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An analysis of self-reported sleep disturbance from nighttime wind turbine noise suggests minimal effects but highlights the need for standardization in research design[a)]

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ABSTRACT:

The World Health Organization Environmental Noise Guidelines provide source-based nighttime sound level (Lnight) recommendations. For non-aircraft sources, the recommended Lnight is where the absolute prevalence of high sleep disturbance (HSD) equals 3%. The Guideline Development Group did not provide an Lnight for wind turbines due to inadequate data. In the current study, calculated outdoor wind turbine Lnight levels ranged from <20.5 to 41.5 dB(A). Between May and September 2013, questionnaires were completed by 606 males and 632 females, 18–79 years of age, randomly selected from households 0.25 to 11.22 km from operational wind turbines. When the source of sleep disturbance was unspecified, the mean prevalence of HSD was 13.3% overall and unrelated to Lnight ($p = 0.53$). As Lnight increased, identifying wind turbines as one of the causes of HSD increased from 0% below 20.5 dB(A) to 3.8% between 35.5–41.5 dB(A) ($p = 0.01$). The 3%HSD benchmark was observed where Lnight was 33.5 dB(A) [95% confidence interval (CI) 31.1–36.1 dB(A)]. Results affirm findings from Health Canada's *Community Noise and Health Study* of minimal impacts of wind turbines on sleep [Michaud *et al.* (2016a). "Effects of wind turbine noise on self-reported and objective measures of sleep," Sleep **39**(1), 97–109], yet noted uncertainties and limitations are discussed, including the suggestion that the HSD benchmark for wind turbines may be too low. https://doi.org/10.1121/10.0034710

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I. INTRODUCTION

The World Health Organization (WHO) Regional Office for Europe published Environmental Noise Guidelines for the European Region (hereafter referred to as "Guidelines") (World Health Organization, 2018) targeting the European Regions but reported to be applicable globally. The Guidelines update the Community Noise Guidelines (World Health Organization, 1999) published two decades earlier by including additional sources, consideration for a wider range of health outcomes and intervention studies. The update provides source-based recommendations pertaining to outdoor sound levels only, based on the outdoor annual average day–evening nighttime sound level (DENL) and outdoor annual average nighttime sound pressure level (SPL) (Lnight) at the most exposed façade (European Commission, 2002).

Guideline content (World Health Organization, 2018) was based on a transparent review of a large body of science, published as a series dedicated to separate health outcomes/risk factors considered to be associated with environmental and leisure noise exposure. Although the individual systematic reviews were published by health outcome (i.e., sleep, annoyance, cognitive impacts, cardiovascular/metabolic responses, adverse birth outcomes, hearing loss, and tinnitus), the Guidelines are presented by noise source (i.e., road traffic, railway, aircraft, wind turbines, and leisure). For non-leisure noise sources, the Guideline Development Group (GDG) recommended Lnight sound levels that were associated with an absolute prevalence of 3% for self-reported long-term high sleep disturbance (HSD). In setting this benchmark, the GDG initially considered 5% for HSD yet resolved that 3%HSD would protect a greater proportion of the population and be more consistent with the prevalence of HSD at Lnight 40 dB(A), the health-based sound level for long-term sleep disturbance in the previously published night noise guidelines (World Health Organization, 2009; Basner and McGuire, 2018). Updated exposure response functions derived through systematic review provided the sound levels rounded to the nearest integer for 3%HSD. Aircraft are an exception, where the GDG noted that the prevalence of HSD was already 11% at Lnight 40 dB(A) and no data were available to reliably estimate the Lnight associated with 3%HSD (World Health Organization, 2018). Also, new to the

[a)]Significant portions of this work were presented in "Michaud *et al.* (2024). A preliminary analysis of long-term self-reported sleep disturbance attributed to wind turbines and modelled outdoor nightly average wind turbine sound pressure level," INTER-NOISE and NOISE-CON Congress and Conference Proceedings, INTER-NOISE24, Nantes, France, October 2024 (Institute of Noise Control Engineering, Wakefield, MA). The authors grant permission to reproduce content for the current publication, with and without modifications.

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Guidelines was the inclusion of a chapter on utility-scale wind turbines.

The GDG considered evidence available up to the year 2015. A conditional recommendation for a DENL of <45 dB(A) to limit the prevalence of high wind turbine noise (WTN) annoyance to 10% was provided. However, no recommendation could be provided for the Lnight level that would limit the prevalence of HSD to 3% because the evidence from the six studies reviewed by Basner and McGuire (2018) was reported to be inconsistent and lacking in quality. Some of the inconsistencies that continue to challenge cross-study comparisons relate to (1) the absence of a common approach to evaluating sleep disturbance and what constitutes HSD, (2) the time reference period for sleep assessment, (3) wind turbine exposure metrics that cannot be used to reliably estimate Lnight, (4) questionnaire content that does not allow one to conclude which attribute(s) of wind turbines is(are) the source of sleep disturbance, and (5) unstructured questionnaires where the questions and response categories used to evaluate sleep are not readily comparable across studies.

Table I summarizes the key attributes from original studies that have evaluated self-reported sleep quality in relation to WTN before and after the Guidelines were published. The table demonstrates the heterogeneity in how each study has assessed self-reported sleep quality as a function of WTN. Because they lack the minimum information required on sleep disturbance and wind turbine Lnight, no study from Table I can be used to estimate the wind turbine Lnight level associated with a prevalence of 3% long-term HSD at home, attributed to wind turbines.

Health Canada's Community Noise and Health Study (CNHS) was completed almost 10 years ago and included an assessment of self-reported and objectively measured sleep in relation to wind turbines (Michaud *et al.*, 2016a; Michaud *et al.*, 2016b; Michaud *et al.*, 2016c). However, the original analysis of HSD was limited insofar as it was not presented by the source of sleep disturbance, nor was the analysis conducted as a function of wind turbine Lnight. To our knowledge, the CNHS remains the only field study to date to include both questionnaire content and an outdoor long-term average nighttime WTN calculation, making it suitable for estimating long-term self-reported HSD as a function of wind turbine Lnight. The exposure–response relationship between outdoor wind turbine Lnight and the prevalence of HSD is provided in the current analysis for the purpose of initiating additional research in this area to inform future updates to the WHO Guidelines. As such, the purpose of the current analysis is not to debate the value in using self-reported sleep disturbance in Guidance development, although the analysis does underscore the need for standardization in the methodology used to assess long-term self-reported sleep disturbance. The reader is referred to Basner *et al.* (2012) for an elaboration on the advantages and disadvantages of the various methods for evaluating sleep quality, including data collected using questionnaires.

