SOUND PROPAGATION FROM OFF-SHORE WIND TURBINE ARRAYS

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SUMMARY

Sound propagates readily across water. This common knowledge and experience is supported by European work on sound propagation modelling backed up by measurements of propagation over water. In the case of an exclusion zone of 5 km, it is demonstrated that for a typical wind-energy generating system, which may include 60 or more large turbines, the sound pressure on-shore level will be 46 dBA on average for the time that the sound power level is 107 dBA per turbine. This is significantly in excess of typical rural night-time background noise levels of 25 to 30 dBA, of the present Ontario 40 dBA noise limit for on-shore wind-energy generating systems and the German night-time limit of 35 dBA. For 10% of the time that the sound power level is 107 dBA per turbine the sound pressure level on-shore will be 51 dBA, well in excess of the Ontario noise limit. This 10% criterion can be used as the worst case scenario, the basis for the Ontario turbine noise regulations. These estimates do not include the effect of turbulence in the atmosphere and its impact on the generation of excess low frequency noise. They do not include any allowance for uncertainty in the estimate, uncertainty in the sound power of the individual turbines or of increase in sound power level of the turbines as they age. The proposed 5 km exclusion zone is far from adequate. The exclusion zone needs to depend upon the number of turbines in the development. Even with the present inadequate Ministry of the Environment turbine noise regulations the exclusion zone needs to vary from a minimum 5 km for a 5 turbine project to beyond 20 km for a 60 plus project.

SOUND PROPAGATION OVER WATER – GENERAL COMMENTS

First and foremost it is our common experience that sound propagates readily over water, particularly at night when background sounds die down and when the atmosphere becomes stable. I well remember a comment by Mr. Phil Brennan, Manager of Environmental Assessment and Approvals Branch at the Ontario Ministry of the Environment (MOE), at the first focus group meeting that I attended: *A neighbour's generator, 2 km across the lake from my cottage, drives me crazy in a way that no noise does at home in Toronto*. (This is not an exact quotation but does represent the point that he was making.) Two things are important here: the ease of sound propagation over water and the low background noise in rural Ontario, particularly at night. The propagation of sound over water is discussed in the next section.

The low background noise at night is what allows the intrusion of turbine noise. Let us be clear here: there is no difference in the average wind speed at hub height (80 to 100 metres) between day-time and night-time and hence no difference in the turbine noise between day-time and night-time. This is demonstrated by the wind energy output of the Ontario wind generating systems. The following table summarizes data from the Ontario Independent Energy System Operator (IESO). The months chosen represent the four seasons. The capacity factor is the monthly average power output (MW) divided by the nameplate power output (1085 MW for the period July 2009 to April 2010). The averages were taken for day-time (6:00 am to 6:00 pm) and night-time (6:00 pm to 6:00 am). The ratios demonstrate that there is no significant difference in power output and hence noise output between day and night.

Month	July 2009	Oct. 2009	Jan. 2010	April 2010
Day-Time Capacity Factor	15.4%	31.4%	32.8%	31.9%
Night-Time Capacity Factor	14.1%	30.9%	33.1%	34.8%
Ratio: Day/Night	1.09	1.02	0.99	0.92

By contrast, there is a significant difference in wind speed at ground level between day and night. To those of us who have any experience of rural areas and particularly of Ontario lakes large and small, this is demonstrated by the calming of the wind and the consequent calming of the lakes at night. For those without that experience, data from meteorological towers offer the proof. A summary of data from 28 sites, world-wide, was that the average (day and night) ratio of wind speed at a height of 10 metres to that at 80 metres was 0.7 ± 0.1 whereas the night-time average was 0.5 ± 0.1. During the summer months the difference is magnified.

SOUND PROPAGATION OVER WATER – LITERATURE REVIEW

The science of noise from off-shore wind turbines has been reviewed by Sondergaard and Plovsing (SP) in a report to the Danish Ministry of the Environment:
http://www2.mst.dk/udgiv/publications/2005/87-7614-687-1/pdf/87-7614-689-8.pdf
The report consists of two parts: (a) measurement of emission of offshore turbine noise and (b) calculation of sound propagation from offshore turbines. Part (a) is not relevant here. The difficulty of measuring sound emission is that the measurement must be made at sea and hence with a sound meter on a boat. The background noise from the boat was 55 to 58 dBA. Nevertheless at the required range of 85 to 125 metres from the turbine the methodology was shown to work. Part (b) was a combination of literature review and calculation using Swedish and Danish propagation models.

SP summarized the earlier work of Hubbard and Shepherd who measured turbine noise propagation over desert sand, like water an acoustically hard surface. Hubbard and Shepherd showed good correlation with spherical spreading and air absorption of sound for “high” frequency sound (630 Hz). However, in the infrasound region the results were better described by cylindrical spreading. Note that at low and infrasound frequencies absorption by the air is negligible. Where the crossover occurs is not known. However, the cylindrical spreading over an acoustically hard surface is very important because it means that the sound pressure level decreases by only 3 dB for each doubling of distance from the turbine rather than 6 dB for spherical spreading.

