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Wind Turbine Noise

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20 Years of Wind Turbine Noise

An immediate end to business as usual is a precondition for planetary survival. [1]

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Summary

In 2005, the first conference of this series was held in Berlin. This paper looks at the advances in knowledge and technique in the generation, propagation and impact of wind turbine noise over the last 20 years and tentatively looks at where we might be in another 20 years in 2045. Most turbines operating in 2005 were stall controlled but about this time pitch-controlled turbines were taking over. Since then we have seen increases in turbine size and power output, particularly since 2015, but there are various reasons why that may not continue at the current rate. A big advance has been our knowledge of source noise generation. This allowed better predictions of noise and the development of STEs and other noise mitigating developments. We have better knowledge of propagation, amplitude modulation, the impact of noise on people. Overall, there have not been dramatic breaks-through but a steady improvement in our knowledge and practice over the last 20 years which is to be welcomed. But our way of work has changed with the overall rapid advance of technology - particularly computer power and storage and connectivity. Will this advance of new technology continue at the same rate? Will there be more remote operation, more accurate smartphone apps? Will we have much more of a soundscape approach to noise limits and to assessment by 2045? And, of course, how can we harness AI to help?

1. Introduction

20 years ago, in 2005, the first conference of this series was held in Berlin. In another 20 years it will be 2045. Will we have achieved Net-Zero? Whatever 2045 brings, life will be very different from now, just is now is different from 2005. On the one hand I want to look back at what we have achieved in terms of knowledge about wind turbine noise and how it affects people, what we haven't achieved and what our priorities need to be for the future.

Inevitably, because I work mostly in the UK, these thoughts are UK centred. Some will apply widely to most other countries but others will vary from nation to nation. This paper is my opinion but enabled by all those that have contributed to the last 10 conferences. I hope some of it might be proved right!

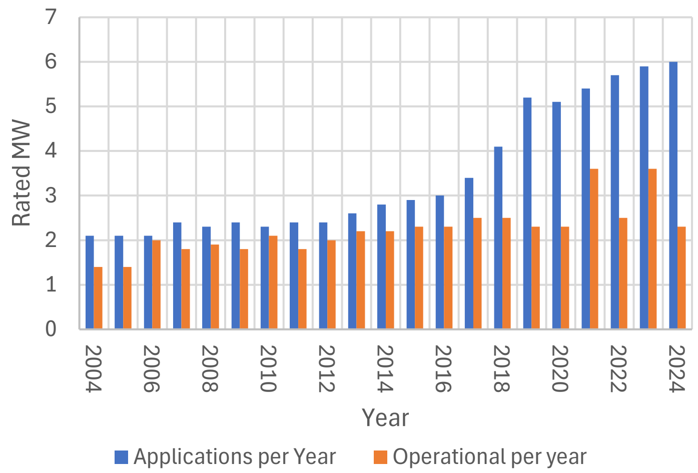
The conferences have been, at their core, about spreading knowledge about wind turbine noise and its effects whether we are researchers or consultants or wind farm developers. There are many things that drive our work but perhaps two in particular. The first is demand; is someone willing to pay for the work? The second is technology and knowledge; on the one hand, do we have or can we obtain the technology to and knowledge to carry out a task.

2. Turbines

Turbines have increased in size in the last 20 years but there is a big lag between planning and operation. In 2005 the time between a planning application and turbines coming into operation for larger wind farms in the UK was about 3 years. It rose to a peak of over 8 years in about 2016 and has now dropped to about 5 or 6 years. And there will likely be two years preparation before planning applications are submitted.

In the year leading up to the 2005 conference the average tip height of turbines installed and becoming operational in the UK was 88m and the rotor average diameter was 63m. The power output was 1.5MW. There was only a slight increase in the size of those turbines starting operation each year, shown by the orange bars in Fig 1, reaching an average of about 2MW in 2012 and not quite 2.5MW by 2020. Since then there has been a bigger rate of increase – though erratic. Those starting operation in the 4 years 2021 – 2024 had an average rating of 3.3MW and tip height of 130m. That is the ones that were operational. As the blue bars in Fig 1 below show, applications for wind farms show power per turbine gradually increasing over more than 10 years from an average of 2MW in 2005 to 3MW in 2016. Then there was a rapid increase in 3 years from 3MW to 5MW in 2019 and to 6MW by 2023 [2]. There will be others reading this who can explain the reason for this sudden increase better than I but clearly blade technology and blade transportation technology must have played a part.

