UNDERSTANDING THE EVIDENCE: WIND TURBINE NOISE

The Expert Panel on Wind Turbine Noise
and Human Health

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
180 Elgin Street, Suite 1401, Ottawa, ON, Canada K2P 2K3

Notice: The project that is the subject of this report was undertaken with the approval of the Board of Governors of the Council of Canadian Academies. Board members are drawn from the Royal Society of Canada (RSC), the Canadian Academy of Engineering (CAE), and the Canadian Academy of Health Sciences (CAHS), as well as from the general public. The members of the expert panel responsible for the report were selected by the Council for their special competencies and with regard for appropriate balance.

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.

Library and Archives Canada Cataloguing in Publication
Understanding the evidence : wind turbine noise / the Expert Panel on Wind Turbine Noise and Human Health. Includes bibliographical references. Electronic monograph in PDF format.

ISBN 978-1-926522-07-4 (pdf)

1. Wind turbines–Canada–Noise. 2. Wind turbines–Health aspects–Canada. 3. Wind turbines–Technological innovations. I. Council of Canadian Academies, issuing body II. Council of Canadian Academies.

Expert Panel on Wind Turbine Noise and Human Health, author

TJ828.U54 2015 621.4’5 C2015-901475-1

This report should be cited as: Council of Canadian Academies, 2015. *Understanding the Evidence: Wind Turbine Noise*. Ottawa (ON): The Expert Panel on Wind Turbine Noise and Human Health, Council of Canadian Academies.

Printed in Ottawa, Canada

Council of Canadian Academies
Conseil des académies canadiennes

Canada This assessment was made possible with the support of the Government of Canada.

The Council of Canadian Academies

Science Advice in the Public Interest

The Council of Canadian Academies (the Council) is an independent, not-for-profit organization that supports independent, science-based, authoritative expert assessments to inform public policy development in Canada. Led by a 12-member Board of Governors and advised by a 16-member Scientific Advisory Committee, the Council's work encompasses a broad definition of *science*, incorporating the natural, social, and health sciences as well as engineering and the humanities. Council assessments are conducted by independent, multidisciplinary panels of experts from across Canada and abroad. Assessments strive to identify emerging issues, gaps in knowledge, Canadian strengths, and international trends and practices. Upon completion, assessments provide government decision-makers, researchers, and stakeholders with high-quality information required to develop informed and innovative public policy.

All Council assessments undergo a formal report review and are published and made available to the public free of charge in English and French. Assessments can be referred to the Council by foundations, non-governmental organizations, the private sector, or any level of government.

The Council is also supported by its three founding Member Academies:

The Royal Society of Canada (RSC) is the senior national body of distinguished Canadian scholars, artists, and scientists. The primary objective of the RSC is to promote learning and research in the arts and sciences. The RSC consists of nearly 2,000 Fellows — men and women who are selected by their peers for outstanding contributions to the natural and social sciences, the arts, and the humanities. The RSC exists to recognize academic excellence, to advise governments and organizations, and to promote Canadian culture.

The Canadian Academy of Engineering (CAE) is the national institution through which Canada's most distinguished and experienced engineers provide strategic advice on matters of critical importance to Canada. The Academy is an independent, self-governing, and non-profit organization established in 1987. Fellows are nominated and elected by their peers in recognition of their distinguished achievements and career-long service to the engineering profession. Fellows of the Academy, who number approximately 600, are committed to ensuring that Canada's engineering expertise is applied to the benefit of all Canadians.

The Canadian Academy of Health Sciences (CAHS) recognizes individuals of great achievement in the academic health sciences in Canada. Founded in 2004, CAHS has approximately 400 Fellows and appoints new Fellows on an annual basis. The organization is managed by a voluntary Board of Directors and a Board Executive. The main function of CAHS is to provide timely, informed, and unbiased assessments of urgent issues affecting the health of Canadians. The Academy also monitors global health-related events to enhance Canada's state of readiness for the future, and provides a Canadian voice for health sciences internationally. CAHS provides a collective, authoritative, multidisciplinary voice on behalf of the health sciences community.

www.scienceadvice.ca
@scienceadvice

Expert Panel on Wind Turbine Noise and Human Health

Tee L. Guidotti (Chair), Fulbright Visiting Chair, Institute for Science, Society and Policy, University of Ottawa (Ottawa, ON)

Hugh W. Davies, Associate Professor, Occupational and Environmental Health Division, School of Population and Public Health, University of British Columbia (Vancouver, BC)