II. METHODS

A. Study locations

Study locations were drawn from areas in southwestern Ontario (ON) and Prince Edward Island (PEI) where there were sufficient dwellings near wind turbine installations. Wind turbines in the study were typically located in areas far from transportation or neighbor noise, both of which could potentially have an adverse effect on sleep. The ON and PEI sampling regions included 315 and 84 wind turbines, respectively. The wind turbine electrical power outputs ranged between 660 kW to 3 MW (average 2.0 ± 0.4 MW). All turbines were monopole tower design with three pitch-controlled rotor blades (∼80 m diameter) with the rotor located upwind of the tower and over 95% had 80 m hub heights.

1. Participant selection

All identified dwellings within approximately 600 m from a wind turbine and a random selection of dwellings between 600 m and 11.22 km were selected from which one person per household between the ages of 18 and 79 years was randomly selected to participate. Participants were not compensated in any way for their participation.

2. Questionnaire

The final questionnaire, available on the Statistics Canada website (Statistics Canada, 2014) and elsewhere (Michaud *et al.*, 2016b) consisted of basic socioeconomic and demographic variables, modules on community noise and annoyance, health effects, lifestyle behaviors. and prevalent chronic illnesses. In addition to these modules, validated psychometric scales were incorporated, without modification, to assess perceived stress, quality of life, and sleep disturbance over the previous 30 days. Questionnaire data were collected through in-person home interviews by 16 Statistics Canada trained interviewers between May and September 2013. The study was introduced as the "Community Noise and Health Study" as a means of masking the true intent of the study, which was to investigate the association between health outcomes/risk factors and wind turbine SPL. Wind turbines were first mentioned prior to the questionnaire when permission to take global positioning system (GPS) coordinates was requested for the determination of dwelling distance from community noise sources. Wind turbines were mentioned as an example, along with road, train, and air traffic.

a. Long-term HSD. The assessment of HSD in the current study was based on the recommended approach for assessing noise annoyance in International Organization for Standardization (ISO) technical specification (TS) 15666 (ISO/TS-15666:2021, 2021). At the end of the sleep module, respondents were asked: "How much was your sleep disturbed in any way in the past 12 months when you are at home?" Response categories included the following: "not at all," "slightly," "moderately," "very," or "extremely." The response categories are consistent with the conventional approach followed for defining high noise annoyance, prior to the proposed weighting scheme introduced as an alternative in the updated version of ISO/TS-15666:2021 (2021).

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TABLE I. Summary of key attributes for original studies assessing self-reported sleep disturbance in relation to wind turbines, presented by date of publication starting with most recent. ESS, Epworth Sleepiness Scale; ICBEN, International Commission on Biological Effects of Noise; ISI, Insomnia Severity Index; PSQI, Pittsburgh Sleep Quality Index.

Reference	Sleep survey	Question(s) used to evaluate sleep	Interview method (N = sample size)	Wind turbine exposure	Notes
Radun *et al.* (2022)	Non-standardized questionnaire to assess health effects including sleep disturbance	How much have you experienced sleep problems all in all in the past 12 months? Sleep problems include difficulty falling asleep, waking up in the middle of the night, poor quality of sleep, and waking up too early in the morning. Response 0 (not at all) to 10 (very much). How often is your sleep disturbed by sounds from your environment? Response <1/y, at least 1/y, at least 1/month, at least 1/week, nearly every day; %Sleep disturbed in general-score of 5+ %Sleep disturbance due to noise-% score of at least 1/month or more.	Mailed questionnaire with online option (N = 676)	Modelled WTN supported by measurements WTN [17–25]; (25–30]; (30–40] dB(A) Control area WTN inaudible at LAeq 15 dB	%disturbed sleep due to noise was unrelated to WTN categories overall but higher in lowest wind turbine category vs control; authors note that sleep disturbance in the lowest category not likely due to WTN as the pattern was not observed at higher WTN areas
Bolders *et al.* (2022)	Adapted from ISO/TS:15666 (ISO, 2003)	Thinking about the last year or so, while you were here at home, how disturbed was your sleep? Where 0 = not at all disturbed and 10 = extremely disturbed. HSD considered 8+ on the 11-point numeric response scale.	Online questionnaire (N = 662)	Proximity to wind turbine <5 km 0–2.5 km compared to 2.5–5.0 km	Authors note the results presented are preliminary Prevalence of HSD due to WTN (3.73% <2.5 km compared to 1.37% between 2.5–5 km)
Liebich *et al.* (2022a)[a]	Consensus sleep diary PSQI, ISI, ESS (screening)	How long did it take you to fall asleep? (minutes)	Online sleep diary (baseline week) (N = 22)	Background 23 dB(A) WTN 33 dB(A)	Subjective sleep onset latency unrelated to WTN
Liebich *et al.* (2022b)[a]	Consensus sleep diary	Sleep efficiency, time in/out of bed, minutes awake and asleep at night, number and duration of awakenings, wake up time and total sleep time.	Online sleep diary (N = 68)	Played back recording from indoor measurements WTN 25 dB(A); included AM; control night 19 dB(A)	No significant association between sleep diary measures and WTN
Qu and Tsuchiya (2021)	Non-standardized questionnaire based on British Household Panel Survey	My sleep is not disturbed at all I sleep less deeply than I would like I often lie awake for a while It's hard for me to fall asleep I occasionally wake up, but I soon go back to sleep I have to take sleeping pills to fall asleep	Mailed or hand-delivered questionnaire Variant 1: responses in relation to wind turbines (N = 359); Variant 2: response not in relation to wind turbines (N = 262)	Proximity to closest wind turbine (500–2000 m) <30 dB(A) to >40 dB(A) Modelled around three suburban wind farms	Disturbed sleep related to noise annoyance but not WTN; visibility of wind turbine reduced odds of reported deep sleep
Turunen *et al.* (2021a)	Sleep questions from the National FINRISK Study questionnaire	Is your sleep disturbed by WTN at your home? (not at all, a little; to some extent, very much or extremely Think about the last month (30 days). Please report how often the following issues have been on your mind or bothered you? Fatigue Difficulties in falling asleep Waking up too early	Mailed survey with follow up by telephone for non-response survey (N = 1411)	Proximity to closest wind turbine ≤2.5 km; >2.5–5 km; >5–10 km Modelled at closest distance group-34 to 43dB(A)	Proximity associated with increased prevalence of sleep disturbance to at least some extent, remained statistically significant after adjusting for confounding variables Waking up too early unrelated to wind turbines

