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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

Table 1
Wind Turbine Sound Limits.

Standard	Quantity	Area	Time	Background $L_{A90(10min)}$	Limit
ETSU-R-97 England	$L_{A90(10min)}$	No financial Involvement	Day	≤ 30 to 35 dB	35 to 40 dB
ETSU-R-97 England	$L_{A90(10min)}$	No financial Involvement	Day	> 30 to 35 dB	BKGND + 5 dB
ETSU-R-97 England	$L_{A90(10min)}$	No financial Involvement	Night	≤ 38 dB	43 dB
ETSU-R-97 England	$L_{A90(10min)}$	No financial Involvement	Night	> 38 dB	BKGND + 5 dB
ETSU-R-97 England	$L_{A90(10min)}$	Financial Involvement	Any	≤ 40 dB	45 dB
ETSU-R-97 England	$L_{A90(10min)}$	Financial Involvement	Any	> 40 dB	BKGND + 5 dB
VIC NZS 6808:1998	$L_{A95(10min)}$	Any	Any	≤ 35 dB(L_{A95})	40 dB
VIC NZS 6808:1998	$L_{A95(10min)}$	Any	Any	> 35 dB(L_{A95})	BKGND + 5 dB
SA EPA 2003	$L_{Aeq(10min)}$ Prediction $L_{A90(10min)}$ Measurement	Any	Any	≤ 30 dB	35 dB
SA EPA 2003	$L_{Aeq(10min)}$ Prediction $L_{A90(10min)}$ Measurement	Any	Any	> 30 dB	BKGND + 5 dB
WA 2004	$L_{Aeq(10min)}$	Any	Any	≤ 30 dB	35 dB
WA 2004	$L_{Aeq(10min)}$	Any	Any	> 30 dB	BKGND + 5 dB
SA EPA 2009	$L_{Aeq(10min)}$ Prediction $L_{A90(10min)}$ Measurement	Standard	Any	≤ 35 dB	40 dB
SA EPA 2009	$L_{Aeq(10min)}$ Prediction $L_{A90(10min)}$ Measurement	Standard	Any	> 35 dB	BKGND + 5 dB
SA EPA 2009	$L_{Aeq(10min)}$ Prediction $L_{A90(10min)}$ Measurement	Rural Living	Any	≤ 30 dB	35 dB
SA EPA 2009	$L_{Aeq(10min)}$ Prediction $L_{A90(10min)}$ Measurement	Rural Living	Any	> 30 dB	BKGND + 5 dB
VIC NZS 6808:2010	$L_{A90(10min)}$	Standard	Any	≤ 35 dB	40 dB
VIC NZS 6808:2010	$L_{A90(10min)}$	Standard	Any	> 35 dB	BKGND + 5 dB
VIC NZS 6808:2010	$L_{A90(10min)}$	High Amenity	Day	≤ 35 dB	40 dB
VIC NZS 6808:2010	$L_{A90(10min)}$	High Amenity	Day	> 35 dB	BKGND + 5 dB
VIC NZS 6808:2010	$L_{A90(10min)}$	High Amenity	Evening or Night less than 6 m/s	≤ 30 dB	35 dB
VIC NZS 6808:2010	$L_{A90(10min)}$	High Amenity	Evening or Night less than 6 m/s	> 30 dB	BKGND + 5 dB
NSW Draft 2011	$L_{Aeq(10min)}$ $L_{A90(10min)}$ + 1.5 dB	Any	Day	≤ 30 dB	35 dB
NSW Draft 2011	$L_{Aeq(10min)}$ $L_{A90(10min)}$ + 1.5 dB	Any	Day	> 30 dB	BKGND + 5 dB
NSW Draft 2011	$L_{Aeq(10min)}$ $L_{A90(10min)}$ + 1.5 dB	Any	Night	≤ 30 dB	35 dB
NSW Draft 2011	$L_{Aeq(10min)}$ $L_{A90(10min)}$ + 1.5 dB	Any	Night	> 30 dB	BKGND + 5 dB
QLD 2016	L_{Aeq} Prediction	Non-host lot	Day and Evening	≤ 32 dB	37 dB
QLD 2016	L_{Aeq} Prediction	Non-host lot	Day and Evening	> 32 dB	BKGND + 5 dB
QLD 2016	L_{Aeq} Prediction	Non-host lot	Night	≤ 30 dB	35 dB
QLD 2016	L_{Aeq} Prediction	Non-host lot	Night	> 30 dB	BKGND + 5 dB
QLD 2016	L_{Aeq} Prediction	Host lot	Any	≤ 40 dB	45 dB
QLD 2016	L_{Aeq} Prediction	Host lot	Any	> 40 dB	BKGND + 5 dB
Demark	L_{Aeq}, 8 m/s@10 m	Standard	Any	Any	44 dB
Demark	L_{Aeq}, 6 m/s@10 m	Standard	Any	Any	42 dB
Demark	L_{Aeq}, 8 m/s@10 m	Noise Sensitive	Any	Any	39 dB
Demark	L_{Aeq}, 6 m/s@10 m	Noise Sensitive	Any	Any	37 dB
Canada, Ontario	L_{Aeq} (1hr)	Urban	Any	≤ 38 dB RefBG	45 dB
Canada, Ontario	L_{Aeq} (1hr)	Urban	Any	> 38 dB RefBG	RefBG + 7 dB
Canada, Ontario	L_{Aeq} (1hr)	Rural	Any	≤ 33 dB RefBG	40 dB
Canada, Ontario	L_{Aeq} (1hr)	Rural	Any	> 33 dB RefBG	RefBG + 7 dB
Sweden	L_{Aeq}, 8 m/s@10 m	Standard	Any	Any	40 dB
Sweden	L_{Aeq}, 8 m/s@10 m	Quiet	Any	Any	35 dB
Netherlands	L_{Aden}	Any	Any	Any	47 dB
Netherlands	L_{Aeq}	Any	Night	Any	41 dB