Fig 1 - Average Turbine size MW

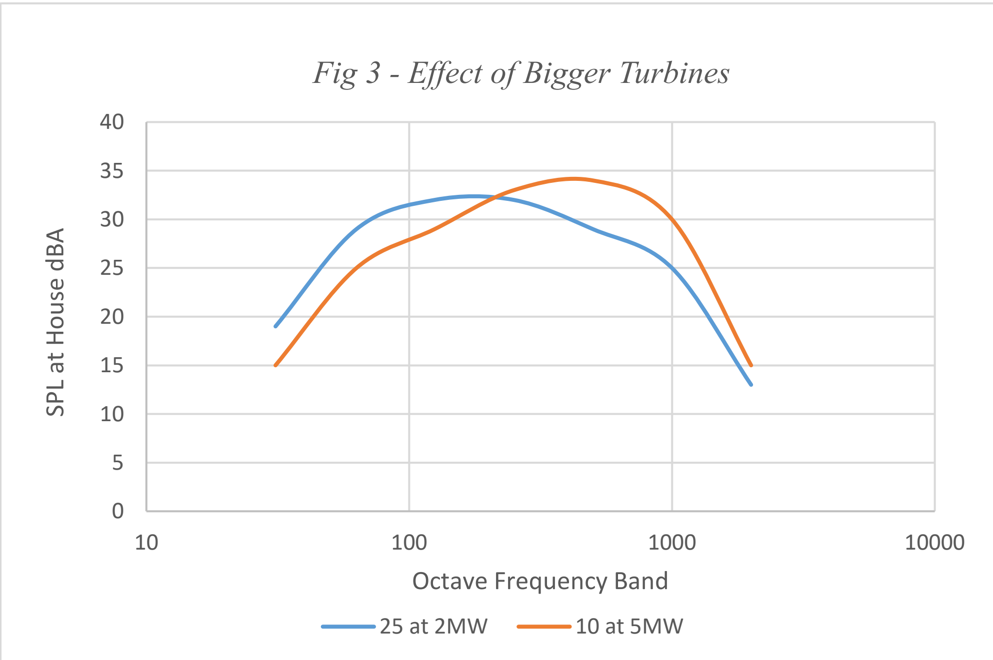


Will this increase in size continue? Undoubtedly turbines coming on stream in the next 4 or 5 years will be in the 5 to 6MW range with a height of up to 250m to blade tip because the applications being submitted and those consented but not yet built are in this range. Beyond that, is there a demand for still bigger turbines? It probably is, and technically, as far as the turbines themselves are concerned, there seems to be no reason why not, as much bigger turbines are becoming available for offshore. In most cases they would have to be run at much quieter modes onshore to meet noise limits. On the other hand there are good reasons why we might have reached a limit of size for onshore wind. There is increasing resistance to larger turbines for visual reasons and transportation of blades and other components becomes more difficult and more disruptive. There are a lot of other factors of course such as improvements in transportation techniques and perhaps we will see airships brought in to deliver turbines to site.

Fig 2 - Airship delivering turbine tower and base.

What of turbine noise itself? How has that changed? Only 3 years before the Berlin conference, IEC 61400-11 had standardised the method of measuring sound power levels of turbines to more or less the method we have now. Prior to that sound power was presented as a value at 8m/s and a slope of dB against wind speed. That suited stall regulated machines whose sound power increased steadily with wind speed but was no use for pitch regulation where sound power levelled off at 7 – 8m/s.

As pitch-controlled turbines have got bigger, unsurprisingly, they have become noisier, but the sound power level per MW seems to have stayed much the same. Perhaps counter-intuitively and certainly in contradiction to turbine sceptics, the increase has been concentrated more to the mid frequencies around 500 and 1k. And as the turbines got bigger less were needed on a particular site. So overall, for moderate sized wind farms, turbine noise at neighbours has not changed much in dBA terms but has shifted up in frequency rather than down. The figure here shows two turbine schemes for the same site fifteen years apart. The first one was 25 turbines at 2MW each and the second was 10 turbines at 5MW each. The