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TABLE I. (*Continued*)

Reference	Sleep survey	Question(s) used to evaluate sleep	Interview method (*N* = sample size)	Wind turbine exposure	Notes
Turunen *et al.* (2021b)	Non-standardized question to assess the belief that wind turbine infrasound affects sleep	How much do you think exposure to infrasound from wind turbines can affect the following things and diseases in general: mood, sleep quality, blood pressure, diabetes, heart disease, cancer? Small effects (0–6); Moderate effects (7–12); Major effects (13–24).	Mailed to random sample within 20 km of each of four wind farms; follow-up telephone call for non-responders (*N* = 1351)	Proximity to closest wind turbine ≤2.5 km; >2.5–5 km; >5–10 km	Areas targeted based on the belief symptoms would be high; reporting health symptoms was more prevalent at closer distances, sleep quality not presented separately
Smith *et al.* (2020)[a]	Non-standardized questions to assess sleep quality based on phraseology recommended by ICBEN.	Based on Fields *et al.* (1997, 2001) with the addition of a final question evaluating a variety of emotional states	Self-administered morning questionnaire (*N* = 50)	WTN exposure night at 32 dB LAeq (continuous synthesized WTN based on short- and long-term recordings including amplitude modulation Control night 13 dB(A)	Self-reported sleep consistently rated as worse following WTN nights Individuals from wind turbine areas reported worse self-reported sleep in both the control and WTN nights
Ageborg Morsing *et al.* (2018)[a]	Non-standardized questions to assess various sleep outcomes	How would you rate your sleep quality during the night? (0–10) How would you rate your sleep quality during the night? (very good to very bad) How are you feeling right now? (1–10) Very rested–very tired; Very relaxed – very tense; Very irritated – very glad How long did it take you to fall asleep last night? (minutes) How many times do you estimate that you woke up during the night before the morning alarm? (#) Did you have difficulty falling back to sleep after an awakening? Yes/No How was your experience of the night and your sleep (1-10): Easy to fall asleep Better sleep than usual Deep sleep Never woke up How disturbed was your sleep by noise from wind turbine during the night? (1-10) Do you think that noise during the night disturbed your sleep so that you: slept badly? were awoken? had difficulty falling asleep? felt tired in the morning? Response options: not at all, slightly, moderately, very, extremely	Self-administered morning questionnaire Two studies – A and B - (*N* = 6 for each study)	5 nights in the lab; baseline sleep 19 dB(A); and the subsequent three nights were as follows: Study A: 29.5 dB LAeq 34.1 dB LAeq 33.7 dB LAeq Study B: 32.8 dB LAeq 32.8 dB LAeq 30.4 dB LAeq Simulated indoor WTN levels with varying filters, frequencies and amplitude modulation were used for the three exposure nights	Pilot study—authors note the limited sample with healthy young participants Significant effect of perceived sleep disturbance by WTN on nights after control night in both studies

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TABLE I. (*Continued*)

Reference	Sleep survey	Question(s) used to evaluate sleep	Interview method (N = sample size)	Wind turbine exposure	Notes
Pawlaczyk-Łuszczyńska *et al.* (2018)	Non-standardized questions to assess sleep quality	Participants were asked about their experiences regarding the following: Waking up well rested; Having difficulty in falling asleep; Awakened by noise with closed window; Awakened by noise with open window; Awakened by wind turbines	Door-to-door questionnaire distribution ($N = 517$)	Receptors 0.24-1.73 km from wind turbines Modelled WTN 30-50dB(A) at receptors	Sleep impacts were evaluated within the context of annoyance and how they may contribute to increased annoyance Reported reduction in sleep quality and an increase in awakenings and day-time tiredness, which were attributed to the wind turbines
Jalali *et al.* (2016a)[a]	Non-standardized measures of subjective sleep quality	Subjective ratings of sleep quality and quantity	Participants were provided with a sleep diary ($N = 16$)	Time 1 (pre-operation): 31.52 dB(A) (indoors); Time 2 (during operation): 31.23 dB(A) (indoors)	Reported sleep qualities were significantly worsened after exposure to wind turbines Participants also reported feeling sleepier in the morning and throughout the day after exposure
Jalali *et al.* (2016b)	PSQI, ESS, ISI Non-standardized questions to assess subjective sleep quality	PSQI = >5 ISI- clinical insomnia defined as $\geq$ 15 ESS- score of 0–7 (absence of insomnia); 8–14 (subthreshold insomnia); 15–21 (moderate insomnia); and 22–28 (severe insomnia) Participants were questioned about different factors that generally interrupt sleep, including aircraft, wind, thunderstorms, and WTN.	Mail delivery of advance notice including study details; door-to-door recruitment; self-administered questionnaire ($N = 50$, Time 1; $N = 37$, Time 2)	Time 1 (pre-operation): 31.52 dB(A) (indoors); Time 2 (during operation): 31.23 dB(A) (indoors)	PSQI, ESS and ISI all significantly increased following exposure Poorer sleep quality related to negative attitude to wind turbines, concerns related to property devaluation, if wind turbine visible. Changes in mean sleep variables were not associated with distance to wind turbines
Kageyama *et al.* (2016)	Non-standardized questionnaire	Do you have any trouble with your sleep? (yes/no) - If yes, choose: 1 = more than 3 times a week; 2 = once or twice a week; or 3 = occasionally	Face-to-face interviews ($N = 1079$)	Calculated WTN based on measurements at multiple locations; most of the estimated exposure levels were: 36-46+ dB(A) in the wind turbine sites and 35 dB(A) or below at the control sites Calculated Lnight (22:00 h–06:00h)	Insomnia was significantly higher where WTN >40 dB(A) 82% of insomniac respondents attributed their sleeplessness to WTN
Lane *et al.* (2016)[a]	Adapted from Pittsburgh Sleep Diary	Sleep diary for time to bed, sleep onset time, awaken time, number of awakenings, and ranking of perceived sleep quality on a 6-point scale Sources of awakening: use of bathroom, child or partner, pain, other, don't know	Self-administered sleep diary each morning (×5) ($N = 22$) (10 participants near wind turbines and 12 not near wind turbines)	Exposure analysed by proximity to wind turbine; exposed avg 795 m; non-exposed avg 2931 m	Exposed group had faster sleep onset times, no difference in rated sleep, significantly less likely to attribute their awakenings to "other" versus unexposed group

