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LONG-TERM WIND FARM NOISE ASSESSMENT OVER DIFFERENT METEOROLOGICAL CONDITIONS

Dr. Krispian Lowe[1*] **Mikel Amatriain**[2] **Sylvia Broneske**[3]

[1] RWE Renewables UK, Reading, UK
[2] RWE Renewables Iberia, Zaragoza, Spain
[3] RWE Renewables UK, Swindon, UK

ABSTRACT

Recently European Court of Auditors (ECA) recommended introducing EU noise-reduction targets and noise limits in the Environmental Noise Directive. The ECA approach would be aligning the noise exposure reporting thresholds, as closely as possible, with the guideline levels in the 2022 update report by the World Health Organization (WHO) in urban areas. WHO Guidelines provide guideline L_{den} and L_{night} levels for specific noise sources. For wind turbines, they provide a guideline level of 45 dB L_{den} with no L_{night} guideline determined. For long term assessment relevant factors must be defined, as the calculation method for yearly L_{den} may be affected by different meteorological conditions, operational states of the turbines, relative position of the source and receptor, background noise and masking levels or applicable daily night-time and short time limits. The determination of how to determine compliance with an L_{den} will be explored.

The present work's aim is the identification of the environmental parameters necessary for sound propagation and the reasonable evaluation time for long term wind farm noise assessment. A detailed knowledge and understanding of the emission and propagation characteristics can allow an optimised noise levels and energy yield, which can be achieved by adapting the operation of the turbine.

Keywords: *long-term, wind, turbine, farm, noise*

[*]***Corresponding author***: *Krispian.Lowe@rwe.com*

1. INTRODUCTION

European Union Directive 2002/49/EC (END) [1] was published to define a common approach intended to avoid, prevent or reduce on a prioritised basis the harmful effects, including annoyance, owing to exposure to environmental noise. Noise indicators L_{den} and L_{night} were selected for the preparation and revision of strategic noise mapping. Day-evening-night level L_{den} in decibels (dB) is defined by the A-weighted long-term average sound level as defined in ISO 1996-2:1987 [2] and the updated to ISO 1996-2:2017 [3]. The equation for the day-evening-night weighted sound pressure level, L_{den}, for the equivalent continuous sound pressure level for day-time, L_{day}, evening-time, $L_{evening}$, and night-time, L_{night}, with the weightings of 0 dB, 5 dB and 10 dB, respectively, is shown in the equation below [4]. The time, in hours, for the day-time, t_{day}, evening-time, $t_{evening}$, and night-time, t_{night}, are normally 12, 4 and 8 hours, respectively. These times may vary for different countries[1].

$$L_{den} = 10\,log_{10}\left[\frac{t_{day}10^{0.1L_{day}} + t_{evening}10^{0.1(5+L_{evening})} + t_{night}10^{0.1(10+L_{night})}}{24}\right] \quad (1)$$

European Environment Agency collects official noise data reported every five years by EEA member countries under the Environmental Noise Directive (END) with last available noise country fact sheets of 2021, including road, rail, aviation and industry sound sources.

The WHO Regional Office for Europe developed environmental noise guidelines for the European Region in 2018 [5], proposing an updated set of public health recommendations on exposure to environmental noise. The

[1] The typical values are day-time of 0700 to 1900, evening time of 1900 to 2300 and night-time 2300 to 0700.

guidelines presented recommendations on reducing noise levels for road, railway, aircraft, wind turbine and leisure noise sources.

A compendium of WHO and other UN guidance on health and environment update of 2022 refers to L_{den} and L_{night} indicators for noise monitoring and exposure assessment adding $L_{Aeq,T}$ for measuring leisure noise exposure. For average noise exposure, sound pressure levels <45 dB L_{den} for wind turbine noise are recommended. There is not any reference for night noise exposure or $L_{Aeq,T}$ for wind turbine noise.

Recently, the European Court of Auditors (ECA) [6], published a special report about Urban pollution in the EU, giving the recommendation of prioritising actions against noise pollution to The European Commission, to assess the feasibility of introducing EU noise-reduction targets in the Environmental Noise Directive and aligning the noise exposure reporting thresholds as closely as possible with those recommended by the World Health Organization with a target implementation date of 2029. The referred indicators are L_{den} and L_{night} without any reference to $L_{Aeq,T}$ levels. The noise sources are focused on road, aircraft and railway noise.

