. If the noise level itself does not reflect noise character can a penalty applied to this level fairly account for noise character either? If the noise level was reduced by 5dB would this render the noise acceptable? Comparison of noise levels from the Cotton Farm Wind Farm and the Kessingland turbines suggests that noise level is not the deciding factor and noise would still be intrusive at levels 10dB lower. Noise levels from the turbine at site F are a further 5dB lower than the Kessingland noise levels, yet site F has the highest prominence (P) value and still generates complaints.

A comparison of the penalty method (ReUK / ETSU) and the penalty / rating method of BS4142 shows a stark difference in acceptability. Complaints were deemed likely from all of the above four examples using the BS4142 approach whereas the ReUk / ETSU penalty approach only indicated a borderline situation at Cotton Farm, assuming the full penalty was applied, thus rendering all examples acceptable, not in need of control. If a penalty approach is favoured, the above examples indicate that this should only be applied in a context type approach such as that of BS4142.

If the character of wind farm noise is to be considered separately to the overall limits then which metric is most appropriate and is acceptability decided on a graduated scale or as a simple pass or fail? The Den Brook condition states that all greater than expected amplitude modulation is unacceptable. The Nordtest prominence method is proposed as a graduated penalty to be applied to the L_{Aeq}. Whilst the Japanese D_{AM} method offers no guidance on acceptability, the papers do suggest that as soon as fluctuation is perceived adverse impact arises and that noisiness increases as fluctuation strength increases. The above examples indicate that each metric will give a slightly different result on acceptability.

Whilst it is the authors' opinion that a separate assessment of noise character is favourable, the assessment metrics used above account only for modulation and fail to consider other factors contributing to adverse noise character such as low frequency noise, unpredictability of the noise and changes in noise character. A separate noise character assessment would certainly help assess the above examples but considerable thought is still needed to ascertain how this might be approached, which character features it would include and what metric is most appropriate and effective.

5. CONCLUSIONS

Wind farm noise character is largely neglected at the planning stage. This appears to be exacerbated by inappropriate comparisons with noise sources that have a similar noise level but an entirely different noise character. Noise limits rarely account for noise character and where they do assessment is typically limited to application of a maximum 5-6dB penalty to the existing noise limits. In cases where noise complaints have been received from wind farm noise there are distinctive intrusive character features in the noise, but the noise is found to be compliant with decibel limits. This is demonstrated in the examples above and is evidence that the current approach to assessing impact is ineffective.

The above four examples show that wind farm noise character can be unique to each development and highly variable within each development. Different assessment metrics result in contradictory outcomes of acceptability at each site. Whilst one aspect of noise character might be well characterised by a modulation index another noise characteristic might be better defined by a prominence rating, other characteristics, such as rhythm, are ignored by all assessment parameters.

The analysis and comparison of assessment methods for each of the four examples confirms that a single assessment parameter does not reflect impact. The worst metric of assessment for noise character is that of a penalty applied to a noise limit, as currently proposed in the UK. Even where multiple assessment parameters are adopted significant character features can still be neglected. The ability of noise measurements to accurately reflect the perception of the listener, including within the dwelling, is further questioned.

It is concluded that assessment of character in wind farm noise is in need of serious review by the acoustics community. The current methods adopted to assess noise impact fail those affected and suggest compliance where significant adverse impacts exist. The above analysis suggests that metrics assessing amplitude modulation in isolation will help to provide an indication of intrusive noise character but still neglect many important characteristics. It is noted that the above examples focus only on short extracts of wind farm noise. Long term exposure to noise is likely to heighten perception and annoyance of specific characteristics. Studies investigating how multiple character features interrelate to judgement of impact and the longitudinal impact of noise with character are recommended.

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