Understanding the Evidence: Wind Turbine Noise

Executive Summary

Council of Canadian Academies
Conseil des académies canadiennes

Science Advice in the Public Interest

UNDERSTANDING THE EVIDENCE: WIND TURBINE NOISE

The Expert Panel on Wind Turbine Noise and Human Health

THE COUNCIL OF CANADIAN ACADEMIES
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This report was prepared for the Government of Canada in response to a request from the Minister of Health. Any opinions, findings, or conclusions expressed in this publication are those of the authors, the Expert Panel on Wind Turbine Noise and Human Health, and do not necessarily represent the views of their organizations of affiliation or employment.

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Expert Panel on Wind Turbine Noise and Human Health

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Message from the Chair

Wind turbines are a relatively new addition to the Canadian landscape and energy mix. Although wind power in the form of windmills is a common sight on the farm and on the Prairies, wind turbines on a commercial scale are a modern phenomenon. Their recent growth in both number and size has raised questions regarding potential health impacts on nearby residents.

In response to public concern, the Government of Canada, through the Minister of Health, asked the Council to determine if there is evidence to support a causal association between exposure to wind turbine noise and health effects.

This report presents the expertise and contributions of a panel of 10 experts from Canada and abroad, drawn from fields as diverse as engineering and medical science, including myself as Chair. I am deeply grateful for my colleagues on the Panel who contributed their substantial time and effort to ensure the depth and quality of this report. I would also like to extend my appreciation to the nine reviewers who assisted the Panel and whose efforts significantly improved the earlier version of the report.

Before this Panel was assembled, Health Canada had started, in 2012, a large cross-epidemiological study to measure potential health outcomes of exposure to sound from wind turbines in areas of Canada where wind energy is used. The preliminary results from this study became available as the Panel was concluding its deliberations and finalizing this report (November 2014). Although results from this study were not included in the body of evidence assessed by the Panel, they are summarized and discussed in this report. I would like to assure readers that Health Canada was not involved in or privy to the Panel's deliberations before publication, nor was the Department given access to drafts of this report.

Finally, the Panel is grateful for the support it received from the staff members of the Council of Canadian Academies who were assigned to this assessment. They are a dedicated and accomplished team of scholars and professionals, and it has been an honour and a pleasure to work with them.

I would like to extend my personal appreciation to the Panel members for their cooperation, rigour, patience, and devotion to the task.

Tee L. Guidotti
Chair, Expert Panel on Wind Turbine Noise and Human Health

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Report Review

This report was reviewed in draft form by the individuals listed below — a group of reviewers selected by the Council of Canadian Academies for their diverse perspectives, areas of expertise, and broad representation of academic, industrial, policy, and non-governmental organizations.

The reviewers assessed the objectivity and quality of the report. Their submissions — which will remain confidential — were considered in full by the Panel, and many of their suggestions were incorporated into the report. They were not asked to endorse the conclusions, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring Panel and the Council.

The Council wishes to thank the following individuals for their review of this report:

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The report review procedure was monitored on behalf of the Council's Board of Governors and Scientific Advisory Committee by **Susan A. McDaniel, FRSC,** Director, Prentice Institute; Canada Research Chair in Global Population and Life Course; Prentice Research Chair in Global Population and Economy; Professor of Sociology, University of Lethbridge (Lethbridge, AB). The role of the report review monitor is to ensure that the Panel gives full and fair consideration to the submissions of the report reviewers. The Board of the Council authorizes public release of an expert panel report only after the report review monitor confirms that the Council's report review requirements have been satisfied. The Council thanks Dr. McDaniel for her diligent contribution as report review monitor.

Janet W. Bax, Interim President
Council of Canadian Academies

Executive Summary

Demand for renewable energy, including wind power, is expected to continue to grow both in Canada and globally for the foreseeable future. The wind energy sector in Canada has grown at an ever-increasing pace since the 1990s, and Canada is now the fifth-largest market in the world for the installation of new wind turbines. As the sector grows, the wind turbines being installed are getting more powerful. The first megawatt-scale turbines were installed in Canada in 2004, with 3 megawatt models arriving in 2008; larger models up to 7.5 megawatt are currently being tested internationally. To produce this power, turbines have also increased in size. As wind turbines become a more common feature of the Canadian landscape, this new source of environmental sound has raised concerns about potential health effects on nearby residents.