TABLE I. (*Continued*)

Reference	Sleep survey	Question(s) used to evaluate sleep	Interview method (N = sample size)	Wind turbine exposure	Notes
Michaud *et al.* (2016a)[a]	PSQI Non-standardized questions to assess magnitude of sleep disturbance over previous year	PSQI mean scores and prevalence >5 How much was your sleep disturbed in any way in the past 12 months when you are at home? Not at all, slightly, moderately, very, extremely Follow-up question for those who reported at least slight disturbance: What do you think is contributing to your sleep disturbance? (more than one source could be spontaneously reported)	Face-to-face ($N = 1238$)	Modelled outdoor long-term average dB(A) supported with measurements <25 to 46 dB(A)	Very or Extremely considered HSD. No association between %HSD (in general) and WTN %slightly sleep disturbed by wind turbines significantly associated with WTN category; wind turbine feature(s) causing sleep disturbance unspecified No association between PSQI and WTN
Song *et al.* (2016)	Non-standardized question to assess sleep disturbance by noise [question based on Pedersen and Persson Waye (2007, 2004)]	When at home, how often is your sleep disturbed by ambient noise? Almost never, at least 1/year, at least 1/month, at least 1/week, almost daily.	Face-to-face questionnaire ($N = 227$)	Modelled WTN 44 to 57 dB(A). Dwellings 70–339 m from wind turbine	Ambient noise source unspecified Disturbance >1/month considered important Disturbance >1/month related to WTN
Magari *et al.* (2014)	Non-standardized questions to assess sleep quality adapted from Pedersen and Persson Waye (2007)	Questions included: Concern about health effects from turbines (Y/N), included sleep disturbance	In-person questionnaire ($N = 62$)	10-min measurements inside/outside each residence. The LAeq (10 min) indoor (6.3–3150 Hz) ranged from 20–65 dB(A); outdoors 32–72 dB(A)	Concern regarding health effects from wind turbines related to prevalence of sleep disturbance; no analysis by WTN
Bakker *et al.* (2012)	Non-standardized question to evaluate presence of sleep disturbances [question partially based on Pedersen and Persson Waye (2007, 2004)]	How often are you disturbed by sound? (almost) never, at least once a year, at least once a month, at least once a week, and (almost) daily 'at least once a month' considered sleep disturbance	Mailed questionnaire ($N = 725$)	The average background levels were 41 dB(A) in rural areas and 49 dB(A) in both rural areas with a major round and built-up areas. Modelled WTN ranged from 21 to 54 dB(A) [average 35 dB(A)]	Sleep disturbance increased with SPL, however, that increase was only significant above 45 dB(A), where 48% of the respondents reported sleep disturbance; may be caused by multiple noise sources
Nissenbaum *et al.* (2012)	PSQI, ESS	PSQI >5 and mean ESS >10 and mean	Either door-to-door or via telephone at two separate windfarms Offered to all residences within 1.5 km and random residences between 3–7 km from wind turbine ($N = 38$)	Proximity to wind turbines 375 m to 6.6 km Maximum predicted 1 hr LAeq – 51 dB at 244 m distance to 35 dB at 1799 m distance Maximum measured 1 hr LAeq – 52 dB at 244 m distance to 37 dB at 1799 m distance	Reported dose-response relationship with mean PSQI and ESS scores and log-distance to wind turbines; results not presented by WTN

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TABLE I. (*Continued*)

Reference	Sleep survey	Question(s) used to evaluate sleep	Interview method (N = sample size)	Wind turbine exposure	Notes
Krogh *et al.* (2011)	Non-standardized questions to assess excessive tiredness and sleep disturbance	Do you feel that since living near a wind turbine you have experienced excess of the following symptoms (i.e., more than you did prior to living near these structures)? Sleep disturbance (y/n)	Mailed questionnaire (N = 109)	Proximity to wind turbine 350–499 m; 500–699 m; 700–800 m; and 900–2400 m	From 350–673 m, 78% of participants indicated disturbed sleep; at 700–808 m - 60%; and 900–2400 m – 59%
Shepherd *et al.* (2011)	Sub-scale of the WHOQOL-BREF (HRQOL)	In the past month, how satisfied were you with your sleep? Very dissatisfied, dissatisfied, neither satisfied nor dissatisfied, satisfied, very satisfied	Hand-delivered questionnaire (N = 197)	Wind turbine area: <2 km; typical noise exposures between 24 dB(A) and 54 dB(A) Non-wind turbine area: >8 km away	Those in wind turbine area reported significantly lower sleep satisfaction and rated their environment as less restful; no analysis by WTN level
Pedersen and Persson Waye (2007)	Non-standardized questions to assess the presence or absence of sleep disturbance	Respondents were asked about their emotions when thinking about wind turbines, their set of values of their living environment, and their status of health, well-being and sleep. Additional content from Pedersen and Persson Waye (2004) regarding sources	Mailed questionnaire (N = 754)	Modelled WTN <32.5 to >40 dB(A)	Annoyance, rather than distance from the wind turbine was reported as the main correlating variable for sleep disturbance.
Pedersen and Persson Waye (2004)	Non-standardized questions to assess the presence or absence of sleep disturbance	Respondents were asked questions about their normal sleep habits: quality of sleep, whether sleep was disturbed by any noise source, and whether they normally slept with the window open. One open question asked what sources of noise felt to result in sleep disturbance, and responses included road traffic, rail traffic, neighbors, and wind turbines.	Questionnaire delivered door-to-door and collected one week later (N = 351)	Exposure was calculated as A-weighted SPL at each residence. The ambient SPL varied from 33 dB LAeq,5 min to 44 dB LAeq,5 min 0.15–1.2 km distance to receptors.	Below 35 dB, none of the respondents reported sleep disturbance from wind turbines; 16% of the 128 respondents living at SPL above 35 dB reported sleep disturbance due to WTN

[a]Study also included objectively measured sleep outcomes.