1.1 World Health Organisation 2018

World Health Organisation (WHO): Regional Office for Europe (ROE) provided Environmental Guidelines for the European Region for the following noise sources: Road Traffic, Railway, Aircraft, Wind Turbines and Leisure Activities. The recommended level for wind turbine noise is an L_{den} value of 45 dB. This latest report works in conjunction with WHO 1999 [7] and WHO 2009 [8] where those guidelines levels also apply, in particular 45 $L_{Aeq,8hour}$ outside a bedroom with a wind open, and 40 dB $L_{night,outside}$, respectively.

The wind turbine guideline level was given a **conditional** recommendation and would require substantial debate amongst stakeholders, since the quality of the evidence used to derive the rating was **low quality.** It was marked as **low quality** owing to heterogeneity, inconsistency and imprecision. No guidelines for L_{night} were produced since the evidence consisted of study limitations, inconsistent results and imprecision.

The WHO themselves state that the L_{den} and L_{night} is a poor acoustic measure for wind turbines in section 3.4.2.3, an excerpt is quoted below:

"*Even though correlations between noise indicators tend to be high (especially between L_{Aeq}-like indicators) and conversions between indicators do not normally influence the correlations between the noise indicator and a particular health effect, important assumptions remain when exposure to wind turbine noise in L_{den} is converted from original sound pressure level values. The conversion requires, as variable, the statistical distribution of annual wind speed at a particular height, which depends on the type of wind turbine and meteorological conditions at a particular geographical location. Such input variables may not be directly applicable for use in other sites. They are sometimes used without specific validation for a particular area, however, because of practical limitations or lack of data and resources. This can lead to increased uncertainty in the assessment of the relationship between wind turbine noise exposure and health outcomes.*".

"*Based on all these factors, it may be concluded that the acoustical description of* ***wind turbine noise by means of L_{den} or L_{night} may be a poor characterization of wind turbine noise*** *and may limit the ability to observe associations between wind turbine noise and health outcomes.*"

It is important to note that the WHO does not provide methodology, procedure or detailed information on how to predict, measure and assess an L_{den} for wind turbines.

1.2 Compendium of WHO and other UN guidance on Health and Environment 2022 update

The compendium of WHO and other UN guidance on Health and Environment report, Chapter 11, provides a short summary of the guideline levels to achieve for a range of sources such as: road traffic noise, railway noise, aircraft, wind turbine, leisure sources [9]. The compendium states an average level of less than 45 dB L_{den} is recommended. There is no other guidance or other information provided for wind turbines in the compendium document.

1.3 Special report 02/2025

The European Court of Auditors (ECA) provides a review of the European Green Deal and the Zero Pollution Action Plan to reduce air and excessive noise on human health with respect to the END [6]. The special report found that there are no EU limit values or reduction targets for noise, and provides recommendations for limits for road, rail and aircraft. There is no mention of wind turbines in the report; however, the ECA special report should assess the feasibility of aligning the reporting thresholds as closely as possible with those recommended by the WHO by 2029. Therefore, wind turbine levels could be passed through without careful consideration.

2. REGULATION ON LONG-TERM ASSESSMENT

The application of the calculation and enforcement of short-term and long-term sound levels from wind turbines varies from country to country owing to noise prediction, noise modelling, legislative frameworks and evidence at the time of the law and/or supplementary guidance creation. Countries such as Spain, Lithuania and Poland may have stated annual limit, but have short-term $L_{Aeq,T}$ levels that are more stringent. . Therefore, in practice, the annual levels are not generally calculated or assessed.

2.1 Netherlands

The Netherlands had a law to assess the annual levels for 47 dB L_{den} and 41 dB L_{night} [10]. The Law seta out the source level for which measurements should be done according to the method in the law or NEN-EN-IEC 61400-11 (2002). These methods determine the sound power level of the wind turbine per wind speed bin at hub height from cut-in to rated power. For sound power levels at wind speeds greater than the rated power, then the sound power level at the rated power can be used for these higher wind speeds.

The wind speed distribution for day, evening and night from a long-term wind statistics should be obtained from KNMI[2]. The annual average sound power level per octave band is calculated for each period of day. The predicted immission level is then determined from subtracting following attenuation terms: geometric divergence, atmospheric attenuation[3], reflecting objects, screening, vegetation, industrial, ground, housing and meteorological corrections. It should be noted that though the propagation methods and parameters are similar to ISO 9613-2:1996 [11] and ISO 9613-2:2024 [12], but the ground attenuation is less in the Netherlands Law. The immission level is then modified for each turbine-receptor based on the relative bearing, owing to the long-term meteorological effects. However, this only comes into effect at a distance 10 times the combined receptor and source heights. Once the immission has been calculated for each period, it is combined into the L_{den}. The receptor height is 5 m.