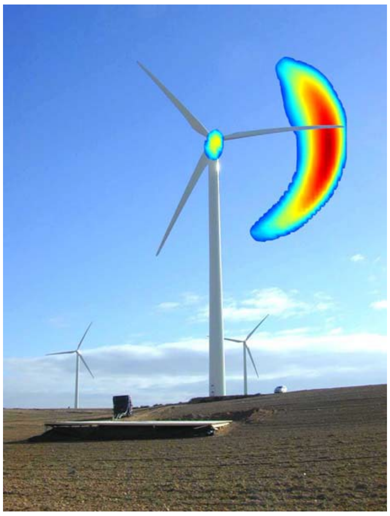


noise level at a neighbouring house about 1.4km away has gone up slightly from 35 to 36dBA but, as the figure shows, the increase is in the 500 to 1000Hz region and low frequency noise in the 31.5, 63 and 125Hz bands is significantly lower by 4-5dB. On the other hand the bigger turbine reaches its maximum sound level at 6m/s while the earlier one did not reach it's maximum until 8m/s (all wind speeds standardised). This is just one example but there does not seem to be any significant evidence that low frequency noise has increased in the last 20 years and there does not seem to be any reason why it should do in the future.

3. SOURCE NOISE GENERATION

The modelling and testing of turbine noise sources was reported in Berlin where we saw the arrival of the now ubiquitous image by Stefan Oerlemans and Beatriz Méndez López in their paper about the SIROCCO project.

Fig 4 - Turbine Noise Sources



Thanks to Stefan and Beatriz for this iconic picture.

An EU funded project called DATA, had already looked at the acoustic design of blades in the few years before using a model turbine in a wind tunnel. The intention of the SIROCCO project was to extend this work to a full-size turbine. The turbine noise calculated by the model was validated using a measurement technique that would localise and quantify noise sources on the rotating blade. The aim of the project was to lower the level of noise by improving the aerodynamic flow at the trailing edge of the blades.

The EU Research and Development Information Service says that “The work carried out by the SIROCCO project has enabled silent, high performance airfoil sections to be developed for the wind turbine industry”. I don’t think that is quite the right story but it formed the basis of future work on airfoil noise.

Schepers in the next conference in 2007 brought us more information about SIROCCO and in 2009 there were four papers dealing with source noise, mainly design of airfoil shape to reduce noise. By 2011 there were 8 papers on source noise with more complex computational models. Significantly there was the first paper (by Petitjean and others) with some results for serrated trailing edges though the effect of serrations was discussed by 4 presenters in the 2005 conference and had been presented elsewhere by Oerlemans and others in 2001. The number of papers on source noise generation peaked in 2015 and 2017 in Glasgow and Rotterdam at 17 and 14 respectively. Recent conferences have seen fewer papers.

It might seem a stupid question but why do we want to reduce turbine noise? Of course it depends on whom you ask. If you ask the windfarm neighbour they will say that it is because it will reduce the noise and improve their amenity. If you ask the developer they will say that that it allows them to get more turbines on a site without breaching the noise limit. In a discussion in Lisbon in 2019, whilst consultants and regulators found trailing edge mitigation research interesting and sometimes helpful, developers saw it as essential to drive down the cost of renewable energy. The fact of the matter is that noise levels at neighbours is determined by regulations; quieter turbines don’t mean quieter residences they mean more turbines.

So the pressure for more work on reducing turbine source noise will come from developers (and hence manufacturers as well). Much of this, if it happens, is likely to stay outside the public domain. There still seems to be some pressure but on the other hand, have we got almost as far as we can go in reducing turbine noise? There are other solutions that have been discussed at several conferences but not yet progressed as far as TES; for example, porous trailing edges, vortex generators and brushes.

We seem to have reached a peak in publicly available work on the reduction of turbine noise but perhaps technological advances will favour development of active noise reduction in some form.

4. Propagation

In 2005, we had no properly validated propagation methodology for wind farms, though there had been quite a bit of work done in the late 1990s to develop methodologies in individual countries and at a European level. Propagation of wind turbine noise often used "Danish Statutory Order on Noise from Windmills (Nr. 304, Dated 14 May 1991)" as produced by The Danish Ministry of The Environment. Hemispherical propagation and octave band absorption or 5dB per km air absorption. In 2005 Kragh, Plovsing and Bo Søndergaard from Delta reported using Nord2000 for wind farms and they were back in 2009 at Aalborg to report on the validation of Nord2000 for wind turbines. In the UK in 2009 the use of ISO 9613 became largely accepted with a set of defined inputs. By the time we met in Glasgow ten years ago, we thought we had got as far as we could – and perhaps we had. But the question of accuracy of propagation calculations would not go away.