Yves Gagnon, Professor of Engineering, Université de Moncton (Edmundston, NB); Adjunct Professor, Mechanical Engineering, École de technologie supérieure (Montréal, QC)

Christian Giguère, Professor, Audiology and Speech-Language Pathology Program, School of Rehabilitation Sciences, University of Ottawa (Ottawa, ON)

Sheryl Grace, Associate Professor, Department of Aerospace and Mechanical Engineering, Boston University (Boston, MA)

Robert V. Harrison, Professor and Vice-Chair – Research, Department of Otolaryngology, Head and Neck Surgery; Professor, Department of Physiology, Institute of Biomaterials and Biomedical Engineering and Institute of Medical Science, University of Toronto; Senior Scientist, Program for Neuroscience and Mental Health, Hospital for Sick Children (Toronto, ON)

Brian Howe, President, HGC Engineering (Toronto, ON)

David A. Johnson, Professor, Department of Mechanical and Mechatronics Engineering, University of Waterloo (Waterloo, ON)

Kerstin Persson Waye, Professor, Occupational and Environmental Medicine, University of Gothenburg (Gothenburg, Sweden)

Jennifer D. Roberts, Assistant Professor, Occupational and Environmental Health Sciences, F. Edward Hébert School of Medicine, Department of Preventive Medicine and Biometrics (Division of Occupational and Environmental Health Sciences), Uniformed Services University of the Health Sciences (Bethesda, MD)

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

Project Staff of the Council of Canadian Academies

Assessment Team:	Emmanuel Mongin, Associate Program Director
	Stefan Jungcurt, Research Associate
	Jonathan Whiteley, Research Associate
	Tess Lin, Program Coordinator
	Weronika Zych, Program Coordinator
	Naomi Shuman, Intern
With assistance from:	Leela Steiner, Consultant
	Carolyn Brown, Editor
	Jody Cooper, Copyeditor
	Accurate Design & Communication Inc., Report Design

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:

Prudence Allen, Director and Associate Professor, National Centre for Audiology, Western University (London, ON)

François Benoit, Scientific and Administrative Lead, National Collaboration Centre for Healthy Public Policy, Institut national de santé publique du Québec (Montréal, QC)

Arline L. Bronzaft, Consultant and Professor Emerita, City University of New York (New York, NY)

Jeffrey M. Ellenbogen, Assistant Professor of Neurology, Johns Hopkins University (Baltimore, MD)

Wendy Heiger-Bernays, Associate Professor of Environmental Health, Boston University School of Public Health (Boston, MA)

Stefan Oerlemans, Senior Key Expert Aeroacoustics, Siemens Wind Power (Brande, Denmark)

Stéphane Perron, Physician and Clinical Adjunct Professor, Montréal Public Health Department, Université de Montréal and McGill University (Montréal, QC)

Bo Søndergaard, Senior Consultant, Department of Acoustics, Grontmij (Aarhus, Denmark)

Jian Wang, Full Professor, School of Human Communication Disorders, Dalhousie University (Halifax, NS)

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

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.

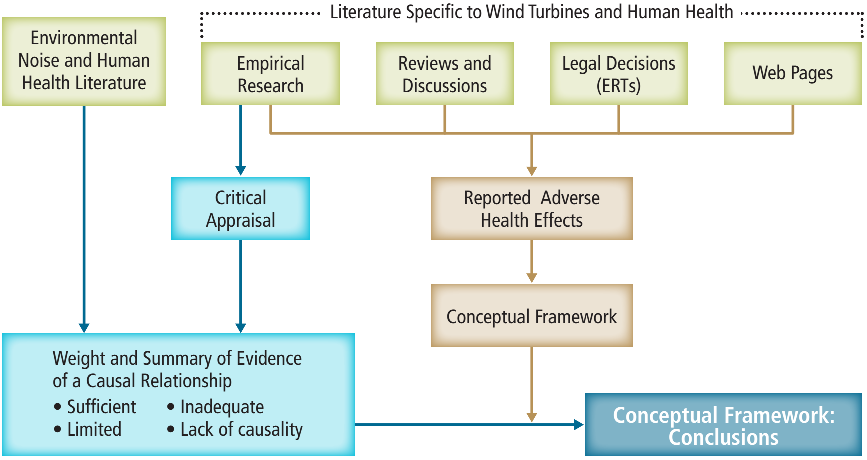


Figure 1

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.