equivalent to an $L_{A90(10min)}$ or $L_{A95(10min)}$ of between 32.5 and 35.5 dBA.

The South Australian Environment Protection Authority [16] set a lower maximum limit for the predicted sound level of $L_{Aeq(10min)}$ equal to 35 dBA. The lower maximum limit for the measured sound level is an $L_{A90(10min)}$ of 35 dBA which appears to come from that set in ETSU-R-97. In both cases, the background level plus 5 dB is used as the maximum limit when it is greater than the constant lower maximum limit given above. Although the predicted level limit is specified in $L_{Aeq(10min)}$, the measured level limit is in $L_{A90(10min)}$ as with ETSU-R-97. Thus the measured limit is equivalent to an $L_{Aeq(10min)}$ of between 36.5 and 37.5 dBA. Since the wind turbine sound levels are not corrected for background noise (the ambient noise, accounting for wind speed, with no wind turbines operating in the area) the effective corrected wind turbine limits are 1 dBA lower. This is because the correction when the background noise is 6 dB below the wind turbine noise is 1 dB when rounded to the nearest decibel.

Western Australian Planning Bulletin Number 67 [17] followed the 2003 South Australian prediction guidelines and set a lower maximum limit of $L_{Aeq(10min)}$ of 35 dBA and used $L_{Aeq(10min)}$ of background plus 5 dB as the maximum limit when it is greater than the constant lower maximum limit given above. It is not specified whether measured values should be $L_{Aeq(10min)}$ or $L_{A90(10min)}$. Use of $L_{Aeq(10min)}$ for measurements would lower the limits by between 1.5 and 2.5 dB compared to ETSU-R-97 and NZS 6808:1998. If there is no correction for background noise level, the corrected wind turbine sound levels would be 1 dBA lower.

In 2009 South Australian Environment Protection Authority [18] revised its guidelines. The 35 dBA lower maximum limit was retained only for rural living areas which were defined as a rural residential ‘lifestyle’ areas intended to have a relatively quiet amenity and not intended for primary production other than for the occupier’s own use. It was recognized that the noise amenity should be quieter than for an urban residential area. A lower maximum limit of 40 dBA was set for all other areas. These two limits appear to originate from the two ends of the day time lower maximum limit range set in ETSU-R-97. The background plus 5 dB limit is used as the maximum limit when it is greater than the constant lower maximum limit given above. These guidelines specify that the measured total sound levels should be corrected for the measured background noise limits as is done in ETSU-R-97.

The New Zealand standard was revised in 2010 [19]. It switched from the use of $L_{A95(10min)}$ to the use of $L_{A90(10min)}$. It introduced a lower maximum limit of $L_{A90(10min)}$ of 35 dBA for 'high amenity'[a] areas during the evening and night when the wind speed is less than 6 m/s while otherwise retaining the previous limits. Thus it uses the top of the ETSU-R-97 range except for evening and night time with low wind speeds in high amenity areas where it uses the bottom of the ETSU-R-97 range. The $L_{A90(10min)}$ lower maximum limit of 40 dBA is based on the L_{Aeq} of 30 dBA sleep limit from Berglund et al. [20] and a typical 15 dB reduction from outdoors to indoors with windows partially open for ventilation. The $L_{A90(10min)}$ internal level of 25 dBA allows 5 dB for the difference between $L_{A90(10min)}$ and $L_{Aeq(10min)}$, which is more than the expected 1.5–2.5 dB difference. This version of the standard specifies that the total measured sound level must be corrected for the measured background noise level. This standard is currently used in Victoria.