Compliance with the limits is determined by a sound power level measurement, since it is not possible to measure an annual level at a receptor location. This is owing to the influence of the dominant background noise on measurements at receptors [10].

The ruling on Dutch wind farms means that law cannot be applied, but a temporary bridging scheme is in place until new rules are in place [13]. The publication of the new draft law and consultation period were in October 2023 to November 2023, whilst the new law will come into force in 2025 or 2026 [13].

2.2 Norway

The guideline for noise is specified in T-1442/2021 as an L_{den} of 45 dB [14]. The prediction of the immission level is according to NORD2000, assuming that the turbines are operating 100 per cent of the time, and the sound power level at wind speed of 8 m/s, at 10 m standardised height, shall be used. There are no set parameters for NORD2000 calculations and it is dependent on the experience of the practitioner; however, the following parameters are typically used:

- Receptor height of 4 m,
- Ground is a uniform class D [4],
- Temperature of 10 degrees Celsius and relative humidity of 70 per cent, and
- Wind speeds at 10 m standardized height.

3. FACTORS AFFECTING LONG-TERM ASSESSMENTS

3.1 Source Sound Power Levels

The sound power level of a turbine should be determined using the IEC 61400-11:2012+AMD1:2018 CSV [15], where the sound power level is determined with respect to hub height wind speeds and third octave frequency. The wind speed bins are centred on the integer and half integer. The sound level index should be expressed as an $L_{Aeq,T}$. Depending on the regulatory context, further treatment of the measured sound power levels should be used, or the warranted levels - usually issued by the manufacturer - or declared sound power levels using IEC TS 61400-14:2005 [16]. A comparison of different representations of sound power levels are shown in Institute of Acoustics (IOA)

[2] www.windenergie.nl

[3] 10 degrees Celsius and 80 per cent relative humidity

[4] 2000 kPas/m2 - Normal uncompacted ground (forest floors, pasture field)

Good Practice Guide (GPG) Supplementary Guidance Note (SGN) 3 [17].

The sound power level should be declared between cut-in to cut-out wind speeds. If the sound power level is not declared for wind speeds above the rated power wind speed, then the rated power sound power level should be used. If the sound power level is unknown for wind speeds between cut-in and the 68 per cent of the rated capacity[5], then care should be taken in extrapolating these data. An example is given in Figure 1. Any omission of sound power levels, at wind speeds where the turbine can generate, will reduce the calculated annual average sound power level.

A larger rotor size for the same rated power would increase the swept area, energy yield and capacity factor[6]. Increasing the energy yield would typically involve shifting the power curve, and sound power level curve, to lower wind speeds. This would increase the L_{den} and L_{night} values, but maximum sound power level, L_{WA}, would remain the same. Increasing the rotor size does not necessarily increase the sound power level, owing to the tip speed being the limiting speed.

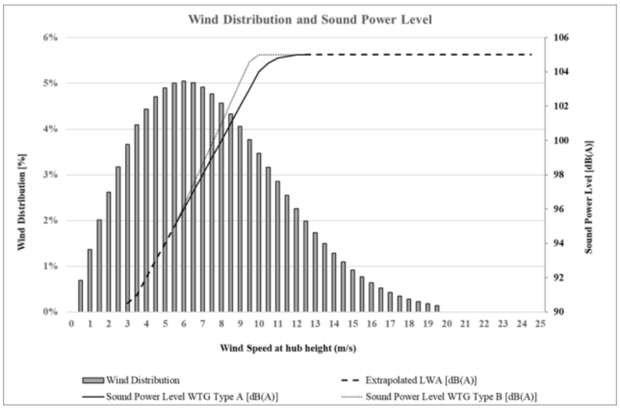

Figure 1. showing an example of sound power level (right y-axis), for Turbine Type A, with respect to hub height wind speed (x-axis) showing the solid black line as the declared sound power level and the dashed black line is the extrapolated level. Turbine Type B is shown as dotted lines. The wind distribution percentage of occurrence (left y-axis) at hub height wind speeds. The maximum sound power level for Turbine Type A and B is 105 dB(A), whilst the average sound power level is 100.8 dB(A) and 101.3 dB(A), respectively. If the wind speed distribution is the same for day, evening and night, then the Lden value would be 107.2 dB and 107.7 dB for turbines Type A and B, respectively.