Therefore, participants that reported to be either "very" or "extremely" sleep disturbed were considered to have "HSD" in the current analysis. The group without HSD was composed of participants from the remaining response categories. Participants who reported at least a "slight" magnitude of sleep disturbance were asked to identify the source they thought was contributing to their sleep disturbance. Respondents were not prompted with options and could identify more than one source. If the identified source was not one that the interviewer could select on their laptop as being spontaneously reported (i.e., wind turbines, children, pets, neighbors), they selected "other" and specified the source(s) identified by the respondent. An analysis of "other" was conducted later to develop a comprehensive list of sources of sleep disturbance. It is important to emphasize that "wind turbines" as a declared source of HSD cannot be assumed to refer to noise from wind turbines, or any other wind turbine feature that may be capable of disrupting sleep (e.g., aircraft warning lights, shadow flicker for daytime sleepers, etc.).

3. Wind turbine SPL at dwellings

Outdoor SPL was estimated at each dwelling using ISO 9613–2 (ISO 9613-2:1996, 1996) as incorporated in commercial software (CadnaA version 4.4, DataKustik GmbH, Gilching, Starnberg, Bavaria, Germany). Calculated sound power levels used wind speed from the wind turbine nacelle anemometers for the year up to and including the study period, the manufacturers' 8 m/s sound power levels, and an assumption of favorable sound propagation conditions. Based on wind turbine nacelle anemometer data and the manufacturers' sound power levels; the yearly averaged sound pressure levels were estimated to be approximately 4.5 dB(A) lower than those calculated for continuous wind turbine operation at 8 m/s wind speed (Keith *et al.*, 2016). Favorable conditions assume the dwelling is either located within approximately 1 km of the noise source; or downwind of the noise source, with a stable atmosphere, and a moderate ground-based temperature inversion. The standard deviation in SPL was estimated to be 4 dB(A) up to 1 km where SPL were typically calculated to be above 31.5 dB(A). At 10 km, the uncertainty was estimated to be +3 to –26 dB(A). Additional modelling details are available elsewhere (Keith *et al.*, 2016).

The average daytime and nighttime levels were verified to be essentially the same at all locations so over the span of a year, Lday = Lnight. Therefore, the resulting calculations are considered to represent long-term average (1 year) nighttime *A*-weighted equivalent continuous outdoor wind turbine SPL and referred to as "Lnight" in the current analysis. Furthermore, this also means that the resulting Lnight categories were not affected by the timing of sleep (e.g., daytime sleep, shift work, etc.). The time reference period was the previous year for the assessment of HSD. Although calculations based on predictions of WTN levels reduce the risk of misclassification compared to direct measurements, the risk remains to some extent. Beyond 1 km, the calculated levels in the current study represent reasonable worst-case estimates expected to yield outdoor wind turbine Lnight levels that typically approximate the highest long-term average levels at each dwelling and thereby optimize the chances of detecting WTN-induced sleep disturbance. All decibel references are *A*-weighted as this filters out low frequencies in a sound that the human auditory system is less sensitive to at low SPL.

4. Statistical analysis

Modelled wind turbine Lnight exposure was classified into the following five categories: <20.5, [20.5–25.5), [25.5–30.5), [30.5–35.5), and [35.5–41.5] dB(A). To describe self-reported sleep disturbance, frequencies and proportions for the entire sample, and broken down by the five categories, were calculated for various groups ranging from "not at all" to "highly" disturbed. Similarly, sources of sleep disturbance identified by participants that reported HSD (i.e., very or extremely) were disaggregated by Lnight categories. Their frequency and relative proportion calculated using the total number of participants in each category as the denominator were computed. To test for associations between each source of sleep disturbance and Lnight categories, Fisher's exact test was performed. This test was specifically selected because it is appropriate for small sample sizes. The same test was used to evaluate the association between high annoyance toward noise from wind turbines and HSD by wind turbines, where the wind turbine feature(s) is(are) unspecified.

The %HSD by any source and the %HSD where wind turbines were among the identified sources were calculated for each 5 dB(A) Lnight category and reported graphically to show the relative contribution of wind turbines to the total %HSD. To look more closely at the relationship between wind turbine Lnight and variations in %HSD when wind turbines were identified, refined 2 dB(A) categories were created. The proportion of participants who reported HSD by wind turbines within each 2 dB(A) category was calculated and reported graphically in Sec. III. The data were analyzed using SAS, software version 9.4 (SAS Institute Inc., Cary, NC).

The wind turbine Lnight level associated with the WHO Guideline benchmark (World Health Organization, 2018) of 3%HSD was determined using the United States Environmental Protection Agency (U. S. EPA) Benchmark Dose Modelling Online software version 3.3.2 (United States Environmental Protection Agency, 2023). Analysis used all of the maximum likelihood models that did not log transform the exposure (i.e., Hill, Gamma, Quantal Linear, Logistic, Probit, Multistage 1°, Multistage 2°, and Weibull). Logic for model acceptance used default values (e.g., goodness of fit *p*-value greater than 0.1, and model selection based on the Akaike information criterion). Models were inspected to ensure they were broadly similar to existing exposure response relationships (European Commission, 2020), and as a result, the Hill model was rejected because its implementation was limited to the range 0%–5.2% HSD.

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The Weibull model was selected because it had the best values for the Akaike information criterion and goodness of fit.

III. RESULTS

Sleep was reported to be affected by multiple sources, including, but not limited to wind turbines, so that the overall prevalence of reported HSD (for any reason), was unrelated to wind turbine Lnight (Table II). Indeed, although some variability was noted, no clear dose–response relationship was observed between the five Lnight categories and the proportion of participants that reported HSD over the previous 12 months. Among the 15 sources of sleep disturbance reported by participants and listed in Table II, very few of the identified sources showed an obvious pattern with the Lnight categories. However, the data did suggest a significant exposure–response relationship between wind turbine Lnight exposure categories and the proportion of participants that identified wind turbines as one of the sources of sleep disturbance ($p = 0.01$). This proportion ranged from 1% or lower for exposure to Lnight less than 30.5 dB(A) and approached 4% for exposure between 30.5 and 41.5 dB(A). High annoyance toward WTN and HSD by wind turbines were strongly associated ($p < 0.0001$). Specifically, 26% of participants highly annoyed by WTN also reported HSD by wind turbines, compared to 1% of participants who were not highly annoyed by WTN (data not shown).

As shown in Fig. 1, when comparing the %HSD where wind turbines were identified as one of the causes of sleep disturbance to the total %HSD by any source, wind turbines

TABLE II. Participants were asked to report their magnitude of sleep disturbance over the last year while at home by selecting one of the following five categories: not at all, slightly, moderately, very or, extremely. Participants that indicated at least a slight magnitude of sleep disturbance were asked to identify all sources perceived to be contributing to sleep disturbance.