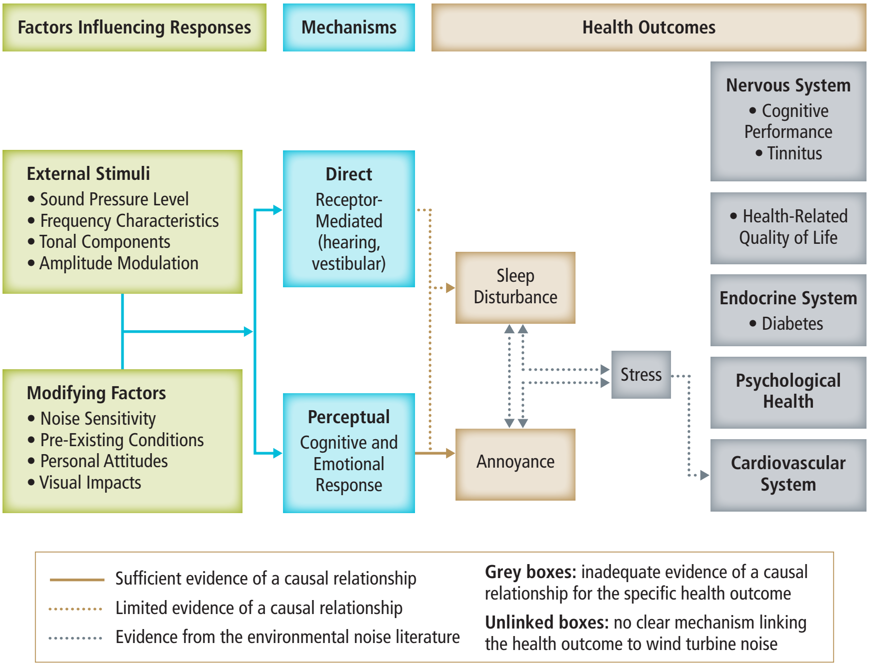


Figure 2

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.

Table of Contents

1

Introduction

- Charge to the Panel
- Interpreting the Charge
- Health Canada Wind Turbine Noise and Health Study
- Organization of the Report

1 Introduction

Wind energy is increasingly seen as a viable source of renewable energy that does not emit greenhouse gases during operation and has a limited environmental footprint. In 2013, the total wind energy capacity installed worldwide approached 320 gigawatts (GW), with more than 35 GW of new capacity installed in that year alone (GWEC, 2014). In Canada, the total wind energy capacity installed was 9.2 GW at the end of 2014, distributed over 206 wind projects with more than 5,114 individual turbines (CanWEA, 2014). Renewable energy demand and wind energy capacity are expected to continue to increase for the foreseeable future.

Wind energy capacity has increased in Canada since the 1990s, but in recent years a growing number of individuals and organizations have expressed concern that sound (see Box 1.1) emitted by wind turbines near people's homes may represent a risk to public health. Wind turbines are often located in rural areas with low levels of background noise, making the noise of wind turbines noticeable to some nearby residents. Sound from wind turbines is characterized by:

- periodic amplitude modulation ("swishing" or "thumping" characteristics);
- unpredictable changes in sound levels depending on wind at the height of the blades;
- increased sound because of higher wind velocity due to increasing height above the ground; and
- a broad spectrum of frequencies.

Box 1.1
On the Use of Terms *Noise* and *Sound* in this Report

In the context of this report, *sound** and *noise* are used largely interchangeably, without affecting the interpretation of the meaning. However, where the Panel describes a simple acoustic signal (e.g., in defining the properties of acoustics, or an acoustic signal before it is cognitively processed), the neutral term *sound* is used. Where the Panel describes a *sound* that is cognitively processed and that may be perceived as unpleasant or unwanted, the term *noise* is used.

---

* Italicized words and terms are defined in the Glossary.

1.1 CHARGE TO THE PANEL

In May 2012, 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 Sponsor also submitted 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?*

To address these questions, the Council convened the Expert Panel on Wind Turbine Noise and Human Health (the Panel), which included 10 Canadian and international experts from relevant medical and engineering fields. This report presents the results of their deliberations and analysis.

1.2 INTERPRETING THE CHARGE

A wide range of health impacts have been attributed to sound from wind turbines, involving not only effects consistent with a narrow definition of health, but also aspects of well-being and quality of life. The Panel therefore decided to take a broad approach that would include the breadth of concerns that have been raised by the public.

The Panel thus decided to guide its deliberations using the World Health Organization's concept of *health* as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO, 1946).