3.2 Wind Speed

The wind speed for calculating the annual average should be measured at the same resolution as the sound power level measurements. The introduction of binning data to a lower resolution or interpolating to a higher resolution, will introduce systematic errors and additional uncertainty. The wind speed should be measured at hub height or at points above and below the proposed hub height. Therefore, care should be taken to ensure that the correct wind speeds are used with the correct hub heights for all turbines. Typically, wind turbines with a lower hub height will see lower wind speeds compared to turbines with a higher hub height. When converting wind speeds from one height to another, wind shear must be taken into account, guidance is provided within IEC 61400-11 [15], IEC 61400-11-2 [18] and the IOA GPG [19] and the IOA GPG SGN 4 [20]. When using wind speed measurements with lower anemometers on a mast, care should be taken to account for the mast wind shadow. When using a LiDAR, data quality and signal to noise must be considered, either by filtering, infilling or omitting some data.

Each site will have its own wind speed and wind direction distributions. In the case of wind measurements, a metrological mast and/or LiDAR should follow to the IEC 61400-50 series, and a robust long-term wind catalogue can be used. Wind speed measurements conducted on the development site may be limited to 1 or 2 years. These "shorter" measurements could be correlated with longer-term wind measurements from a national or international wind catalogue. Wind speed distribution will vary year by year; therefore, the annual average sound power level of the turbine will vary year by year. The wind speed distribution can be approximated to a Weibull distribution. The wind speed distributions and power curves are used to calculate representative wind energy yield(s). The calculated energy yield should be considered as the greatest values. In real-life power output is likely to be slightly below these values due to downtimes: maintenance, grid outages, sector managements and others (see section 3.4).

Wind speed distribution should be grouped for the day-time, evening-time and night-time periods. These time periods may vary for different countries or regions, and that

[5] 0.8 times the 85 per cent of the maximum power as per section 5 in IEC 61400-11.

[6] Capacity factor is the actual or predicted energy yield divided by the maximum potential energy yield.

the hour change to and from summer-time should also be taken into account. Therefore, the average sound power level, for a period of day, per octave band, $L_{W,period,j}$, Eqn (2), is the logarithmic sum between cut-in and cut-out wind winds speeds for the frequency of occurrence of the wind speed bin, V_i, for the corresponding sound power level per octave and wind speed bin, $L_{W,i,j,}$

$$L_{W,period,j} = 10\log_{10}\left[\sum_{i=v_{cut-in}}^{v_{cut-out}} V_i 10^{(0.1L_{W,i,j})}\right] \quad (2)$$

The sum of V_i may not equal 1 owing to wind speeds outside of the cut-in and cut-out region.

For simple flat sites it may be appropriate to use a single point for the entire wind farm, but for larger wind farms or those with complex terrain, multiple wind speed measurement locations may be needed. In addition, when a wind turbine is downwind of another turbine, the wind speed may be lower. Determining the "mean" sound power level from the arithmetic mean wind speed is an incorrect method this is owing to 1) the wind speed distribution follows a Weibull distribution rather than a Gaussian distribution, and 2) the annual average is based on weighted logarithmic average.

3.3 Wind Direction

Wind direction will have an effect at the receptor location owing to the shadow zone for the upwind and close to cross wind positions [19 and references within]. The prevailing wind direction may change owing to the season and time of day, in particular for regions in coastal or areas close to large bodies of water. Treatment of the effect of wind direction on the sound propagation is discussed further in ISO 9613-2:2024 Annex C [12] and the IOA GPG section 4.4 [19].

The distribution of wind directions is important for the siting of wind turbines in a wind farm. A wind rose shows probability of a wind from a certain sector. In addition, the wind speed distributions can be different for these wind direction sectors.

Higher wind speeds may be associated with the prevailing wind directions, whilst lower wind speeds in for non-prevailing wind directions. The wind direction may vary across the site, especial for site with complex terrain and inter- and intra-wind farm turbulence.

When assessing the directional effects, it is prudent to create an attenuation matrix of wind speed, wind direction and period for each receptor turbine pair.