In 2011, the draft New South Wales Guidelines [21] adopted a lower maximum limit of an $L_{Aeq(10min)}$ of 35 dBA and background plus 5 dB as the maximum limit when it is greater than the constant lower maximum limit given above. The draft guidelines say that the criteria have been set to restrict sound generated by wind turbines to 5 dBA below the lowest acceptable sound criteria for a suburban or rural amenity area (which is 40 dBA at night) unless the area experiences background noise levels higher than the average 30 dBA in which case the sound criteria can be up to 5 dBA above the L_{A90} background noise level. These criteria apply to all periods of the day regardless of whether the acceptable amenity is higher during the day or night.

The guidelines specify that 1.5 dB be added to the measured $L_{A90(10min)}$ to obtain the measured $L_{Aeq(10min)}$. Thus the measurement lower limit is actually an $L_{A90(10min)}$ of 33.5 dBA and an $L_{A90(10min)}$ of background plus 3.5 dB as the maximum limit when it is greater than the constant lower maximum limit given above. The guidelines reference AS 4959–2010 [22] for this difference. AS 4959 actually specifies the use of a difference of at least 1.5 dB and references the 1.5–2.5 dB difference given in ETSU-R-97 [6]. Since the wind turbine sound levels are not corrected for background noise, the effective corrected wind turbine limits are 1 dBA lower.

The New South Wales [21] draft guidelines also set wind turbine sound limits of L_{Ceq} of 65 dBC during the day and 60 dBC during the night. These criteria appear to have come from Hessler [23] and Broner [24]. We note that the practicality of measuring these C-weighted sound levels in rural areas has not yet been well tested, but it could be that on occasions (and particularly when it is windy), ambient noise levels could exceed these levels in the absence of any wind turbine sound.

In 2016, the Queensland guidelines specified a night time lower maximum limit of an L_{Aeq} of 35 dBA and L_{Aeq} of background plus 5 dBA as the maximum limit when it is greater than the constant lower maximum limit given above for non-host lots, which are the same as the draft NSW any time of the day limits. For day time, the Queensland non-host lower maximum limit is increased by 2 dB to 37 dBA. For host lots, the lower maximum limit is an L_{Aeq} of 45 dBA and an L_{Aeq} of background plus 5 dBA as the maximum limit when it is greater than the constant lower maximum limit given above. This is because it is known that receipt of benefits reduces the reported level of annoyance [1]. The Queensland guidelines have also specified the same C-weighted limits as NSW. These are an L_{Ceq} of 65 dBC during the day and 60 dBC during the night. The Queensland guidelines do not specify compliance measurements. If $L_{Aeq(10min)}$ is used for compliance checking then the $L_{A90(10min)}$ limits would be 1.5–2.5 dB lower. If the wind turbine sound levels are not corrected for background noise, the effective corrected wind turbine limits would be 1 dBA lower.

The Queensland guidelines also specify a minimum setback distance of 1.5 km. This distance appears to come from a National Health and Medical Research Council (NHMRC) information paper [25] which states: "Although individuals may perceive aspects of wind farm noise at greater distances, it is unlikely that wind farm noise would be considered disturbing at distances of > 1500 m. At this distance, wind farm noise is usually below 30–35 dBA, below the sound levels of household devices and similar to a quiet residential area … [26–28]." However, although they are the source of the 30–35 dBA limit, the WHO and Basner et al. documents are not specifically about wind turbine sound. Bullmore and Peplow [26] compare three different sound propagation prediction methods over hard ground and over grassland for receiver heights of 1.5 and 4 m at distances of 500 and 1500 m. The sound source is a single typical large scale wind turbine for which octave band sound power data is available. At 1500 m the predicted A-weighted sound pressure level varies between 29 and 35 dBA. The NHMRC appears to have used 1500 m because all the predicted levels are less than or equal to 35 dBA [28], although they do not provide this rationale or refer to this (or any other) sound limit data.