This understanding is also reflected in the approach taken by Health Canada, which states that health is not an objective concept but varies among individuals and societies (Health Canada, 2011). Health is therefore a concept that is open to interpretation and discussion. The Panel recognized that health outcomes include clinical symptoms and other outcomes that harm well-being, such as annoyance or sleep disturbance.

This report considers both the incidence of health impacts following exposure to sound from wind turbines, as well as the exacerbation of pre-existing conditions. In many cases, the development of new health conditions post-exposure is determined in part by a person's overall health condition before exposure, particularly conditions that might lead to increased sensitivity to sound or noise. First, the Panel developed a broad list of all health conditions, symptoms, and other outcomes that have been attributed to sound from wind turbines, based on a survey of sources that includes scientific literature, grey literature,[1] media reports, and legal documents, as well as self-published sources such as websites and blogs. In a subsequent step, the Panel conducted a structured review of a range of sources to assess the existing evidence on the relationship between exposure to sound from wind turbines and the conditions identified in step one. If published research had not yet considered a particular health outcome in relation to wind turbine noise, or if available evidence was limited, the Panel also considered analogous research on the health conditions with respect to other sources of environmental noise. The assessment methodology applied several concepts from evidence-based and evidence-informed public health: A structured definition of the problem, systematic search of the literature, and critical appraisal of the literature, as well as the use of Bradford Hill guidelines. Those guidelines are commonly used in weighing a body of evidence to assess causal relationships between an exposure to a potential hazard (e.g., sound from wind turbines) and health outcomes (Bradford Hill, 1965).

The scope of the assessment was limited to health impacts that are thought to be caused by, or associated with, exposure to sound emitted by wind turbines. This focus excluded other potential sources of health impacts from these turbines, such as shadow flicker, ground vibrations, and occupational health risks for service personnel. The Panel also focused on modern upwind utility-scale wind turbines, which are the most common type used in the wind energy industry in Canada and around the world.

---

[1] *Grey literature* refers to documents in electronic and print formats that are "not controlled by commercial publishing; i.e., where publishing is not the primary activity of the producing body" (GreyNet International, 2014).

There have been several reviews of health effects of wind turbine noise over the past 10 years. This report, however, differs from previous reviews in the following ways:

- a Canadian context and focus, with international comparisons where possible;
- a review of claimed health outcomes attributed to wind turbine noise drawn from a variety of sources (from peer-reviewed primary studies to web pages);
- the use of a broad evidence base, including peer-reviewed literature but also grey literature, a book, a graduate thesis and other sources of direct evidence related to utility-scale wind turbines, as well as broader literature on biological effects of noise;
- identification of knowledge gaps and areas of research that are justifiable because of the plausibility of potential adverse health effects; and
- a consideration of promising practices to minimize adverse responses to wind turbine noise.

1.3 HEALTH CANADA WIND TURBINE NOISE AND HEALTH STUDY

The Sponsor of this assessment, Health Canada, also conducted a separate study of wind turbine noise and health, begun in July 2012. Preliminary results of this epidemiological study were released in November 2014. As the Panel had retrieved the primary evidence used to assess the health effects of wind turbine noise in August 2014 (see Appendix B) and was finalizing this report when the preliminary study results from Health Canada were released, the Panel was unable to incorporate those results in its deliberations. However, the results of the Health Canada study are presented in Box 7.1.

Like all Council assessments, this assessment was researched and written independently by the Panel in response to the Sponsor's questions. The Sponsor was not involved in Panel deliberations or given access to drafts of the report.

1.4 ORGANIZATION OF THE REPORT

Chapter 2 provides an overview of the Canadian and international contexts of wind energy production and future growth in Canada. It introduces the general framework for regulation of wind turbines in Canada. Chapter 3 introduces key concepts and background information concerning acoustics and sound measurement, as they apply to the emission and transmission of sound from wind turbines. Chapter 4 clarifies the general principles of sound transduction within the ear as well as other possible pathways of sound perception and how it may vary among individuals. Chapter 5 explains the process used for the evaluation of adverse health effects. Chapter 6 provides a detailed overview of the scientific evidence available to assess causation between sound from wind turbines and the health outcomes previously described. Chapter 7 summarizes the findings from Chapter 6 and describes knowledge gaps that pose challenges to understanding adverse health effects of wind turbine noise. Chapter 8 lists promising technologies or practices identified in other jurisdictions that might be considered in Canada to minimize adverse community response towards wind turbine noise. Chapter 9 summarizes the main findings of the report in response to the Charge.