According to the IEC TS 61400-14, the apparent sound power level shall be declared by combining the mean sound power level and the confidence level. Aerodynamic sound theories and experiments have demonstrated that the sound pressure levels in the crosswind direction are lower than those in the up- or downwind direction [21] [22]. There is no definition of emission directivity in the manufacturer's sound power declaration.

3.4 Turbine Operation

The operation of the turbines on a wind farm will affect the annual average owing to, but not limited to, the following:

- Availability of the turbine, where turbines are subject to maintenance, expected levels of stoppages owing to faults and grid outages. The availability of a wind farm will not be 100 per cent but expected to be greater than 95 per cent.
- The wind farm may be constrained by the grid restriction based on capacity load, where the wind farm may have to run a reduced power mode or shutdown owing to oversupply or other restrictions by the grid operator.
- Individual turbines operate in curtailed modes or shut down at specified wind speeds, wind directions and time of day owing to turbine wakes, turbulence from the terrain, noise mitigation, bat and bird protection, shadow flicker, intra-wind farm grid constraint, loading, etc.

These operational constraints may be known for the development under assessment but may be unknown for neighbouring wind farms that are not under the operator's control. Assuming that the wind farm will be operational 100 per cent of the time would often lead to an over estimation of the annual average.

3.5 Propagation

The depending on the propagation model (NORD2000, ISO 9613-2 etc) some of the attenuation parameters may vary over the year. The predicted levels according to ISO 9613-2 is for downwind conditions under a moderate ground-based temperature inversion, such as commonly occur on clear and calm nights.

Geometric divergence should be the same irrespective of the time and date. However, the parameters for atmospheric absorption and ground attenuation will vary. Ambient temperature, temperature gradient, relative humidity and atmospheric pressure will change throughout the day and through each season. Wind farms coexist with agricultural activities and the ground factor may change over the course of the year depending on the land use. For example, there may be crops in the summer, bare ground in winter and spring, frozen, snow or flooded during the winter. Therefore, full evaluation of temperature, relative humidity and ground conditions should be used; however, a pragmatic approach could be to use the average values.

If turbine rotors are obscured by landforms relative to the receptor location, the screening attenuation for that turbine at the receptor, is limited to 3 dB according to ISO 9613-2:2024 Annex D or 2 dB according to the IOA GPG Section 3[7] . Where there is a concave ground occurs between the source and the receptor, then an additional 3 dB can be added to the contribution of that turbine at that receptor according to ISO 9613-2:2024 and IOA GPG Section 3. However, it should be noted that the calculation of the mean propagation height and the trigger criteria are different in ISO 9613-2 and the IOA GPG.

3.6 Receptor locations

The receptor location for the predicted levels should be carefully selected. Country specific requirements such as prediction on the façade closest to the wind farm or in free field conditions should be used. Care also needs to be taken, as national legislation could mandate the precise location for measurements, such as in Germany, where the immission level should be measured 0.5 m in front of the open window, outside, of the most affected room in need of protection, such as bedrooms [23].

4. MEASUREMENT AND ENFORCEMENT

Measurement of an annual average at receptor locations will be impracticable owing to the effect of background noise, road, rail, aircraft, industry or other anthropogenic sources. Therefore, it may be impracticable to determine the specific sound level of the wind farm or wind turbine at receptor locations, owing to the unknown contribution of the other sounds. Also, the presence of measurement equipment in at receptor locations, may have a disruptive effect on inhabitants of the dwelling and affect their subjective response to the source of noise.

To implement long-term (annual) immission measurements at several receptor positions around a wind farm, during the development and operation, would increase the cost of energy production and the security of supply, owing to the number and complexity of the measurements and precision instrumentation needed for the task. In addition, a clear description of uncertainties in any methodology should be calculated and stated.

In shorter term measurements, assessed against L_{Aeq}, L_{A50}, L_{A90} indices, it is a proper approach to perform shutdowns and logarithmically subtract the shutdown levels from the total levels, to give the specific sound pressure level owing to the source [18] [24]. However, it is impracticable to have regular shutdowns, over a year, for the wind farm, since this will impede the generation of electricity. In addition, neighbouring wind farms that were stopped for various reasons throughout the year would provide an incorrect picture of the cumulative noise exposure.

The Netherlands and Norway, where the L_{den} index is used, state that measurements at receptor locations are impracticable. They sate that compliance is assessed with sound power level measurements with a prediction of immission levels at receptor locations [10] [14]. Therefore, given the multiple meteorological effects on propagation it is more logical to use receptor measurements to compare to L_{Aeq}, L_{A50}, L_{A90} or other similar indices for sound level limits, rather than attempt to measure an annual average.

