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Wind turbine sound limits: Current status and recommendations based on mitigating noise annoyance

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ABSTRACT

This paper describes existing wind turbine sound limits in Australian states and several other countries with similar constraints, how these were established and a method that could facilitate their harmonisation. Most existing limits appear to have been adopted to avoid sleep disturbance using data derived from sound sources other than wind turbines. This seems to have been a reasonable approach at the time of their adoption because of the paucity of other suitable data. More recently the concept of "annoyance" has been used to encapsulate negative reactions to wind turbine sound. Many studies have now demonstrated a significant relationship between annoyance and wind turbine sound level, whether or not sound was the major source of the annoyance. Thus there is a logical basis for now deriving a wind turbine sound limit based on limiting annoyance. This paper describes such an approach. The derived limit is compared to existing Australian and international limits. Its value lies within the range of these other limits. It provides a method for harmonisation of future limits based on direct assessments of human response to wind turbine sound.

1. Introduction

Wind turbines are recognised as being important because they allow energy generation using a renewable resource with low carbon emissions. However, while having a positive environmental impact in this regard, they can be visually imposing and are a source of audible sound. If placed near to where people live these issues can cause "annoyance" and may have more specific effects on health and well-being. A recent multiple logistic regression model for wind turbine noise annoyance [1] has a base model containing wind turbine sound level and province which had a coefficient of determination (R^2) of 0.11. Adding "closing bedroom windows to reduce noise during sleep when wind turbine noise was identified as the source" increased the R^2 by 0.3. Including annoyance with blinking lights added another 0.09 to R^2. The addition of eight more variables increased the R^2 by a further 0.08. Given that wind turbines are potentially perceived through vision and sound and at night visual perception (apart from warning lights) is negated, it is not surprising that sound and blinking lights are such important influences. Furthermore, sound is a factor that can be mitigated though regulation, as it needs to be to ensure community acceptance of the implementation of this technology. To this end, wind turbine sound limits have been established in many countries to place a lower limit on the setback distance of wind turbines relative to dwellings and population centres. A setback distance, while primarily determined on the basis of the wind turbine sound based lower limit, will also reduce the impact of shadow flicker during the daytime and blinking lights during the night time.

In this paper, the rationales for the wind turbine sound limits that have been used, are being used, or are proposed for use in Australia and New Zealand are reviewed. These limits are based on data obtained from psychoacoustic studies of sound sources other than wind turbines. The derived sound limits are compared to wind turbine sound limits adopted in some other countries which use specific wind turbine rather than generic sound parameters. Given that "annoyance" has been identified in several studies as the key variable in determining tolerability of wind turbines [2], this paper then examines the annoyance response to wind turbines as a function of wind turbine sound level and the possibility of utilising this behavioural response to derive sound limits acceptable to most individuals.

Existing published data on the percentage of a population exposed to wind turbine sound that is highly annoyed with wind turbines, as a function of the wind turbine sound level, produces curves which are not smooth. Michaud et al. [1] fitted individual curves to the data using the "Community Tolerance Level" (CTL) model [3,4]. The "Community

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Tolerance Level" (CTL) model has proved successful in modelling the percentage of people who are highly annoyed as a function of sound level for aircraft, road and railway noise. The average CTL for wind turbine sound is used in this paper to derive wind turbine sound limits which could be used to replace the range of wind turbine sound limits which are currently being used in Australia and New Zealand. These current wind turbine sound limits appear to be based on avoiding sleep disturbance from sound sources other than wind turbines. Furthermore, published evidence is inconsistent regarding the potential relationship between wind turbine sound level and sleep disturbance [5].

Hence, a major purpose of this study was to address these deficiencies by deriving a sound limit recommendation that is based on annoyance as a function of wind turbine sound exposure data. In so doing it was recognised that, while the reduction of wind turbine sound level between outdoors and indoors is important, for practical reasons wind turbine noise limits need to apply to the outdoor wind turbine sound levels.

2. Wind turbine sound limits in Australasia

This section reviews the development and adoption of wind turbine sound limits in Australian states and New Zealand. Since the limits that have been developed are often expressed using slightly different parameters and may either include or exclude prevailing ambient sound levels, it is necessary to account for these differences to permit direct comparison of the levels. The wind turbine sound limits discussed in this paper are summarised in Table 1.

ETSU-R-97 [6] is a report on the assessment and rating of noise from wind farms prepared by the United Kingdom Department of Trade and Industry over 20 years ago. The wind turbine sound limits used in Australasia have been strongly influenced by this English report. ETSU-R-97 [6] recommends the use of $L_{A90(10min)}$ to measure wind turbine sound. $L_{A90(10min)}$ is the fast response A-weighted sound pressure level which is exceed for 90% of the time in a 10 min time interval. This sound level has been adopted rather than the $L_{Aeq(10min)}$, which is usually adopted for 'industrial' sound sources, because the wind turbine sound level is typically very close to the background sound level, and the $L_{Aeq(10min)}$ sound level could be significantly affected by other ambient sound and therefore not be representative of the wind turbine sound. $L_{Aeq(10min)}$ is the level of the energy averaged A-weighted sound pressure over a 10 min time interval. ETSU-R-97 recommends measuring and assessing the outdoor sound levels at the sound sensitive properties because of several practical issues with measuring these levels inside houses. This approach raises the need for a better understanding of the difference between indoor and outdoor levels [7] because of the possible influence of a number of types of resonance including building cavity resonances on the indoor sound levels [8]. ETSU-R-97 states that wind turbine $L_{Aeq(10min)}$ levels can be expected to be about 1.5–2.5 dB higher than the $L_{A90(10min)}$ levels. $L_{Aeq(10min)}$ will be assumed to exceed $L_{A90(10min)}$ by the range of 1.5 to 2.5 dB or by the mean value of 2 dB in this paper.