Determining whether wind power causes adverse health effects in people is therefore important so that all Canadians can equitably share in the benefits of this technology.

THE CHARGE TO THE PANEL

In response to growing public concern about the potential health effects of wind turbine noise, the Government of Canada, through the Minister of Health (the Sponsor), asked the Council of Canadian Academies (the Council) to conduct an assessment of the question:

Is there evidence to support a causal association between exposure to wind turbine noise and the development of adverse health effects?

The Charge also includes the following sub-questions:

- *Are there knowledge gaps in the scientific and technological areas that need to be addressed in order to fully assess possible health impacts from wind turbine noise?*
- *Is the potential risk to human health sufficiently plausible to justify further research into the association between wind turbine noise exposure and the development of adverse health effects?*
- *How does Canada compare internationally with respect to prevalence and nature of reported adverse health effects among populations living in the vicinity of commercial wind turbine establishments?*
- *Are there engineering technologies and/or other best practices in other jurisdictions that might be contemplated in Canada as measures that may minimize adverse community response towards wind turbine noise?*

The Panel defined *health* in a way that is consistent with the World Health Organization's concept of health: "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO, 1946). The Panel interpreted *noise* to include both objective measures of acoustic signals in the environment (*sound*), as well as subjective perceptions of sound sensations that are unwanted by the listener (*noise*). As there are a variety of wind turbines available worldwide, with differing sound characteristics, the Panel focused specifically on the type that constitutes almost all of the installed turbines in Canada: modern, three-bladed, tower-mounted, utility-scale (500 kilowatt capacity or more), upwind, horizontal-axis wind turbines that were land-based.

THE PANEL'S APPROACH

To respond to the Charge, the Panel used an evidence-based approach to identify and review relevant research. First, the Panel identified more than 30 symptoms and health outcomes that have been attributed to exposure to wind turbine noise, based on a broad survey of peer-reviewed and grey literature, web pages, and legal decisions.

Empirical evidence related to any associations between these health outcomes and exposure to wind turbine noise was then collected from several sources, including peer-reviewed journal articles, conference papers, and grey literature. More than 300 publications were found through a comprehensive search, and these were narrowed down to 38 relevant studies related to the health effects of wind turbine noise. The body of evidence concerning each health outcome was appraised and assessed according to Bradford Hill's guidelines for causation, and summarized using standard terms adopted from the International Agency for Research on Cancer (IARC). The major steps of the Panel's approach are illustrated in Figure 1.

KEY FINDINGS

Based on its expertise and review of empirical research, the Panel made findings in the following areas:

- Acoustic characteristics of wind turbine noise;
- Evidence of causal relationships between exposure to wind turbine noise and adverse health effects;
- Knowledge gaps and further research; and
- Promising practices to reduce adverse community response.

Other aspects of the Charge, such as the prevalence of adverse health outcomes in Canada, could not be answered because of a lack of data.

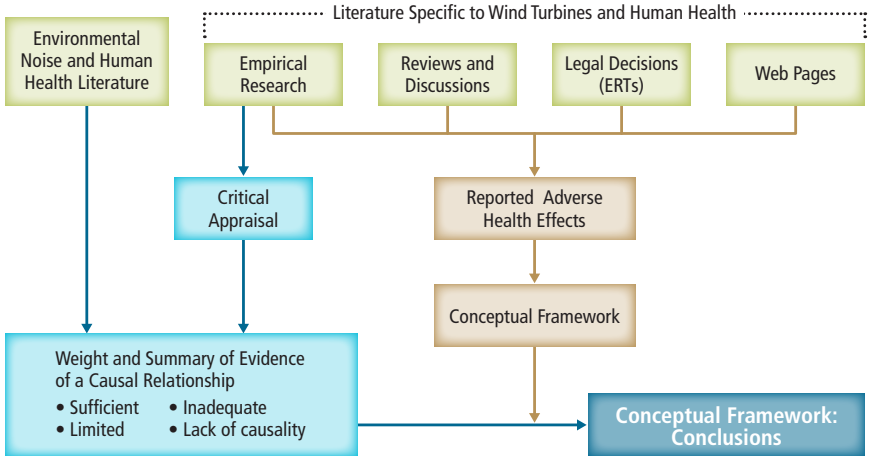

Figure 1

Evidence Assessment Process

Brown lines show information used in defining potential health outcomes and building a model of pathogenic mechanisms; blue lines show the literature review process with reference to causal associations between wind turbine noise and each potential health effect.