SP go on to discus propagation models formulated in Europe. The so-called Danish method is very simplistic with spherical spreading, a single parameter for air absorption (0.005 dB/metre) and a +3 dB correction for incoherent reflection from acoustically hard ground. In 1998, further work under the auspices of the European Union was presented for propagation over ground and water. This new model took account of the frequency dependence of the air absorption coefficient and so was viable for larger propagation distances. However, the model for propagation over water was tested for distance only up to 350 metres.

In 2001, a Swedish report specifically addressed larger distances both over ground and over water. The model assumed a transition from spherical spreading to cylindrical spreading at a distance of 200 metres. This 200 metre break point is a function of the sound speed gradient in the atmosphere. In turn, the sound speed gradient depends upon the wind speed gradient and the temperature gradient. Both of these gradients, and therefore the sound speed gradient, vary with time. This Swedish propagation model, for distances larger than 200 metres, is written as:

$$L = L_s - 20\log(r) - 11 + 3 - \Delta L_a + 10\log(\frac{r}{200})$$

L is the sound pressure level at the observer, L_s is the turbine sound power (e.g. 105 dBA), 11 is 10 log (4π), 3 is 3 dBA of ground reflection, ΔL_a is the integrated frequency dependent absorption coefficient, a function of r, and *r* is the distance from turbine hub to the observer. The second term on the right gives the spherical spreading and the final term corrects for cylindrical spreading beyond 200 metres. SP have calculated the integrated absorption coefficient and show the result in figure 17 of their report. For instance, at a distance of 5 km, it is 8 dBA. Given that the break point distance for the onset of cylindrical spreading was uncertain, the authors of the model specify that the model gives an upper limit to the sound pressure level at the observer.

In a report for the Swedish Energy Agency - *"Long-Range Sound Propagation over the Sea with Application to Wind Turbine Noise"*,

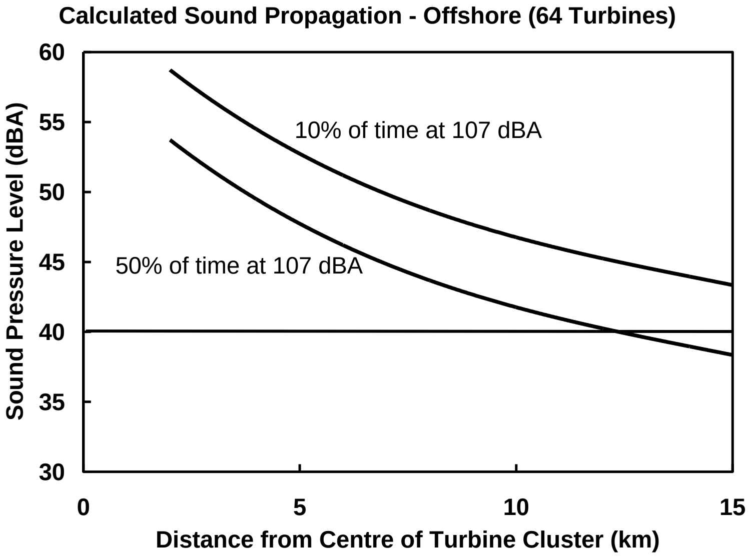
http://www.vindenergi.org/Vindforskrapporter/V-201_TRANS_webb.pdf

Boué investigated the Swedish propagation model by making sound propagation measurements over sea in the Kalmar Strait between Sweden and the island Öland in the Baltic Sea. The separation between source and receiver was 9.7 km. Measurements of <u>average</u> sound transmission loss showed agreement with the Swedish propagation model with a break between spherical and cylindrical spreading at 700 metres rather than the token 200 metres in the model. Furthermore, the measured TL(90), the transmission loss exceeded 90% of the time, was in agreement with the Swedish propagation model with the 200 metre break point. Therefore, Boué's measurements allow a reliable estimate of the sound pressure level as a function of distance over water from a turbine. Interestingly, Dr. Phillip Dickinson, Emeritus Professor of Acoustics at Massey University, has found the break point of 750 metres for turbine noise propagation over land. (See Sound, Noise Flicker, B. Rapley and H. Bakker, eds.; Atkinson and Rapley (2010), p. 175)

I would like to add to this discussion and enlarge on an aspect of the Swedish model. At large distances, such as 5 km, the path difference between the direct and reflected pathways from turbine to receptor become small. For instance, at a distance of 5 km, the path difference is equal to or less than a quarter-wavelength for frequencies at and below 1700 Hz. That is, for the spectrum of sound that reaches a receptor the direct and reflected sound waves add coherently. This adds 3 dB to the sound pressure level.