2

Wind Energy Context

- Wind Turbine Design
- Canadian and International Contexts
- Health Surveillance
- Noise Limits and Setbacks
- Chapter Summary

2 Wind Energy Context

Key Findings

- Canada ranked fifth in the world for new wind energy capacity installed during 2013, and ninth in the world in terms of total installed wind energy capacity at the end of 2013.
- Most of Canada's installed wind energy capacity is located in Ontario, Quebec, and Alberta.
- The pace of wind energy development has varied among Canadian provinces. Wind energy capacity in Alberta has grown slowly but steadily since 1993, driven by market forces and green energy marketing programs by utilities, while capacity in Ontario has expanded rapidly since 2006 as a result of provincial government incentives. Capacity in Quebec has grown steadily since 1999 but accelerated dramatically in 2013.
- Wind energy development in Canada is subject to regulations at the federal, provincial, and municipal levels, and risks associated with wind turbine noise are managed differently in different jurisdictions. There are no national standards for setbacks or noise limits in Canada, although the noise limits across Canadian jurisdictions are comparable to those used internationally.

It is important to have some understanding about the development of wind energy in Canada throughout any discussion about possible adverse health effects created by this technology. While Canada has long had both experimental and operational wind energy installations, these have grown rapidly in recent years, with wind turbines becoming a familiar sight on the Canadian landscape. As with many new technologies, the growth of wind energy has raised regulatory and social issues that need to be addressed if Canadians are to rely increasingly on this source of energy.

Currently, the most accurate source of information on wind energy capacity, technology, and development is the wind energy industry itself. The Canadian Wind Energy Association (CanWEA) is a national non-profit association of wind turbine owners, operators, manufacturers, and service providers to the industry. CanWEA maintains a database of wind energy projects in Canada, including the number of wind turbines and their power ratings. These data are collected directly from members and reported to international organizations such as the Global Wind Energy Council (GWEC). The Panel used these data, in combination with other published analyses where available, to describe the wind energy sector in Canada.

Most wind energy projects in Canada are located in rural communities, yet most of the electricity they produce feeds demand in larger urban centres. Individual wind turbines occupy relatively little land area, requiring only enough land for the foundation at the base of the turbine and for an access road. However, turbines are tall structures, often exceeding a height of 80 metres at the hub (see Chapter 3), and can have a visual and auditory presence in an otherwise quiet rural landscape. Wind turbines usually do not prevent other uses of the surrounding land, such as agriculture, hiking, hunting, or highways, provided these uses are not negatively affected by wind turbine operation. However, the construction phase may cause short-term disruptions. Some rural landowners can supplement their income by leasing a small portion of land to a wind turbine operator. Wind project operators argue that, because wind turbines require regular maintenance and monitoring, they create technical jobs in the communities where they are installed.

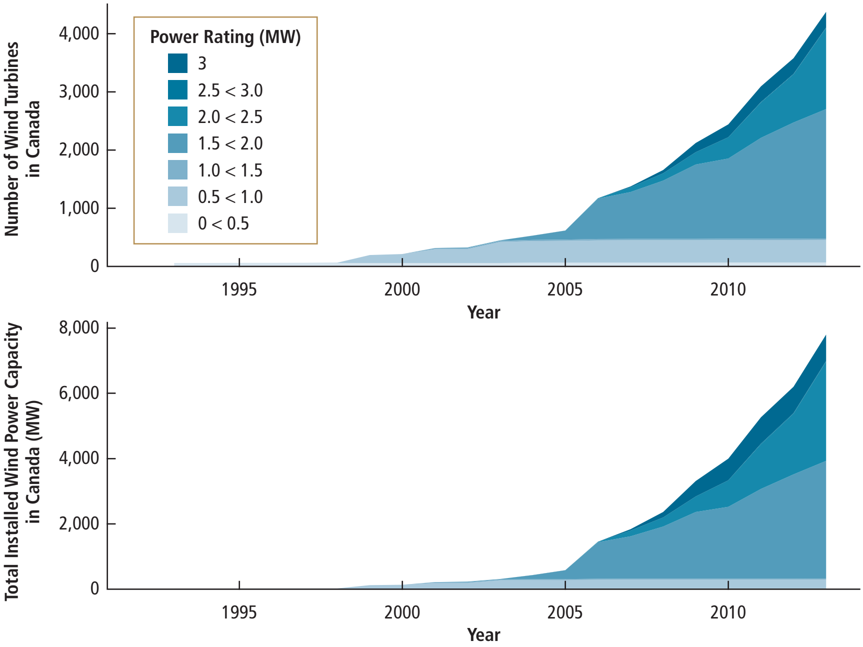
2.1 WIND TURBINE DESIGN

Devices capable of converting the kinetic energy of the wind into electrical energy are referred to as *wind turbines*. Wind turbines are classified by various design characteristics, including axis of rotation, position of the blades (rotor orientation), number of blades, rotor control, and alignment with the wind (see Manwell *et al.*, 2010).