In summary, the current or proposed wind turbine sound lower maximum limits in Australasia are $L_{A95(10min)}$, $L_{A90(10min)}$ or $L_{Aeq(10min)}$ equal to 35, 37 or 40 dBA for non-host properties for low background noise levels. The maximum limit is background noise level plus 5 dBA when this is greater than the applicable constant lower maximum limit given above. Queensland and New South Wales also have limits of L_{Ceq} of 65 dBC. For host lots in Queensland the lower maximum sound limit is an $L_{Aeq(10min)}$ of 45 dBA.

3. International wind turbine sound limits

Only a few other countries have specific wind turbine sound limits. In most other countries, industrial noise limits are applied to wind turbines. The English limits are referred to in section II above, as they inform Australian limits. In the Netherlands, the limits are an L_{den}[b] of 47 dBA and an L_{night} of 41 dBA [29]. Assuming that wind turbine sound level is constant for constant wind speed, 6.4 dBA needs to be subtracted from L_{den} to obtain L_{Aeq} and L_{night} is equal to L_{Aeq}. This correction is discussed further in Section 4. Thus both these limits reduce to an L_{Aeq} of 41 dBA. Subtracting 2 dBA [6] gives an equivalent limit of an $L_{A90(10min)}$ of 39 dBA. Although this is close to the highest of the lower maximum limits used in Australia, it applies for *all* background noise levels.

Sweden and Denmark both specify L_{Aeq} limits for a wind speed of 8 m/s at a height of 10 m Above Ground Level (AGL) [29]. It is necessary to add 4.7 dBA to obtain L_{den} [30] and then to subtract 6.4 dB to obtain a long term L_{Aeq}. This gives a total correction of −1.7 dB. A further correction of −2 dBA is necessary to obtain $L_{A90(10min)}$. Thus the standard Danish and Swedish limits of 44 and 40 dBA respectively are equivalent to an L_{Aeq} of 42 and 38 dBA and an $L_{A90(10min)}$ of 40 and 36 dBA which are fairly similar to the range of lower maximum limits in Australia. Again, there is no increase for high background levels.

For designated quiet or noise sensitive areas, the respective Danish and Swedish limits of 39 and 35 dBA become an L_{Aeq} of 37 and 33 dBA and an $L_{A90(10min)}$ of 35 and 31 dBA. This range is either at or below the lowest end of the range of lower maximum limits used in Australia. There is no increase described for high background levels. Denmark also has standard and noise sensitive limits of an L_{Aeq} of 42 and 37 dBA for a wind speed of 6 m/s at a height of 10 m AGL.

The province of Ontario in Canada has urban and rural lower

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[a] Note that the reference to 'High Amenity' areas in the New Zealand standard refers specifically to a zoning adopted in NZ Planning law, and there is generally no directly equivalent zoning in most Australian planning schemes.

[b] L_{den} is an energy averaged 24-h measurement similar to $L_{Aeq,24hr}$, but with the evening period sound levels penalised by 5 dB, and the night period sound levels penalised by 10 dB.

maximum limits of an L_{Aeq} of 45 and 40 dBA respectively [29]. These are equivalent to an $L_{A90(10min)}$ of 43 and 38 dBA. The range of these lower maximum limits covers the top end of the range used or proposed to be used in Australia and extends above the Australian range. Ontario uses a calculated reference background and the limit is the reference background plus 7 dBA if this exceeds the constant maximum sound level given above. In terms of $L_{A90(10min)}$ this higher maximum level is equal to the reference background plus 5 dB. Larger wind turbines in Ontario also have a minimum setback distance of 550 m. The Ontario wind turbine sound level limits do not apply to properties on which any part of the wind turbine farm facilities are located. Other Canadian provinces have different wind turbine sound level limits.

Hence the range of wind turbine sound limits used or proposed for use in Australian states and New Zealand lies within and towards the lower end of the range of limits used internationally.

4. Annoyance

Previous studies consistently demonstrate a relationship between annoyance with wind turbines and the wind turbine sound level [2]. This does not necessarily mean that the annoyance is due to the wind turbine sound level because the relationship between wind turbine sound level and annoyance is potentially confounded by a range of other influencing factors, such as visual impacts and philosophical attitudes towards wind turbines [25]. It may just mean, for some individuals at least, that the wind turbine sound simply reminds people of the presence of wind turbines.

However the analysis of Michaud et al. [1] demonstrates that sound related variables such as the sound itself, the necessity for closure of bedroom windows to reduce noise during sleep when wind turbine noise was identified as the source, vibrations/rattles and sleep disturbance together contributed more significantly to annoyance than other factors such as blinking lights and visual annoyance. Furthermore, of these variables wind turbine noise is the most amenable to modification given that blinking lights are required for aircraft safety.