	Wind turbine Lnight, dB(A)						Fisher
Variable	<20.5	[20.5-25.5)	[25.5–30.5)	[30.5–35.5)	[35.5–41.5]	Overall	*p*-value[a]
N	83	95	304	519	234	1235	
Self-reported sleep disturbance *n*(%)							
Not at all	29 (34.9)	44 (46.3)	112 (36.8)	208 (40.1)	85 (36.3)	478 (38.7)	
At least slightly[b]	54 (65.1)	51 (53.7)	192 (63.2)	311 (59.9)	149 (63.7)	757 (61.3)	0.382
HSD[c]	13 (15.7)	11 (11.6)	41 (13.5)	75 (14.5)	24 (10.3)	164 (13.3)	0.530
PSQI[d]							
Mean (95% CI)	6.2 (5.3,7.1)	5.9 (5.1,6.8)	6.0 (5.5,6.5)	5.7 (5.3,6.2)	6.1 (5.6,6.6)	5.9 (5.7,6.2)	
n (%) score > 5	40 (49.4)	45 (48.9)	138 (46.5)	227 (44.4)	106 (46.7)	556 (46.0)	
Source of sleep disturbance (among participants highly sleep disturbed) *n*(%)[e]							
N	13	11	41	75	24	164[f]	
Wind turbine	0 (0.0)	1 (1.1)	2 (0.7)	20 (3.9)	9 (3.8)	32[g] (2.6)	**0.010**
Children	1 (1.2)	4 (4.2)	5 (1.6)	7 (1.3)	6 (2.6)	23 (1.9)	0.315
Pets	1 (1.2)	2 (2.1)	1 (0.3)	11 (2.1)	0 (0.0)	15 (1.2)	**0.031**
Neighbors	1 (1.2)	2 (2.1)	2 (0.7)	4 (0.8)	1 (0.4)	10 (0.8)	0.489
Stress/anxiety	2 (2.4)	2 (2.1)	7 (2.3)	12 (2.3)	4 (1.7)	27 (2.2)	0.982
Health/Physical pain	4 (4.8)	4 (4.2)	21 (6.9)	20 (3.9)	4 (1.7)	53 (4.3)	**0.049**
Transportation noise	3 (3.6)	1 (1.1)	3 (1.0)	6 (1.2)	0 (0.0)	13 (1.1)	0.086
Bed partner related	2 (2.4)	4 (4.2)	2 (0.7)	8 (1.5)	2 (0.9)	18 (1.5)	0.107
Work related	0 (0.0)	0 (0.0)	1 (0.3)	1 (0.2)	1 (0.4)	3 (0.2)	0.870
Age related	0 (0.0)	0 (0.0)	1 (0.3)	2 (0.4)	0 (0.0)	3 (0.2)	1.000
Washroom	1 (1.2)	1 (1.1)	1 (0.3)	1 (0.2)	0 (0.0)	4 (0.3)	0.196
Indoor noise	0 (0.0)	2 (2.1)	2 (0.7)	3 (0.6)	0 (0.0)	7 (0.6)	0.229
Discomfort	0 (0.0)	0 (0.0)	1 (0.3)	3 (0.6)	0 (0.0)	4 (0.3)	0.901
Weather	0 (0.0)	0 (0.0)	1 (0.3)	1 (0.2)	0 (0.0)	2 (0.2)	1.000
Other	1 (1.2)	0 (0.0)	5 (1.6)	6 (1.2)	2 (0.9)	14 (1.1)	0.852
Don't know	1 (1.2)	0 (0.0)	2 (0.7)	4 (0.8)	0 (0.0)	7 (0.6)	0.527

[a]The Fisher exact test was used to test for an association between each source of sleep disturbance and wind turbine Lnight categories. This test is appropriate for small sample sizes and for sparse tables.
[b]At least slightly sleep disturbed includes participants reporting slightly, moderately, very, or extremely.
[c]HSD includes participants who reported the very or extremely categories. The prevalence of reported sleep disturbance was unrelated to Lnight levels.
[d]Pittsburgh Sleep Quality Index (PSQI) score above 5 is considered to represent poor sleep; 1208 participants had valid PSQI values.
[e]The percentage is calculated using the total number of participants in each Lnight category as the denominator. Columns may not add to sample size totals as some participants identified more than one source as the cause of their sleep disturbance.
[f]Of the 164 participants reporting HSD, 104 reported being very sleep disturbed and 60 reported being extremely sleep disturbed.
[g]Of the 32 highly sleep disturbed participants reporting wind turbines as a source ($n = 18$, very; $n = 14$, extremely), 15 identified it as the sole source.

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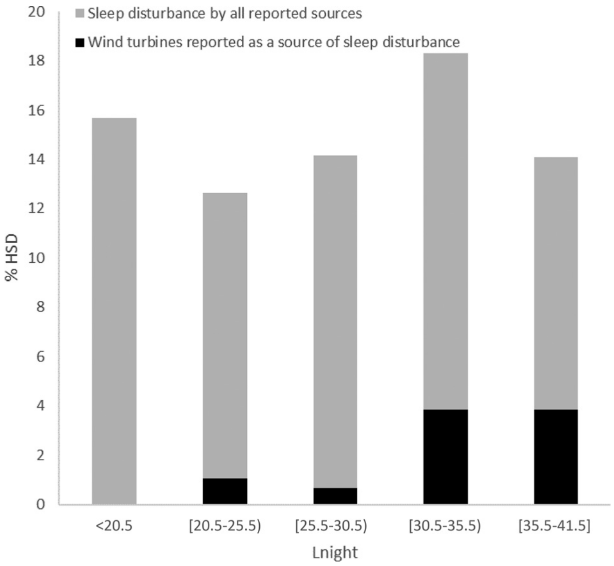

FIG. 1. Self-reported HSD at home over the previous 12 months as a function of calculated outdoor wind turbine Lnight. The %HSD was calculated for each 5 dB(A) wind turbine Lnight category using the total number of participants in each category as the denominator.