ACOUSTIC CHARACTERISTICS OF WIND TURBINE NOISE

1. Sound from wind turbines is complex and variable

Like sound from any source, wind turbine noise can be described by frequency components (which determine pitch), sound pressure levels (which determine *loudness*), and the way both of these change over time. Sound from wind turbines is highly complex and variable, but has some characteristics that are similar to other sources of community noise, such as road and airport traffic noise:

- Sound from wind turbines is *broadband*, composed of sound over a broad range of frequencies.
- The overall sound pressure levels outdoors vary greatly depending on distance, wind speed, and transmission from the source to the receiver.
- However, higher frequencies tend to be reduced indoors and with increasing distance, leading to an emphasis on lower frequencies.
- It is amplitude modulated, with sound levels changing over time.

Wind turbines also emit sound with the following characteristics, which are less common than other sources of community noise:

- Sounds from wind turbines may extend down to the infrasonic range and, in some cases, may include peaks or tonal components at low frequencies.

- Sound emissions from a wind turbine increase with greater wind speed at the height of the blades, up to the turbine's *rated wind speed* (speed at which it generates maximum power), above which sound does not increase.
- Sound from wind turbines can exhibit periodic *amplitude modulation*, often described as a "swishing" or "thumping" sound. The causes and consequences of this periodic amplitude modulation are areas of ongoing research, as wind turbine designers and manufacturers seek ways to reduce or mitigate it.

Most sound from wind turbines is produced by interactions between the surface of the blade and the air flowing over it (aerodynamic processes), which is strongest near — but not at — the blade tips. Mechanical noise from the physical movements of the gearbox, generator, and other components produces low-frequency tones in some cases.

2. Standard methods of measuring sound may not capture the low-frequency sound and amplitude modulation characteristic of wind turbine noise

Measurement of sound for health surveillance and research uses standard methods. The most commonly used methods include A-weighting, which emphasizes the frequencies according to human hearing sensitivity, and de-emphasizes low and very high frequencies. Although A-weighted measurement is an essential method, it may fail to capture the low-frequency components of wind turbine sound. In addition, measurement is often averaged over time (L_{eq}), which does not convey changes in sound pressure levels occurring in short periods (for example, within a second). Time-averaged measurement may thus fail to capture amplitude modulation.

A-weighted measurements are an important first step in determining people's exposure to audible sound in most cases, but more detailed measurements may be necessary in order for researchers to fully investigate the potential health impact of specific sources of wind turbine noise. The metrics of sound exposure most relevant to potential health outcomes are not completely understood, however, and remain an important area for further research.

WIND TURBINE NOISE AND ADVERSE HEALTH EFFECTS

The relevant empirical evidence was reviewed and weighted in order to determine the strength of evidence for a causal link between wind turbine noise and each potential adverse health effect.

3. The evidence is sufficient to establish a causal relationship between exposure to wind turbine noise and *annoyance*

The evidence consistently shows a positive relationship between outdoor wind turbine noise levels and the proportion of people who report high levels of annoyance. However, many factors can modify the strength of this relationship, such as a person's attitudes toward wind turbines and any economic benefits the person derives from them. As well, visual and noise effects of wind turbines are difficult to isolate from each other. The current state of the evidence does not allow for a definite conclusion about whether annoyance is caused by exposure to wind turbine noise alone, or whether factors such as visual impacts and personal attitudes modify the noise-annoyance relation — and to what extent, since the studies completed to date do not measure these factors independently of each other. It is also unclear which sound characteristics contribute to long-term chronic annoyance, although low-frequency components and periodic amplitude modulation have been investigated as likely candidates.

4. There is limited evidence to establish a causal relationship between exposure to wind turbine noise and *sleep disturbance*

The available evidence suggests that a direct causal relationship or an indirect (via annoyance) relationship between exposure to wind turbine noise and sleep disturbance might exist. While sleep disruption has been investigated in several studies, the resulting evidence base is smaller than that which examines the relationship between wind turbine noise and annoyance.