Given this and previous findings, a strong rational exists for defining wind turbine noise limits based on the percentage of people annoyed, notwithstanding the observation of Michaud et al. [1] “that that trust or misfeasance with source authorities, community engagement in project development in addition to community expectations, all have an influence on community annoyance”.

Because there is a statistically significant relationship between annoyance with wind turbines and wind turbine sound level [5], the nature of this relationship warrants examination. Michaud et al. [1] review 6 studies of the annoyance of wind turbine sound, with Fig. 1(a) to (f) of their appendix showing the percentage of highly annoyed people versus the day-night average wind turbine sound level (L_{dn}) for these studies. The studies considered consist of two from Sweden [31,32], two from Canada [1,33], one from the Netherlands [34] and one from Japan [35]. The collective results of these studies are shown in Fig. 1 of the present paper.

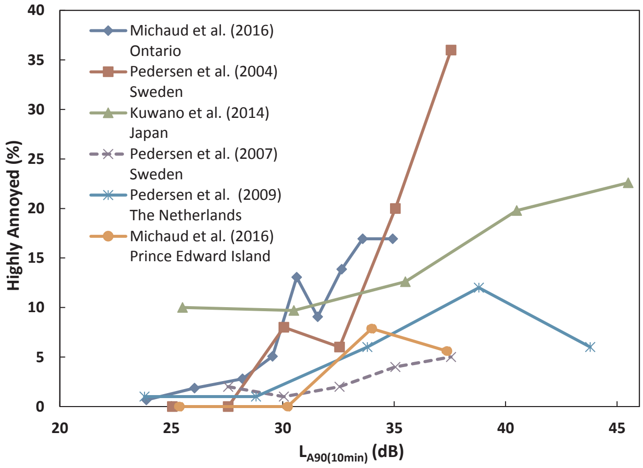

Fig. 1. The percentage of highly annoyed people as a function the outdoor wind turbine sound level exceeded for ninety percent of the time in a 10 min period. The sound pressure levels have been converted to $L_{A90(10min)}$ from their original values.

The Pedersen et al. (2004), the Pedersen et al. (2007) [32], and the Pedersen et al. (2009) “highly annoyed percentages” are taken from the “outdoors very annoyed” rows of Table V of [31], of Study 1 in Table 5 of [36], and of Table II of [34] respectively. The sound pressure level limits of the bins are the calculated outdoor A-weighted equivalent sound pressure levels from the nearest wind turbine(s) determined for a neutral atmosphere at a constant wind velocity of 8 m/s at a height of 10 m above ground level in the direction towards the respondent [37]. The first two of these three studies used middle bin widths of 2.5 dB while the third study used middle bin widths of 5 dB. The bottom bin in all three studies included sound pressure levels less than the sound pressure level at the top of the bin and the top bin in all three studies included sound pressure levels greater than the sound pressure level at the bottom of the bin. Each of the middle bins was labelled with the sound pressure level at its mid-point. The bottom and top bins were labelled with the sound pressure level of half the width of one of the middle bins below the top of the bottom bin or above the bottom of the top bin respectively. These bin labels were converted from the A-weighted sound pressure level for a wind speed of 8 m/s at a height of 10 m above ground level to L_{den} levels by adding 4.7 dB [1,30,37]. According to van den Berg [30] this conversion has an uncertainty of ± 1.5 dB. Janssen et al. [37] state that “While in principle the correction depends on the wind velocity distribution at a specific location, the type of wind turbine and the hub height, statistical wind velocity data was not available for all study locations. Furthermore, using a variable correction factor for the situation in the Netherlands did not provide a better prediction of annoyance in comparison to L_{den} calculated with the fixed correction factor.”

The “highly annoyed percentages” and their corresponding calculated L_{dn} sound pressure levels for Ontario and Prince Edward Island were read from Fig. 1(a) and 1(f) of Michaud et al. [1]. L_{den} and L_{dn} were assumed to be approximately equal [1,30], which is correct for a constant sound pressure level. The five above sets of L_{den} or L_{dn} were converted to the 24 h L_{Aeq} by subtracting 6.4 dB [1,30] which is correct for a constant sound pressure level [30]. Nevertheless, it is not necessary to assume constant sound pressure level, but only that the percentage of time for which a certain wind speed occurs and the time weighted sound power level at a certain wind speed are similar for the day, evening and night periods. This assumption is justified by Fig. 1 of [30]. A variation in the distribution of wind directions between the day, evening and night periods would alter the relationship between the sound level descriptors. However, such an effect will be site dependent and the effect is likely to be minimized when data are averaged over different sites. The 6.4 dB conversion is based on the facts that L_{dn} is calculated using 15 h of day and 9 h of night and that L_{den} is calculated using 12 h of day, 4 h of evening and 8 h of night.