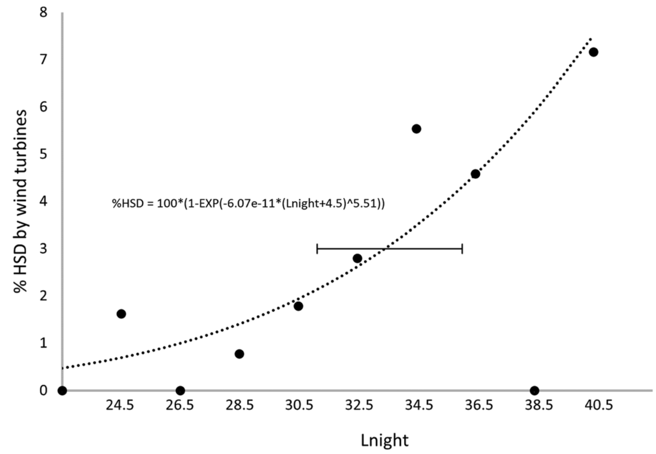

FIG. 2. Proportion of participants who reported HSD at home over the previous 12 months where wind turbines were identified as one of the causes of sleep disturbance, as a function of calculated outdoor wind turbine Lnight. The horizontal line shows the relative size of the 95% confidence interval for the 3% benchmark for the prevalence of HSD proposed by the WHO (World Health Organization, 2018). The %HSD was calculated for each 2 dB(A) Lnight category using the total number of participants in each category as the denominator. The notable drop in HSD by wind turbines among participants in the 37.5–39.5 dB(A) category was further examined. The higher proportion reporting personal benefit from wind turbines in the area provides only a partial explanation; other causes are unknown and would be speculative.

as a source was almost never reported as a cause of sleep disturbance by participants exposed to less than 25.5 dB(A). A small proportion of those exposed to WTN of at least 25.5 dB(A) reported wind turbines as a source of sleep disturbance. Even though this proportion increased significantly as a function of WTN exposure, it remained very low when compared to the proportion of participants reporting HSD by any source.

To assess the robustness of the findings, a sensitivity analysis was conducted removing participants who self-reported personal benefit from having wind turbines in the area, given the strong association between personal benefit and reduced annoyance toward WTN in the CNHS (Michaud *et al.*, 2016c) and the aforementioned correlation between noise annoyance and HSD. Results produced an almost identical figure, revealing no significant changes in the proportion of participants who reported HSD by any source. A slight increase in less than 1% in the proportion of participants highly sleep disturbed by wind turbines in the upper two noise exposure categories was observed, because none of the participants with personal benefit reported HSD by wind turbines (data not shown).

Figure 2 plots the observed proportion of participants who reported HSD by wind turbines at the mid-point for each 2 dB(A) category. Only three individual data points at the upper end of the Lnight exposure categories are above the 3%HSD benchmark. Self-reported HSD by wind turbines was notably absent below the 24.5 dB(A) point (23.5–25.5 dB(A) category). However, as observed in Table II and Fig. 1, an exposure–response relationship between %HSD among participants identifying wind turbines as one of the sources and wind turbine Lnight seems to only emerge above 25.5 dB(A). Figure 2 shows a trend line fitted using a Weibull model crossing the 3%HSD benchmark at an Lnight of 33.5 dB(A) (95% CI 31.1–36.1 dB(A)).

IV. DISCUSSION

Grounded in the noise annoyance literature, HSD can be defined as a response to a social survey question on sleep in the top two categories on a five-point verbal scale (e.g., not at all, slightly, moderately, very, or extremely) or the top 27%–29% of an anchored numeric scale. By linking HSD to a long-term home environment, questionnaire responses aim to reflect a sustained sleep condition. It is this habitual HSD that the WHO has assigned a disability weight of 0.07 in their analysis of the burden of disease from environmental noise, whereby the calculated burden escalates as the proportion of a population experiencing noise-induced HSD increases (World Health Organization, 2011). In its defense of HSD, the WHO reported that HSD is the "most meaningful, policy-relevant measure" of disturbed sleep because of its high prevalence in the general population, and through its effects on quality of life, a potential risk factor that may lead to health effects (World Health Organization, 2018).

The results of the current analysis showed an increase in the prevalence of spontaneously reporting wind turbines as at least one of the sources of HSD and elevating wind turbine Lnight levels. Although several studies have evaluated self-reported sleep disturbance in relation to wind turbines over the past 25 years, there are no studies from Table I that can be directly compared to the current analysis due to significant differences in the methods used to assess self-reported sleep. The preliminary results presented by Bolders *et al.* (2022) are most similar insofar as sleep disturbance was evaluated using an adaptation of ISO/TS 15666 (ISO/TS-15666:2003, 2003); however, their prevalence data are

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presented in a dichotomous categorization of proximity to wind turbines and not by wind turbine Lnight.

A limitation to the current analysis is inherent to self-report and the potential for misattribution in identifying the cause of sleep disturbance (Basner *et al.*, 2012). Therefore, it should be considered that the absence of an association between HSD (in general) and Lnight among the full study sample, compared to the increase in prevalence when wind turbines were identified as a cause of HSD among a much smaller sub-sample of respondents, may reflect a misattribution bias. This possibility exists because HSD by wind turbines was much more common among respondents who were highly annoyed by WTN and their annoyance may be motivating them to retrospectively attribute sleep disturbance to wind turbines. On the other hand, it could be argued that reporting to be "bothered," "disturbed," or "annoyed" by WTN is caused by, at least to some degree, adverse impacts on sleep, making it impossible to disentangle annoyance/sleep responses. Misattribution can also occur in areas where wind turbines are louder, as people may incorrectly attribute sleep disturbance to turbine noise if it coincides with a spontaneous awakening (Basner *et al.*, 2012). However, there was no evidence of this occurring in a recent laboratory study where self-reported sleep outcomes were statistically similar across exposure conditions that included continuous WTN exposures throughout the sleep night, pausing, or initiating clearly audible exposures during polysomnography-verified shifts to light/awake sleep states. This was the case even among participants recruited from areas where they reported to be annoyed by WTN (Liebich *et al.*, 2022b).

Two additional caveats to our analysis that result from shortcomings in the study design are worth emphasizing because they affect the interpretation of the findings. Most notably, the wind turbine feature(s) causing sleep disturbance is(are) unknown and could plausibly result from the noise emitted by wind turbines, aircraft warning lights on the turbine nacelle, and/or rumination due to excessive daytime annoyance toward wind turbines. Furthermore, the current design does not permit a determination of the source considered to be contributing the most to HSD insofar as respondents were not asked to rank the sources identified nor given instructions to think about only the most intrusive source. These and other issues discussed below emphasize the need for standardization in how self-reported sleep quality is measured in relation to wind turbines, particularly given its significance in shaping guidance development where the emphasis is placed on HSD.