5. The evidence suggests a lack of causality between exposure to wind turbine noise and *hearing loss*

There is convincing evidence that exposure to wind turbine noise at typical levels associated with regulated noise limits and setbacks (distance from structures) does not cause loss of hearing, even over a lifetime of exposure.

6. The Panel found inadequate evidence of a direct causal relationship between exposure to wind turbine noise and *stress*, although stress has been linked to other sources of community noise

Available evidence suggests that a direct or indirect mechanism between exposure to wind turbine noise and stress might exist, similar to the finding for sleep disturbance, but the evidence lacks methodological and statistical strength. *Stress* has been identified as a risk factor for a number of other diseases, such as cardiovascular diseases, in the context of long-term exposure to community noise from other sources, such as road, rail, and air traffic. The current evidence related to exposure to wind turbine noise and stress is inconsistent, however.

7. For *all other health effects* considered (fatigue, tinnitus, vertigo, nausea, dizziness, cardiovascular diseases, diabetes, etc.), the evidence was inadequate to come to any conclusion about the presence or absence of a causal relationship with exposure to wind turbine noise

Hypertension and other cardiovascular diseases, diabetes, tinnitus, cognitive or task performance, psychological health, and health-related quality of life have all been the subject of empirical, population-based, wind-turbine noise studies. The evidence, however, was inconsistent or the studies had methodological limitations preventing the determination of a causal relationship between these effects and exposure to wind turbine noise. None of the other health effects considered have been the subject of a population-level study or experiments in the context of wind turbine noise. Therefore, the evidence for a causal association is largely lacking for these other effects.

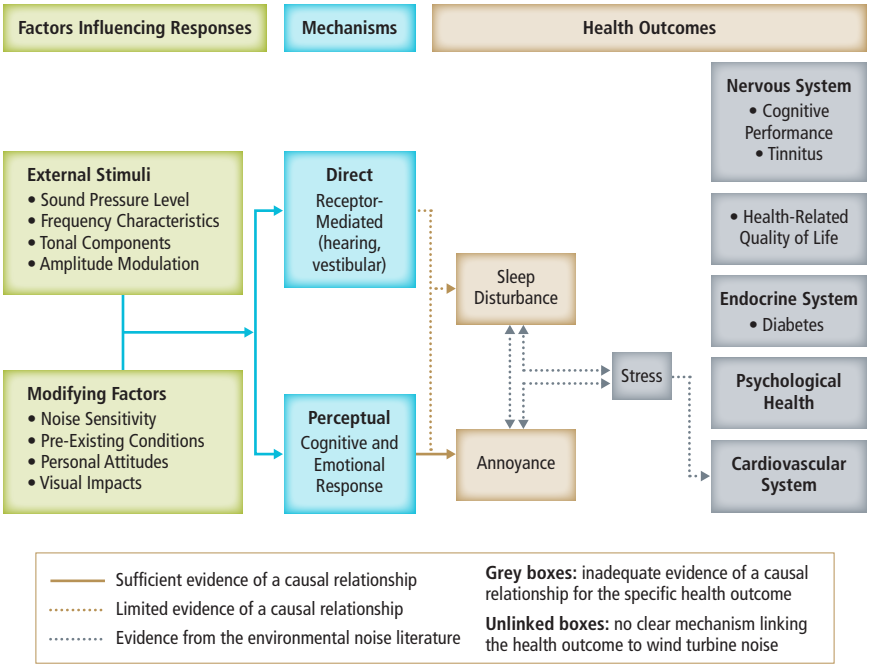

Figure 2

Summary of Evidence for Causal Pathways Between Exposure to Wind Turbine Noise and Adverse Health Effects

Conclusions about causal relationships are therefore lacking for most of the health effects postulated in a wide variety of sources reviewed by the Panel, mainly as a result of lack of evidence or problems with the quality of evidence. However, research on environmental noise has shown that annoyance can be a contributing factor or precursor to adverse health effects such as sleep disturbance, stress and cardiovascular diseases. The Panel thus developed a conceptual framework of pathways through which sound from wind turbines could plausibly result in health outcomes. Figure 2 shows this framework and summarizes the Panel's findings on the potential causal pathways between exposure to wind turbine noise and the development of adverse health effects, or the exacerbation of existing health conditions.