The Japanese “highly annoyed percentages” were taken from the “extremely or very annoyed (% VA)” column of Table 2 of Kuwano et al. [35]. The Japanese study used middle bin widths of 5 dB and the procedure for labelling the bins was the same as described above for the Pedersen studies. The Japanese sound pressure level bin labels were the L_{Aeq} from 22:00 to 06:00 h. Based on Fig. 1 of [30] and the discussion above, these L_{Aeq} values were assumed to be equal to the 24 h L_{Aeq} values and to the average $L_{Aeq(10min)}$.values.

The above six sets of average $L_{Aeq(10min)}$.bin labels were converted to average $L_{A90(10min)}$ bin labels by subtracting 2 dB [6,14,21,22]. The size of this conversion factor is a function of the short term steady state nature of wind turbine sound which is not exhibiting excessive amplitude modulation. ETSU-R-97 [6] gives the uncertainty of this conversion factor as ± 0.5 dB. Although wind turbines have increased in size and power output since ETSU-R-97 [6] was published, the authors are not aware of any papers which have disputed this conversion.

Pedersen et al. (2004) [31] and Pedersen et al. (2007) [32] used [38] to calculate the outdoor downwind sound pressure levels that their respondents were exposed to. Pedersen et al. (2004) [31] used a surface roughness length of 0.05 m. Pedersen et al. (2007) [32] added a correction of 1.5 dB in two of their eight different areas. Pedersen et al. (2009) [34] used ISO 9613–2 [39] with a ground sound absorption coefficient of 1 to calculate their outdoor sound pressure levels. The Ontario and Prince Edward outdoor sound pressure levels for a wind speed of 8 m/s [1] were also calculated using ISO 9613-2 [39]. The L_{dn} values were estimated by adding 4.7 dB to the L_{Aeq} for 8 m/s wind speed [1], as has been done in the present paper for the Pedersen et al. data. The Japanese sound pressure levels [35] were estimated from a logarithmic regression based on seven or eight measurements at different distances from the wind turbines at each of their 34 wind turbine sites.

In assessing annoyance, the Canadian and Japanese social surveys asked the respondents to rate how annoyed indoors or outdoors they were with wind turbine sound as 'extremely', 'very', 'moderately', 'slightly', 'not at all' or 'did not hear'. Michaud et al. [1] classified the first two categories as 'highly annoyed'[40]. In the Swedish and Dutch social surveys, the ratings of wind turbine sound annoyance outdoors were 'very annoyed', 'rather annoyed', 'slightly annoyed', 'notice but not annoyed' or 'did not notice'. Michaud et al. [1] classified the first category as 'highly annoyed' [40].

There is a high degree of variability in the extent of annoyance at particular wind turbine sound levels as shown in Fig. 1. Michaud et al. [1] fitted individual curves to the data using the "Community Tolerance Level" (CTL) model which is based on the human response to noise [3,4]. The CTL model is a curve of the form

$$\%HA = 100\exp\{-\ln(2)/[10^{(DNL-CTL)/10}]^{0.3}\}, \qquad (1)$$

where $\%HA$ is the percentage of people highly annoyed, DNL is $L_{dn} = L_{A90(10min)} + 8.4$ dB and CTL is the Community Tolerance Level. CTL is the DNL at which 50% of people are annoyed. Eq. (1) can be inverted to obtain

$$DNL = CTL - \frac{100}{3}\log_{10}\left[\ln\left(\frac{100}{\%HA}\right)/\ln(2)\right]. \qquad (2)$$

Eq. (2) shows that the DNL at which 10% of people are highly annoyed can be obtained by subtracting 17.38 dB from the CTL. This applies for all sound sources. For the case of wind turbine sound, subtraction of a further 8.4 dB is necessary to obtain $L_{A90(10min)}$.

The CTL curves are shown in Fig. 2. To average the curves and estimate the confidence limits of the average curve, Michaud et al. [1] calculated the mean and standard deviation of the CTL values. The CTL values for each of the separate studies are 57.07, 57.96, 59.30, 63.80, 63.97 and 64.57 dB. The mean and standard deviation of these CTL values are 61.11 and 3.08 dB respectively. It should be noted that these correct values are different from the mean and standard deviation given in Michaud et al. [1] which are incorrect, as confirmed by personal communication with the authors [41].