A. Standardization in methodology to inform guidance development

As mentioned in Sec. I, the WHO has placed an emphasis on long-term self-reported HSD (World Health Organization, 2018), although the GDG could not provide a recommendation for the Lnight level that would limit the prevalence of HSD to 3% for wind turbines. They attributed this to inconsistent and poor-quality evidence. Of the studies that have observed an association on reported sleep quality, the impact of wind turbines did not appear to be substantial. Indeed, the current results indicated that, relative to other sources attributed to HSD, very few respondents reported HSD from wind turbines, even in the areas where wind turbine Lnight was highest. These results add to the few studies that did report an association between reduced sleep quality and wind turbine exposure but highlight the inconsistency in study findings noted in a recent systematic review (Liebich *et al.*, 2021).

To inform future updates to the WHO Guidance (World Health Organization, 2018), research investigating the association between sleep disturbance and noise would undoubtedly benefit from standardization on questionnaire content. Drawing upon the recommendations in ISO/TS 15666 (ISO/TS-15666:2021, 2021) for noise annoyance may be a good starting point. As such, reporting the magnitude of sleep disturbance over the previous year aligns with the time-reference period defined by Lnight. By specifying sleep disturbance "in any way" ensures the respondent is free to report on the nature of sleep disturbance most meaningful to them, be that awakenings, delayed sleep onset, premature awakenings, reduced sleep time, or any combination thereof. Evaluating sleep "at home" is necessary to discount transient disturbances in sleep that may be owing to unfamiliar environments (e.g., hotels). In this regard, while laboratory studies offer an optimal method for comprehending polysomnography-measured sleep within controlled settings (Liebich *et al.*, 2022a; Liebich *et al.*, 2022b; Smith *et al.*, 2020; Ageborg Morsing *et al.*, 2018), their utility diminishes when assessing long-term sleep disturbances within the comparatively stable home environment.

To assess the prevalence of long-term HSD, it would seem advantageous to adopt either the five-point verbal and/or the 11-point numeric response categories recommended for noise annoyance (ISO/TS-15666:2003, 2003), where the prevalence of HSD would be defined as originally recommended by Schultz (1978) and affirmed in the updated ISO/TS-15666:2021 (2021). Given that questionnaire content comes at a premium, the value gained by including both scales in a survey, as recommended in the original ISO/TS-15666:2003 (2003) is debatable (Clark *et al.*, 2021) and now an option in the updated TS (ISO/TS-15666:2021, 2021). Following ISO/TS-15666:2021 (2021) and the WHO (World Health Organization, 2011), HSD would be derived from responses in either of the top two categories on the verbal scale and/or the top 27%–29% on a numeric scale. As more research is pursued, there may be value in considering the viability of weighting the fourth category on the five-point verbal scale before conducting comparative analyses with studies that have defined HSD using a numeric scale. This approach has been defended through an analysis of a large body of research on noise annoyance (ISO/TS-15666:2021, 2021) that does not yet exist for HSD. In the current analysis, applying a 0.4 weighting factor to the fourth response category resulted in a prevalence of HSD that never exceeded 3% at any wind turbine Lnight level below 41.5 dB(A) (the highest calculated SPL).

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Although we found no evidence for a statistical association between PSQI and wind turbine Lnight in the current analysis, an alternative strategy could involve defining HSD by adopting one of several already validated and extensively used sleep scales (Fabbri *et al*, 2021). While some may be more appropriate than others, this approach would eliminate the burden of reaching consensus on the wording of the question(s) and response categories used to define HSD (e.g., numeric versus verbal, versus weighted verbal). Indeed, these issues also continue to plague noise annoyance research to this day (Clark *et al*., 2021), despite early efforts by Schultz (1978) and the International Commission on the Biological Effects of Noise (Fields *et al*., 1997; 2001) to standardize the assessment of noise annoyance in socio-acoustic surveys through the publication of ISO/TS:15666 two decades ago (ISO/TS-15666:2003, 2003).

It is readily apparent that there are numerous challenges in attempting to standardize how HSD is assessed in this field of research. The concerns mentioned above are in addition to other factors that can undermine cross-study comparison. Designing studies that can statistically adjust for important variables like shift work, sleep disorders, age, medication, health status, stressors, bed partners, background noise, etc., is also important. Similarly, as Lnight is defined in World Health Organization (2009) to represent the most exposed façade, it may be beneficial to know whether the respondent sleeps on the quiet side of the home, a noted limitation in the current analysis. While acknowledging the significant challenges posed by these issues, the field stands to gain considerable advantages through the establishment of standardized methodologies for assessing self-reported sleep disturbance in socio-acoustic studies. This standardization will play a pivotal role in shaping the effectiveness of such studies in informing the development of guidance.

V. CONCLUSION

The WHO Guidelines (World Health Organization, 2018) identified 3%HSD as the absolute benchmark to recommend Lnight limits. To our knowledge, Health Canada's CNHS remains the only study conducted to date to include questionnaire content that permits an assessment of %HSD at home based on a time reference period that aligns with wind turbine Lnight. Although the study sample is limited and may not be generalizable to other areas, our data suggest that 3%HSD is attained for a wind turbine Lnight of approximately 33.5 dB(A). This is below the Lnight 40 dB(A) health-based limit set by the WHO as adequately protective against the health effects associated with sleep disturbance for even the most vulnerable groups (World Health Organization, 2009). With the health-based limit as a reference point, the current analysis would suggest that the HSD benchmark for wind turbines should be around 7%, which is closer to but still above the 5% initially contemplated by the GDG (World Health Organization, 2018). It is apparent that additional research is required to verify what the most appropriate benchmark should be. Nevertheless, our results clearly show that wind turbines were not the dominant source of sleep disturbance when compared to all other sources combined, even at the highest Lnight category. Source-based guidelines for HSD would be more meaningful and result in less residual sleep disturbance if the recommended Lnight was representative of the acoustical area where there was a clear separation between the targeted source and other causes of sleep disturbance. Admittedly, this may be unachievable for wind turbines due to their relatively low contribution to overall sleep disturbance observed in this study and others.

AUTHOR DECLARATIONS

Conflict of Interest

This research received no external funding. The authors have no conflicts to disclose.

Ethics Approval

The Health Canada and Public Health Agency of Canada Human Research Ethics Review Board approved the Community Noise and Health Study (protocol #2012-0065 and #2012-0072).

DATA AVAILABILITY

The dataset can be accessed publicly through data access requests to Statistics Canada Research Data Centres (Statistics Canada, 2014).

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