In this report, a wind turbine refers to a device that is:

- **Modern:** Able to convert kinetic energy in wind to electricity by mechanically turning blades mounted on a rotor connected to a generator. Modern wind turbines almost always have three blades.
- **Horizontal-axis wind turbine (HAWT):** Having a main axis of rotation parallel to the ground (like the axle of the wheels on a truck).
- **Upwind:** Having blades that rotate in front (upwind) of a supporting tower.
- **Utility-scale:** Connected to an electrical grid, and having a power rating of at least 500 kilowatts (kW). Most utility-scale wind turbines currently sold worldwide are rated at 1.5 megawatts (MW) or more, and designs are expected to continue to increase in capacity and size. Some authors have described these as “industrial wind turbines.”
- **Onshore:** Located on land.

These are the characteristics of most modern wind turbines used in the wind energy industry worldwide (Manwell *et al.*, 2010) and describe the vast majority of wind turbines installed for utility-scale electricity generation in Canada. Figure 2.1 shows that all but a few turbines installed in Canada have a rated power of at least 500 kW, while growth in capacity since 2005 has been from turbines with increasingly larger power ratings (at least 2 MW). Note that most utility-scale wind turbines sold today have a power rating of at least 1.5 MW, but several important studies of health effects of wind turbine noise are in the context of older and slightly smaller turbines, all of which have a power rating of at least 500 kW.



Data Source: CanWEA, personal communication, 2014

Figure 2.1

Number of Turbines and Total Installed Wind Power Capacity in Canada, by Power Rating, 1992–2013

The vast majority of wind turbines (top panel) and installed wind power capacity (bottom panel) in Canada consist of turbines with a rated power of 500 kW or more. Most growth in capacity since 2005 has come from the installation of larger turbines with a rated power of at least 2 MW.

This report will not consider wind turbines that have a vertical axis of rotation, have a downwind design, are located offshore, or are designed to provide power to a single dwelling (residential scale). Canada had no offshore *wind energy facilities* at the time of this report writing. Other designs are not considered because they are not used for utility-scale electricity generation, and some have very different acoustical properties (Wagner *et al.*, 1996; Oerlemans, 2011). Downwind turbines, for example, are known to produce high levels of *infrasound* and *low-frequency sound*, which is one reason why they have not become an industry standard (Jakobsen, 2005; van den Berg, 2011). This report therefore discusses the technologies currently used in Canada and technologies likely to be used in the future.

The major components of a modern utility-scale wind turbine are illustrated in Figure 2.2. The shape of the blades creates aerodynamic lift and drag when wind flows around them, much like the wing of an airplane. On a wind turbine, however, these forces are used to generate torque, which causes the blades to spin the rotor on its axis, creating mechanical power that is converted into electricity in a generator housed in the nacelle.

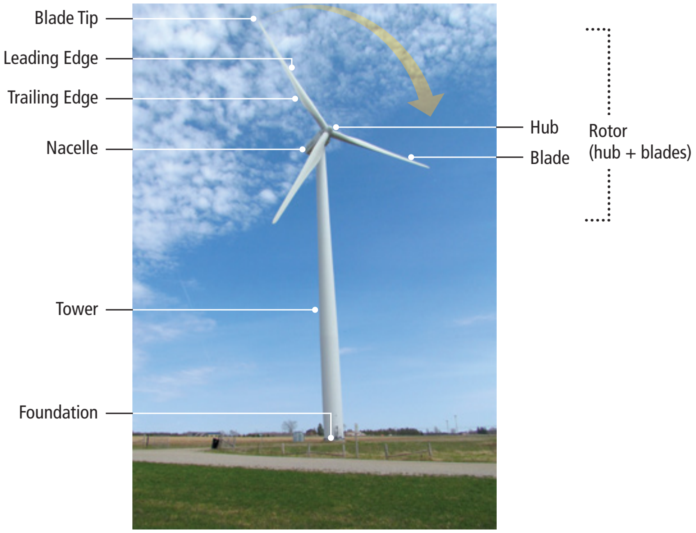


Figure 2.2

Components of a Typical Modern Utility-Scale Wind Turbine

The major components typical of a modern wind turbine, as discussed in this report, are shown here in this image of a General Electric 1.5 MW wind turbine at the Melancthon Wind Facility near Shelburne, Ontario. The rotor consists of three blades mounted on a central hub, which rotates as a single unit in response to wind flow over the blades. Each blade has a leading edge and a trailing edge behind. The hub connects the rotor to a generator and other mechanical components inside the nacelle, which converts the mechanical energy of the rotor movements into electrical energy. The nacelle and rotor are mounted on top of the tower, which carries cables that connect the generator to an electricity grid. The entire turbine is anchored by the foundation.