Fig. 3 displays the CTL model curves for the percentage highly annoyed vs sound level for the mean CTL and for one standard deviation above and below the mean CTL. The purpose of plotting the CTL curves across a range of sound levels is to facilitate adoption of a limit according to a communal judgment of the proportion of people the community is prepared to accept may remain highly annoyed with the limit in place. If a community is known to have a high level of resistance to a wind turbine development, decisions based on the CTL value equal to the mean minus one standard deviation may be appropriate. Alternatively, if a community is known to have a low level of resistance to a wind turbine development, the use of the CTL equal to the mean plus one standard deviation for decision making could be considered. Decisions based on a CTL value equal to the mean minus one standard deviation could also be made in order to provide a margin of safety.

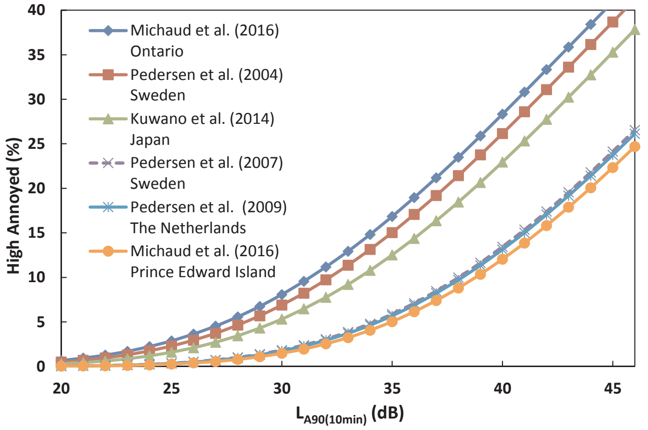

Fig. 2. The percentage of highly annoyed people according to the CTL model as a function the outdoor wind turbine sound level exceeded for ninety percent of the time in a 10 min period. The sound pressure levels have been converted to $L_{A90(10min)}$ from their original values.

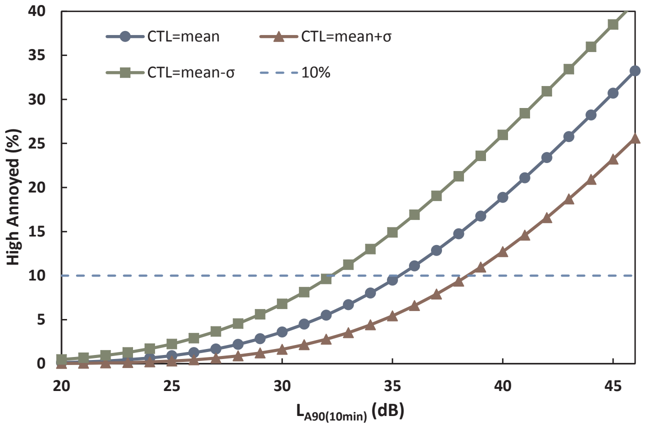

Fig. 3. The percentage of highly annoyed people as a function the outdoor wind turbine sound level exceeded for ninety percent of the time in a 10 min period. The sound pressure levels have been converted to $L_{A90(10min)}$ from their original values.

Our analysis derives a maximum sound level limit for wind turbine sound based on permitting no more than 10% of the population to be highly annoyed when exposed to wind turbine sound at the maximum sound level limit. Such a 10% threshold is commonly used when setting hearing protection noise limits [42,43] and is similar to the 8% used when setting the Dutch wind turbine sound limits [29]. Thus Fig. 3 and Eq. (2) suggest that the mean limit for wind turbine sound should be an $L_{A90(10min)}$ of 35 dBA. Allowing for some imprecision, one standard deviation in CTL either side of this mean provide an allowable range of limits between an $L_{A90(10min)}$ of 32 dBA and 38 dBA. Adding 2 dB to obtain $L_{Aeq(10min)}$ yields a range between 34 and 40 dBA with a mean value of 37 dBA. These values are similar to the lower maximum limits of $L_{Aeq(10min)}$ used or proposed for use in Australia of 35, 37 and 40 dBA. The $L_{A90(10min)}$ lower limit of 40 dBA which equates to an L_{Aeq} limit of 42 dBA is just above the range of values derived in this paper.