The annual average sound level indicators may not reflect the neighbours experience of sound at their dwelling. For example, the character or level of the sound that may occur under specific conditions that may cause a complaint. Would a complaint be resolved if the annual average was compiled with?

There are some challenges with showing compliance with the annual limit under the following circumstances:

- The nature of the annual average implies that the short-term immission level would be greater than the annual average limit. Therefore, if a

[7] If the landform is close to the receptor, then a reduction of 10 dB can be used.

limit was X dB L_{night}, then the source could remain at X+3 dB $L_{Aeq,T}$ for 50 per cent of the year, and then shutdown for the rest of the year and meet the limit.

- If the annual average is calculated from the operational data , would the wind turbine(s) or wind farm have to cease operating, or the operator would be subject to penalties, if they reach the annual limit before the 12 months? Would it be a fixed 12 months or a rolling 12 months?

5. SUMMARY

The EU Directive 2002/49/EC aims to mitigate harmful effects of environmental noise using indicators like L_{den} and L_{night} for strategic noise mapping. The WHO European Region issued noise guidelines in 2018, recommending guideline levels for various noise sources including wind turbines. However, the WHO guidelines levels in 1999 and 2009 are still extant. The WHO guidelines level was given a **conditional** recommendation and still requires substantial debate, since the quality of evidence used to derive this guideline level was **low quality**. In addition, the WHO 2018 report states that the L_{den} and L_{night} is a poor acoustic measure for wind turbines.

A 2022 guidance update references L_{den} and L_{night} for noise monitoring, recommending L_{den} < 45 dB for wind turbine noise, with no L_{night} or $L_{Aeq,T}$ reference for wind turbines. The ECA recommended prioritising noise pollution actions and assessing EU noise-reduction targets within the END. These targets should align with WHO recommendations by 2029, focusing on indicators L_{den} and L_{night} for road, aircraft, and railway noise.

The Netherlands has set annual sound limits at 47 dB L_{den} and 41 dB L_{night}, assessing turbine sound power levels with NEN-EN-IEC 61400-11 and KNMI wind statistics for immission predictions. Currently, a temporary bridging scheme is active whilst the Netherland's wind farm laws are under review, with new regulations anticipated by 2025 or 2026. Norwegian guideline T-1442/2021 sets a 45 dB L_{den} limit for noise prediction using NORD2000, with turbines assumed to operate continuously. Sound power level is based on 8 m/s wind speed at 10 m height. Norway and Netherlands calculate the L_{den} in different ways and therefore a direct comparison is not advised. Both countries do not recommend receptor measurements for the determination of the annual levels, but a sound power level measurement with a prediction to the receptor is required to determine compliance.

Sound power levels must be declared from cut-in to cut-out wind speeds, using rated levels if not specified above rated speeds. Extrapolation outside of measured levels requires caution to avoid reducing the annual average sound power level. The resolution of wind speed measurements for calculating annual averages shall be the same as the sound power levels, avoiding errors from binning or interpolating. Measurement of wind speeds should be at hub height or appropriate heights, considering wind shear to convert between heights, guided by IEC standards and good practice guides.

Wind direction affects the immission at receptor locations, especially in shadow zones, with variations owing to season and time, notably near coasts and large water bodies. Wind direction distribution, illustrated by wind roses, is crucial for turbine siting in farms, with differing wind speed distributions across these sectors.

Prediction of annual levels at the receptor will have to take account the wind statistics, meteorological conditions, operational conditions and variations in the propagation attenuation over the year and lifetime of the wind farm. Assuming the turbines are operating at full rated capacity would be an overestimation of the annual averages. Annual average sound levels may not reflect the neighbours' experience, as long-term averages often miss short-term variations, character and specific disruptive conditions.

Measuring annual average sound levels at receptor locations are impactable owing to background noise and the presence of measurement equipment, which may disrupt inhabitants and affect their response to wind farm noise. Long-term immission measurements around a wind farm increase costs and complexity, requiring precision and clear methodology, whilst trying to minimise uncertainties in the result.

Challenges in meeting annual sound limits include potentially exceeding short-term immission levels and needing shutdowns to comply. Questions arise about operations ceasing and penalties if limits are reached, whether on a fixed or rolling 12-month basis.

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