Wind turbines are often described in terms of rotor diameter (the diameter of the swept area of the blades, roughly equal to twice the blade length plus the hub diameter), and hub height (the height of the hub on the tower). Hub height is usually 1 to 1.5 times the rotor diameter (Manwell *et al.*, 2010). For example, one of the most common wind turbines installed in Canada is the GE 1.5s, manufactured by General Electric. It has a rotor diameter of 70.5 metres (231 ft.), a hub height ranging from 65 to 100 metres (213 to 328 ft.), weighs 157 tonnes, and is capable of producing up to 1.5 MW of electricity in 12 metres per second (m/s) winds (GE, 2004). The largest wind turbine currently being manufactured for onshore use, the Enercon E-126, has a hub height of 135 metres (443 ft.), a rotor diameter of 126 metres (413 ft.), and a rated power of 7.5 MW — it is not currently installed in Canada. Technical specifications of some commonly used wind turbines are listed in Table 2.1. These are examples for illustrative purposes only, and the table is not intended to present a comprehensive list, nor an endorsement of available wind turbine models.

Table 2.1

Examples of Utility-Scale Wind Turbines and Their Specifications

Manufacturer and Model	Rotor Diameter (m)	Hub Height (m)	Rated Power (kW)	Maximum Sound Power Level dB(A) *	Cut-In Wind Speed (m/s)	Rated Wind Speed (m/s)	Cut-Out Wind Speed (m/s)	% of Canadian Capacity (end of 2013)
Legacy — In use in Canada, but no longer sold								
GE 1.5s	70	65–100	1,500	NA	4.0	12	22	11.4
Vestas V80	80	60–100	1,800	105.0	4.0	15	25	7.0
Vestas V47	47	40–55	660	102.0	4.0	15	25	1.5
Currently sold and used in Canada								
Enercon E-82 E2	82	78–138	2,000	NA	2.0	12.5	34	9.9
Vestas V90-3.0	90	65–105	3,000	109.4	3.5	15	25	7.8
Vestas V90-1.8	90	80–105	1,800	NA	4.0	12	25	7.2
GE 1.5sle	77	65–80	1,500	NA	3.5	12	25	6.8
Siemens SWT-2.3-101	101	80	2,300	NA	3–4	12–13	25	5.8
Senvion MM92	92.5	68–100	2,050	103.2	3	12	24	3.4
Enercon E-70	71	57–113	2,300	104.5	2.5	15	34	3.3

Manufacturer and Model	Rotor Diameter (m)	Hub Height (m)	Rated Power (kW)	Maximum Sound Power Level dB(A) *	Cut-In Wind Speed (m/s)	Rated Wind Speed (m/s)	Cut-Out Wind Speed (m/s)	% of Canadian Capacity (end of 2013)
DeWind D9.2	93	80–100	2,000	NA	4.5	12	25	0.1
Global — Not in use in Canada, but sold worldwide								
Senvion 6.2M126	126	100–117	6,150	NA	3.5	14.5	25	0
Enercon E-126	127	135	7,580	NA	3.0	16.5	34	0
Vestas V164 **	164	site specific	8,000	NA	4.0	13.5	25	0

Data Source: van den Berg *et al.*, 2008; Bauer, n.d.; CanWEA, personal communication, 2014

The models listed are examples of common utility-scale wind turbines in use in Canada and/or in other countries, and do not account for 100% of Canadian capacity; this list is not exhaustive. All models and technical specifications are the same for those used in other countries (wind turbines are also sold in a global marketplace).

* The sound power level of a wind turbine, measured in decibels (dB), varies with wind speed: this column shows the highest estimated sound power level for wind speeds between 3 and 11 m/s at 10 m height in a neutral atmosphere and a standard ground roughness (van den Berg *et al.*, 2008). Note that these are *sound power levels*, which estimate total sound emission by the wind turbine; the *sound pressure level* (sound immission at a receiver) is a function of the power level, distance, and other factors (see Section 3.1.1).