One of the striking points that came out of the 2019 conference was the difference in research requirements between the consultants and regulators on the one hand and developers and manufacturers on the other. The former were generally happy with the quality of the models available. Models such as ISO 9613 and Nord2000, if used with care, were able to provide the answer within a couple of decibels and by being conservative, that was good enough for an environmental assessment. For developers and manufacturers, however, two decibels might make the difference between a viable or non-viable wind farm, so more accurate propagation methods and, importantly, verification of the methodology was important.

These pressures are likely to continue and the advance in technology is favourable so I can see that we will hear more about this in the next 20 years. It is likely that weather conditions and topography will be incorporated in more detail.

5. Amplitude Modulation

Frits Van den Berg gave two papers in 2005. The second one dealt with the difference between turbine noise in the day in an unstable atmosphere and at night in a stable one. In particular he concluded that the reason for amplitude modulation (though he did not call it that) was the difference between the angle of attack at the top and the bottom of the rotation due to the difference in wind speed because of wind shear, and that was often more at night. That explanation for AM has been developed and there is a consensus that this may be at least one cause. There are other possibilities though, including those associated with atmosphere – such as at a location upwind of a turbine which is in the shadow zone of the bottom of the rotor but not it the shadow zone when the rotor is at the top. Similar shadowing can be created by topography. All these have been discussed at conferences from time to time but not in great depth.

It is certainly a complicated issue and highly dependent on meteorological and topographical conditions. Most of the work that has been done has been theoretical and we do not really know how it occurs and so when it might happen. We also know little about how common and how severe it is.

AM seems to be a rather "British thing". Of the roughly 30 papers on AM in the last 10 years, 50% have been from Britain. In Britain – and in Ireland where there have been a number of court cases where AM has been a factor in overturning planning consents – there is a perception among wind farm objectors that AM is a problem. It is a character of the noise unique to wind turbines and identifies in people's minds, rightly or wrongly, why wind turbine noise is subjectively different from other noise and so more annoying.

Although several of the theories would suggest that bigger turbines would produce more AM than smaller ones there is not any compelling evidence that that is the case, but that may be because we do not yet have enough of the 150m plus high turbines in operation to have the evidcence.

It is difficult to know whether there is significant demand for more work on AM. Wind farm neighbours are not in a position to drive research. Developers are not going to be interested in investing in research unless they are going to be penalised if their wind farm produces AM. Source noise is clearly the domain of the manufacturer. So one difficulty is that no-one has complete ownership of AM. There will be advances in our knowledge of the mechanism of AM in the future but how big those advances are, depends on what the next generation of turbines brings and on how much pressure there is from those who consider it a major issue.

6. Background Noise, Noise Limits and Compliance Testing

Some countries set noise limits relative to background noise – or at least as part of a hybrid limit. The UK has ETSU-R-97 which is a hybrid limit – 5dB above background noise or a fixed limit whichever is the greater.. Whether or not it was intentional, or whether it was based on precedent from other noise controls is not clear but relating turbine noise to background was a logical thing to do in the 1990s. Most turbines at the time were stall controlled so the sound power level continued rising with wind speed continuously in the same way as background noise. At about the time of our first conference, as I mentioned earlier, pitch-controlled turbines were taking over from stall control. When pitch control became dominant it might be argued that, because the turbine noise levelled off a point around 7 or 8m/s a fixed limit might be the better way of control. But none of that has actively driven the setting of limits anywhere as far as I know. Few limits have significantly changed in most countries over the last 20 years.

The turbines we have now are much more flexible pitch-controlled turbines that can, or might shortly be able to, be controlled in such a way as to shape the turbine noise level to the required noise limit. A turbine with 14 sound modes could presumably be controlled to run at the same sound power level in all winds or to follow a background noise curve.

So background noise data is still going to be needed at present. In any case it would arguably be required in the preparation of an Environmental Impact Statement under European and most other regulations as a statement of baseline conditions. Improvements in the measurement of background noise in the last 20 years have mostly come about through technological developments becoming available rather than driven by any specific demand. For example longer battery life and remote monitoring. It is often forgotten that the data processing is as important as data collection and it is increased speed and flexibility of data analysis and accumulated experience that have advanced. These have made it easier to recognise anomalies in the data such as water noise and the dawn chorus of birds and to evaluate topography more quickly.