KNOWLEDGE GAPS AND FURTHER RESEARCH

8. Knowledge gaps prevent a full assessment of public health effects of wind turbine noise

The Panel identified specific knowledge gaps for each health condition studied, where specific types of evidence would help clarify the strength of associations, minimize bias, or eliminate possible confounding factors with respect to exposure to wind turbine noise. For example, it is unclear whether the possible pathway that could lead to sleep disturbance or stress is the direct result of exposure to wind turbine noise or of annoyance as a mediating factor.

Most existing epidemiological studies of wind turbine noise lack sufficient power to detect small changes in the risk of adverse health effects, or were designed in a way that could not rule out bias in responses or adequately control confounding factors. The Panel also identified an absence of longitudinal studies. The Panel stresses that there is a paucity of research on sensitive populations, such as children and infants and people affected by clinical conditions that may lead to an increased sensitivity to sound.

The use of adequate methods and procedures for measuring and modelling sound exposure from wind turbines, particularly indoors, would improve the quality of future studies on adverse health effects (see Key Finding 2).

9. Research on long-term exposure to wind turbine noise would provide a better understanding of the causal associations between wind turbine noise exposure and certain adverse health effects

Chronic annoyance and sleep disturbance have been linked to stress responses in studies of long-term exposure to other sources of noise, such as air and road traffic. Furthermore, these health effects are themselves risk factors for other diseases, such as cardiovascular diseases, which have previously been associated with long-term exposure to other sources of community noise. Given the

burden of cardiovascular diseases on society and Canada's health care system, further research on the long-term effects of exposure to wind turbine noise, in particular on stress and sleep disturbance, would provide more data to assess the health effects of wind turbine noise. Finally, the Panel stresses that the available evidence does not allow conclusions with regard to the prevalence of annoyance or other health effects within the population exposed to sound from wind turbines in Canada. Further research and surveillance would provide a better understanding of this prevalence, both in those exposed to wind turbine noise and in the general population.

PROMISING PRACTICES AND TECHNOLOGIES TO REDUCE ADVERSE COMMUNITY RESPONSE TO WIND TURBINE NOISE

10. Technological development is unlikely to resolve, in the short term, the current issues related to perceived adverse health effects of wind turbine noise

Wind turbine designs, modifications, and technology that could reduce sound emissions are currently being explored by wind turbine manufacturers. Ongoing technological development has contributed to lower sound emissions for turbines of a given size over the previous generation of turbines, with further improvements expected. Other factors such as power output favour larger turbines, however, which can offset overall reductions in sound emissions per kilowatt of electricity produced.

11. Impact assessments and community engagement provide communities with greater knowledge and control over wind energy projects and therefore help limit annoyance

Equity and fairness have been crucial for the acceptance of wind turbines in many communities, with perceived loss of social justice and disempowerment being significant barriers to acceptance in some cases. One important regulatory approach is to conduct a noise impact assessment of any proposed project; several Canadian provinces and other countries require such an assessment. In some of the international practices reviewed by the Panel, wind energy developers engaged in consultation and communication with local authorities and residents beginning at an early stage of project development, through all stages of implementation, and even after installation. Community engagement helps to inform and educate local residents, as well as involve them in a wind energy project with the goal of fostering social acceptance.

Wind turbines are a progressively familiar sight in Canada and contribute an increasing share of the electricity consumed in Canada. Concerns over the health effects of wind turbine noise have been expressed in many ways but rarely with

detailed, reproducible, and rigorous data sufficient to support a conclusion on either causation or magnitude of any potential health effect. The Panel's final report is an attempt to objectively and rigorously review empirical research on the causal link between wind turbine noise and adverse health effects, as well as potential solutions to noise-related issues contemplated elsewhere, all of which may help in addressing concerns about wind turbine noise in Canada. The report is intended not only as a tool to inform decision-making and academic research on the subject, but also to inform the continuing dialogue across Canada and internationally, and across many sectors, about wind turbine noise and adverse human health effects.