Although there are potential concerns about the suitability of an exponential growth model for data that is essentially saturating (suggesting a logistic function) the CTL model draws on and is consistent with the literature to date. Furthermore, because of concerns about the percentage of highly annoyed people for an $L_{A90(10min)}$ of 25.5 dBA in

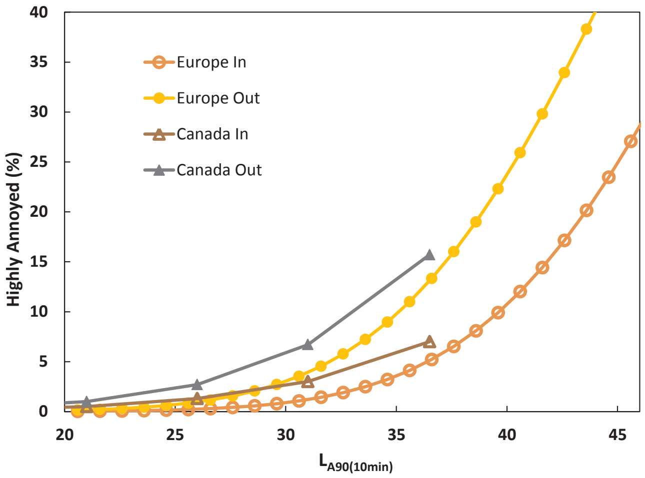

Fig. 4. The percentage of highly annoyed people indoors and outdoors as a function the outdoor wind turbine sound level $L_{A90(10min)}$. The Canadian curves are based on survey data from Ontario and Prince Edward Island provinces [33]. The European curves are based on Dutch and Swedish survey data [44]. The original L_{den} and L_{Aeq} levels have been converted to $L_{A90(10min)}$.

the Japanese data, a sensitivity analysis was conducted by excluding the Japanese data. The only value which changed was the upper limit (obtained from CTL plus one standard deviation) which changed from an $L_{A90(10min)}$ of 38 to 39 dBA.

Our analysis also examines the relationships between the proportion of people highly annoyed outside and highly annoyed inside buildings as functions of the outdoor wind turbine sound level $L_{A90(10min)}$ [33,44]. Fig. 4 shows that people are less annoyed by wind turbine sound when they are indoors. To keep the percentage of people highly annoyed when outdoors to below 10%, the Canadian and European data suggest lower maximum limits of an $L_{A90(10min)}$ of 33 and 35 dBA respectively. For inside the lower limit is about an $L_{A90(10min)}$ of 40 dBA. This means that the building envelope provides a reduction in annoyance which is equivalent to a reduction in sound level of between 5 and 7 dBA. This reduction is less than the 10–15 dBA reduction that is usually assumed for the sound insulation of a building façade with partially open windows. This is probably due to the fact that the outdoor background noise is also attenuated by the building envelope. This appears to justify the ETSU-R-97 [6] decision to set a higher night time lower limit because people are more likely to be indoors. However, Michaud et al. [33] have shown that people are more annoyed by wind turbine sound during the evening and night and during the summer than during the morning or afternoon or other seasons. This may be because people like to spend the long summer evenings outside while during the day they are working well away from wind turbines. It is also likely to be due to the fact that the background noise level is usually lower at night because of lower wind speeds near the ground [45].

The Netherlands limit, which is equivalent to an $L_{A90(10min)}$ of 39 dBA, is based on the fact that less than 8% of the people are annoyed indoors according to the European indoor curve in Fig. 4. [29]. This 8% is close to the 10% limit adopted in this paper. The Netherlands limit is higher than the lower sound limit suggested in the present analysis because the present analysis used annoyance when both outdoors and indoors. Because the present analysis recommends the use of background noise plus 5 dBA when this is greater than the applicable constant lower maximum limit, while the Netherlands limit is fixed, the difference between the limits is not as great as it may first appear.

5. Conclusions

This paper provides the first chronological history of wind turbine sound limits used in Australia and the rationale for them. These and most of the international wind turbine limits are based on sound limits which do not disturb sleep derived from sound sources other than wind turbines. The Dutch L_{den} wind turbine sound limit is based on annoyance with wind turbine sound, but only indoors. The present paper derives wind turbine sound limits based on annoyance both outdoors and indoors.

The wind turbine sound limits currently used or proposed for use in Australia are generally within the range of values used as limits overseas. Defining desirable limits based on restricting the proportion of individuals who are highly annoyed to a level that has been considered reasonable by various jurisdictions yields a similar range of values and provides a rational basis on which to harmonise the varying limits that exist in Australia. Ultimately, these limits have to be decided by state or local governments balancing the need to reduce annoyance and provide reasonable amenity for the local community against the wider society's need for renewable energy resources. However, a common approach based on transparent and objective criteria may help reduce contention in this potentially controversial domain.

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