NUMERICAL EXAMPLES

It is instructive to consider numerical examples based upon the Swedish propagation model with both the 200 and 700 metre break points. These correspond to the sound pressure levels exceeded 10% and 50% of the time respectively. Consider 64 large turbines (say 3MW) each generating 107 dBA of sound power. The total sound power is then L_S =125 dBA (107 + 10 log 64). The result of the model is shown in the figure below as the sound pressure level, exceeded 10% and 50% of the time that the turbines are emitting a sound power of 107dBA, as a function of distance. For multiple turbines this distance is from the mean position of the turbines cluster. The turbines will not emit at 107 dBA all of the time. However, for fixed speed turbines such as the Siemens 2.3MW machines, the <u>sound</u> power level reaches its maximum value at an electrical power output of about 25% of its nameplate electrical power output.



As an appendix, similar graphs are given for clusters of 32, 16 and 8 off-shore turbines. Consider also, for interest, the specific case of the proposed Wolfe Island Shoals wind generating system with 24 turbines located 5 to 7 km from the nearest shoreline and a further 100 located 12 to 15km from the shoreline. Although not specified, these will probably be 2.3 MW turbines with a sound power of 105 dBA. The sound pressure level at the nearest shoreline will be greater than 50 dBA and 45 dBA for 10% and 50% respectively of the time that the turbines are operating with a sound power of 105 dBA. Again note that the sound power will be 105 dBA for all times that the electrical power generation is at and above about 25% of the nameplate power.

This review of the work of SP and the measurements made by Boué and the above analysis makes clear that a 5 km setback of wind turbines from rural shorelines is far from adequate from an acoustic perspective. For the cases considered, the predicted sound pressure levels are collected into a table for an exclusion zone of 5 km. A setback for the centre of the cluster is 6 km in each case; apart from the Wolfe Island Shoals project (WIS) for which the proposed turbine locations are used.

Number of Turbines (3MW)	8	16	32	64	WIS
Sound Pressure Level (10%) (dBA)	42	45	48	51	50
Sound Pressure Level (50%) (dBA)	37	40	43	48	45

In all cases, treating the 10% results as representative of the worst case scenario, the on-shore sound pressure level is far in excess of the typical night-time rural background sound pressure level, the present Ontario wind turbine noise limit of 40 dBA and the more realistic 35 dBA German night-time limit. There are other concerns that to date have been ignored by the Ministry of the Environment.

DISCUSSION

All measurements and calculations are subject to uncertainty. Specifications for turbine noise quote uncertainty of 1 or 2 dBA. ISO 9613, the standard model for calculating noise at a receptor from an on-shore wind turbine, includes an uncertainty of 3 dBA. SP made a measurement of turbine sound power level for an off-shore turbine and found a difference from the sound power level of a same type on-shore turbine of between 1 and 3 dBA, depending upon the wind speed. They write: *"The difference is within what could be expected when comparing two different turbines of the same type on land".*

There is turbulence in the atmosphere over water just as there is over land. In a published paper Barthelmie has measured a turbulent intensity at a Danish off-shore turbine site to be

7%. The author was more interested in the turbulence of the downwind wake from the turbines and so was not looking for the range of turbulence out at sea. Turbulence adds significantly to turbine noise, particularly to the low frequency component of the turbine noise. It is the low frequency noise which propagates with little absorption by the atmosphere, which is most subject to cylindrical spreading and coherent reflection and which causes the most annoyance. Part of any renewable energy approval process should be the measurement of the turbulent intensity over the range of height traversed by the blades.

It is now clear that the MOE noise regulations for on-shore wind turbines were and are woefully inadequate. They allow noise intrusion of more than 15 dBA in rural areas at night; neglect MOE's own general penalty of 5 dBA for noise of a periodic or cyclic character (amplitude modulation); included an allowance for masking noise for several years beyond the time that research in Europe had shown that masking noise is generally just not present at night; ignore the contribution of turbulent air to low frequency turbine noise; ignore the uncertainty in the sound power of turbines and in the propagation models; and finally, ignore the recommendations of medical and other authorities that setbacks from modern large up-wind turbines should be 1.5 to 2 km. The failure of MOE to correct these inadequacies (masking noise apart) could be the embarrassment of admitting its initial lack of judgement, knowledge or spine.

Now that we are seeing the advent of off-shore turbines in Ontario it is vital to get things right at the beginning. The proposals coming forward involve hundreds of turbines in the Great Lakes. A 5 km exclusion zone is far from adequate. The exclusion zone needs to vary from a minimum 5 km for a 5 turbine project to beyond 20 km for a 60 plus project. I would like to support a point made by Bill Palmer in his EBR commentary. In Europe, as they have gained experience with off-shore wind turbines, regulators have been increasing the setbacks from shore, to far beyond the meagre 5 km proposal for the Great Lakes. Rather than go through the same learning curve, Ontario needs to make use of the European experience.
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APPENDIX - Calculated Sound Pressure Levels at Shore for Clusters of 32, 16 and 8 Turbines.

The sound pressure levels are calculated with the Swedish model supported by Boué’s measurements of sound propagation over water. In addition, 3 dBA has been added for coherent reflection at the ground.