ETSU-R-97 also recommends the use of the background sound level plus 5 dBA as the limit except where background sound pressure levels are low. This approach is adopted from BS 4142:1990 [9] which relates to industrial sound emission more generally. BS 4142 uses background sound level plus 5 dBA because its authors believed that this sound level is of marginal significance to exposed persons. BS 4142 states that complaints are likely if the limit level exceeds the background sound level by approximately 10 dBA or more. A difference of 5 dBA is considered to be of marginal significance, with lesser differences associated with progressively fewer complaints [10].

A rationale for a plus 5 dBA threshold is that the BS 4142 sound limit applies to the industrial sound alone (i.e. a sound estimate corrected to remove the influence of the prevailing background sound) rather than the *total* sound. Most standards [e.g. [11]] that allow background sound correction, limit the application of the correction to the case when the total sound is 6 dB or more above the background sound. This restriction is imposed to limit the percentage uncertainty which occurs when subtracting one large quantity from another large quantity in order to remove the background sound from the total sound measured. Notably, this subtraction is performed in the pressure squared domain rather than in the decibel domain. For a difference of 6 dB the correction is −1 dB rounded to the nearest decibel. This means that the smallest sound level that can be accurately measured at the sound sensitive locations is the background level plus 5 dBA.

The ETSU-R-97 limit is equivalent to an L_{Aeq} of the background sound plus 6.5 to 7.5 dBA if the background sound is measured as $L_{A90(10min)}$ because $L_{Aeq(10min)}$ is 1.5 to 2.5 dB greater than $L_{A90(10min)}$.

ETSU-R-97 argues that there also needs to be a lower limit for the sound level limit. For night time sound it starts with the L_{Aeq} of 35 dBA indoor limit for sleep that was recommended by the WHO Environmental Health Criteria 12 [12]. It then adds 10 dBA to account for the attenuation from outdoors to indoors provided by an open window and subtracts 2 dB to convert from $L_{Aeq(10min)}$ to $L_{A90(10min)}$. This gives an outdoor night time limit of $L_{A90(10min)}$ of 43 dBA. The WHO Environmental Health Criteria 12 quotes Beland et al. [13] for the 35 dBA limit. It should be noted that Beland et al. used aircraft sound to obtain the recommended sleep sound limit.

ETSU-R-97 argues that for periods during the day, the defined external sound limit should lie somewhere between that required to avoid sleep disturbance in the outdoors locale and the higher level that would, with attenuation from outdoors to indoors, prevent sleep disturbance inside the property. ETSU-R-97 then recommends that the lower limit should be between 35 and 40 dBA which is between a sleep limit of 35 dBA and a reduction (to 40 dBA) of the outdoor night limit of 43 dBA limit [$L_{A90(10min)}$] described above based on a belief that it does not offer sufficient protection to the external amenity in quiet areas during the day. These limits have been of great influence in Australia and New Zealand even though the limited data available at the time of their description means that they have a relatively weak evidence base. The described range is at the low end of typical industrial sound limits. However, somewhat arbitrarily, ETSU-R-97 recommends a greater lower limit of 45 dBA if the owners of the sound sensitive property have a financial involvement with the wind turbines, presumably on the basis that they will accept a higher level of impact because of their compensation.

The first New Zealand wind turbine standard NZS 6808:1998 [14] refers to Berglund and Lindvall [15] (an update of WHO Environmental Health Criteria 12 [12]) for a sleep limit of L_{Aeq} between 30 and 35 dBA. It assumes a reduction from outdoors to indoors of 10 dB with open windows and appears to assume that $L_{A95(10min)}$ is approximately equal to $L_{A90(10min)}$, because while it notes the ETSU-R-97 [6] statement regarding the difference between $L_{A90(10min)}$ and $L_{Aeq(10min)}$ it uses $L_{A95(10min)}$, although a 2010 update of the standard reverts to $L_{A90(10min)}$. On this basis, it then sets a lower maximum (external) limit of $L_{A95(10min)}$ of 40 dBA because this is equivalent to an indoor $L_{Aeq(10min)}$ of between 31.5 and 32.5 dBA which is within the 30–35 dBA range recommended by Berglund and Lindvall (1995). NZS 6808:1998 adopts the same outdoor background plus 5 dB limit as ETSU-R-97 when this is greater than the constant lower maximum level given above, except that it applies to $L_{A95(10min)}$ rather than $L_{A90(10min)}$. This New Zealand standard specifies the total measured sound level for compliance checks, rather than the total level corrected for background level as used in ETSU-R-97. As a result, its lower level limit is equivalent to a corrected level of $L_{A95(10min)}$ of 39 dBA. This standard was used in Victoria and still applies to older wind turbines there.

Berglund and Lindvall [15] assume that "the reduction" of the facade "from outside to inside with the window open is 15 dB" and hence suggest an outdoor limit of L_{Aeq} of 45 dBA which is equivalent to an $L_{A90(10min)}$ or $L_{A95(10min)}$ of between 42.5 and 43.5 dBA. However, they also say that the actual reduction maybe only 5–7 dB, which gives an outdoor sound pressure level limit of 35–37 dB $L_{Aeq(10min)}$. This is