It is difficult to see any great change coming in the measurement of background noise other that more automation and remote monitoring and in particular coordination of all the elements of the analysis. There is no driver for big improvements in accuracy. By 2045 perhaps we shall have much more of a soundscape approach to noise limits and to assessment methodology. I can see this as much more of a public awareness of soundscape generally.

The subject of compliance testing was a late starter in the conference series, perhaps because in the early days there were relatively few complaints. As time went on, more turbines were built and social media facilitated the setting up of residents and objectors groups complaints rose and there were more compliance measurements. Well before 2045, it should be possible for wind farm operators to get live feedback of the subjective and objective impact of their wind farm.

7. Impact on People

Of course, if there were no impact of wind turbine noise on people then we would not need to hold these conferences. In 2005, Eja Pedersen and Kerstin Persson Waye presented a paper which gave the results of a survey to establish the likelihood of being annoyed (rather and very annoyed) by wind turbine noise and concluded that there was little annoyance where turbines were designed to be below 35dB at a wind speed of 8m/s and about 10% of people were annoyed around 38 to 40dB. Equally important was that they looked at the way in which other factors moderated the reaction to noise. For example hardly anyone who was unconcerned with the change in the landscape brought about by turbines was annoyed by the noise. Pedersen, with others, did further work over the years which generally confirmed her first research and these, together with a few others were used by WHO in the 2018 Environmental Noise Guidelines for the European Region. David Michaud's extensive work in Canada which he reported in 2015 was too late for the WHO cut-off date but again was broadly supportive of earlier work including the influence of non-acoustic factors. It took longer for work on sleep disturbance to get going. Other than a clutch of papers in the 2011 conference which were largely inconclusive, there has been little reporting of the subject until the last 3 conferences.

By 2015 it had been established in several studies that there are no significant direct health effects on people. The notable impact that had been observed was on a segment of the population who experience health issues related to stress induced by annoyance. The implication of non-acoustic factors within the complaints about noise has been well known for over 50 years in the case of aircraft noise. In 2023, in Dublin, Hübner reported a previous paper [3] that the strongest predictor of annoyance in wind farm neighbours is the planning process. However, its not clear whether it is the process itself or the result of the process (to allow the wind farm to be built) that is the problem. Whilst there has been more research and some useful work, our overall knowledge of the situation has not changed much in the last 20 years though it does show signs of changing now. We can predict the proportion of the population annoyed at a particular noise level but we cannot get anywhere near predicting the impact on any individual because the level of noise is only one factor.

We have always had one or two delegates and contributors from the field of medicine – David Michaud, has been with us most conferences since 2005 and David Colby has been another regular. The last few conferences, and in particular the last one, have seen a welcome rise in other delegates with medical or associated expertise to bring more into the debate. The 2023 conference also saw a small shift of emphasis with a look at different perceptions stakeholders have of noise, and indeed of wind farms in general. It also looked in more detail at what conditions of turbine operation people were most annoyed. This, together with the possibility of getting feedback through Apps in real time, opens up new possibilities for control of wind farm noise.

Apps that allow residents to report their reaction to turbine noise and other aspects of turbines are possible. The apps allow people to feel they have more control if they can report annoyance easily. Also they give operators a better understanding of conditions under which annoyance occurs. The app can provide each residence with information about predicted noise levels and other factors such as shadow flicker. Combined with monitoring of weather conditions such an arrangement could provide very powerful information. But how could that possibly be converted into action. It is clearly not going to be acceptable to operators for the wind farm to be controlled solely by the views of the neighbours. In any case, though it is used by WHO, it has not been established that annoyance is the best measure to judge the impact of noise.

One problem is that we don't really know what the incidence of complaints is in the UK, and I'm not clear whether other countries have figures or not. It is clear that the number of people likely to be affected is a small proportion of the population because nearly all turbines are located in areas where population density is low.

8. Technology and Knowledge

I have discussed individual aspects of technology advances in wind turbines which have played key roles in advancing our knowledge of wind turbine noise and its effect on people. However, it is the general rather than the specific advance in technology and knowledge that, arguably, has made most of the difference in the last 20 years and almost certainly will in the next twenty unless perhaps Politics, which I discuss briefly in the next section, intervenes. It seems extremely unlikely that the progress of technology will diminish as we move forward in the next two decades. It maybe difficult, even for those who were working 20 years ago to remember how things have moved on since 2005 There was no Twitter/X, no Netflix, no significant mobile internet, no iphone though we did have the Blackberry. Less than half homes in the UK were on broadband, though probably more than half of businesses were. Speeds of 0.5 to 1Mbs were around the maximum for most people.

Fig 5 – Phone from 2005

Apart from a few people ahead of the game, we could not receive data remotely and in real time. LIDAR and SODAR were available but I am not aware of anyone using them for wind farm developments until about 2011. Sound Level Meter batteries needed a lead acid battery back-up to run for more than a week

When we look at the technological advances in the last 20 years, there is no reason why the next 20 years should not bring equally big advances. In fact it seems to me more likely that we will have a faster advance. Perhaps we could predict a few of these but most will evolve over time. There is little evidence of a major break with the current technology of three-bladed HAWTs. No doubt there is plenty of work going on in the background but it seems unlikely at present that we are suddenly going to discover that VAWTs or Multi-rotors some other innovation can be more efficient or profitable.

I suggest the most predictable advances will be with artificial intelligence. AI is already making inroads into acoustics. The writing of field notes to incorporate photographs, measurements, topography and weather automatically. Noise source identification and sound source location are all using AI now, though in early stages. It is inevitable that AI will be able to help us in the analysis of data and identify anomalies. I would expect individual companies and people regularly to write their own apps for targeted tasks – using AI to help with the software writing.

But, while AI will certainly be used to help develop turbine technology I do not see that, of itself, AI will change the direction in which technology moves - it is likely to have more influence, for the time being at least, on the way we work rather than the way hardware develops. More accurate propagation predictions will undoubtedly involve variations with weather, that means that real time weather information may be required on a wind farm site; the presence of amplitude modulation may be alerted by neighbours with smartphone apps (this already happens in pilot studies). Perhaps we will have AI driven AM monitoring stations; all these will be brought together and processed by AI, perhaps directly to modify the operation of the turbines but more likely to inform controllers in the first place. .Things go together – if we can measure compliance more accurately then there is an incentive to make propagation calculations more accurate.

9. Conclusions

Demand over the last 20 years has been driven by our knowledge about climate change and how that will affect our futures. A consensus has built over a broad range of political views that we need to take action to mitigate the effects of climate change. But there is a spectrum of views on the urgency with which we need to do this – and of course some who do not believe the climate is changing at all. In an Irish High Court case [1] the interplay between local planning decisions and national climate obligations was tested. The developer sought permission to construct a 13-turbine wind farm and ABP, Ireland's national planning authority, denied the application, citing visual impacts and that the County Development Plan said the area was unsuitable for wind farms. The developer challenged this decision, and the High Court ruled that ABP had not adequately considered its obligations under the Climate Action and Low Carbon Development Act 2015. The judge said that climate goals should take precedence over concerns like visual impacts, stating, "An immediate end to business as usual is a precondition for planetary survival."

Similarly there is strong political pressure to build wind farms in most jurisdictions though with varying enthusiasm. But political pressures change happens. Since 2005, there have been four presidents of France, four presidents of the USA and eight Prime Ministers of the UK! Though things change more slowly elsewhere - Angela Merkel became chancellor of Germany just two months after our first conference in Berlin in 2005 and has not long ago been replaced.

Nevertheless, even if there is a dramatic change in technology or a dramatic change in world politics, I think we shall still building wind farms and assessing noise from them in 2045.

Acknowledgments

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References

[1] Coolglass Windfarm Limited v. An Bord Pleanála [2025] IEHC 1

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

[3] Pohl, J., Hübner, G., Liebig-Gonglach, M., & Hornberg, C. (2020). Verbundvorhaben: Objektive Kriterien zu Erschütterungs- und Schallemissionen durch Windenergieanlagen im Binnenland (TremAc); Schlussbericht zu den Teilvorhaben Umweltpsychologische Analyse der Windenergie-Immissionswirkungen auf Akzeptanz und Wohlbefinden der Anwohner (MLU) und Umweltmedizinische Analyse der Wirkung von Windenergieanlagen auf Gesundheit und Wohlbefinden von Anwohnern/innen (UBI).