** Designed exclusively for offshore use.

For comparison, a Canadian football field (CFL) is 100.6 metres (110 yards) between goal lines and 59.4 metres (65 yards) wide. Smaller wind turbines are about as tall as a football field is long, when measured from the base of the tower to the top of the spinning blades (hub height plus half the rotor diameter). Most turbines, however, would be too large to fit inside a football field if lying flat on the ground, and, for some larger turbines, the tower alone is about as tall as a football field is long. A single blade from most wind turbines would cover the width of a football field, while the largest would exceed this width.

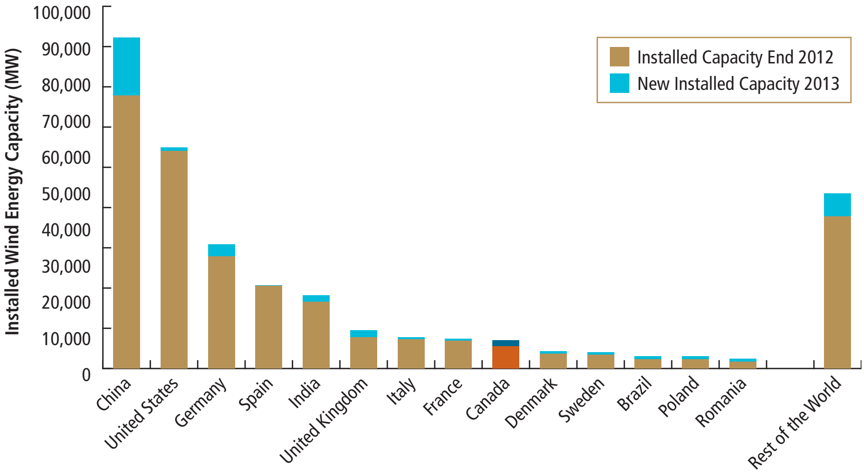
All wind turbines require a minimum wind speed at hub height to generate power, called the *cut-in wind speed*, and have a maximum *cut-out wind speed*; between these two wind speeds, determined on the basis of engineering and design constraints, the turbine will deliver power safely. When the wind speed exceeds the cut-out rating, control systems adjust the pitch of the blades so that the rotor stops turning, and power production is cut off to prevent damage to the turbine. The maximum power output of the generator is the *rated power* or *nameplate capacity* (in kW or MW), which occurs at the *rated wind speed* at hub height. For example, the rated power of the GE 1.5s wind turbine is 1.5 MW, which is the power produced at a rated wind speed of 12 m/s at hub height (see Table 2.1).

Wind slows down near surfaces, due to friction, creating a steep gradient of wind speed between the ground and increasing height, an effect called wind shear (Manwell *et al.*, 2010). Taller turbines can take advantage of higher wind speeds farther above the ground to produce greater amounts of energy. Taller turbines can also accommodate larger blades. The use of fewer turbines with larger rotor diameters can produce more energy per unit of land area and is generally more cost-effective than a larger number of smaller turbines (EWEA, 2005). These factors create incentives to build increasingly larger and taller turbines, which are limited in size primarily by available construction and transportation technologies.

2.2 CANADIAN AND INTERNATIONAL CONTEXTS

Wind turbines are expected to have an operating life of 20 to 25 years, and current capacity in many countries represents many years of cumulative investment. Five countries accounted for 72% of the global wind energy capacity as of the end of 2013: China, United States, Germany, Spain, and India (GWEC, 2014) (Figure 2.3). Canada ranked ninth in the world in terms of installed capacity, contributing around 2.5% of global wind energy production. However, Canada ranked fifth in terms of new capacity installed in 2013, making it one of the fastest-growing markets. Only China, Germany, United Kingdom, and India added more wind energy capacity than Canada during 2013.

Canada had 9,219 MW of installed wind energy capacity as of the end of 2014, which meets about 4% of Canada's electricity demand (CanWEA, 2014). CanWEA (2008) argues that wind energy could satisfy 20% of Canada's electricity demand by 2025. This would require the installation of about 50,000 MW of additional capacity (roughly six times the current capacity), occupying a total land area about the size of Prince Edward Island, but distributed over 450 locations across Canada. However, the National Energy Board — the independent federal agency that regulates oil, gas, and electric industry development in Canada — has forecast that total wind capacity will likely reach only 16,000 MW by 2035 (NEB, 2013). Many provinces in Canada have targets for wind power or for renewable energy including wind.



Data Source: GWEC, 2014

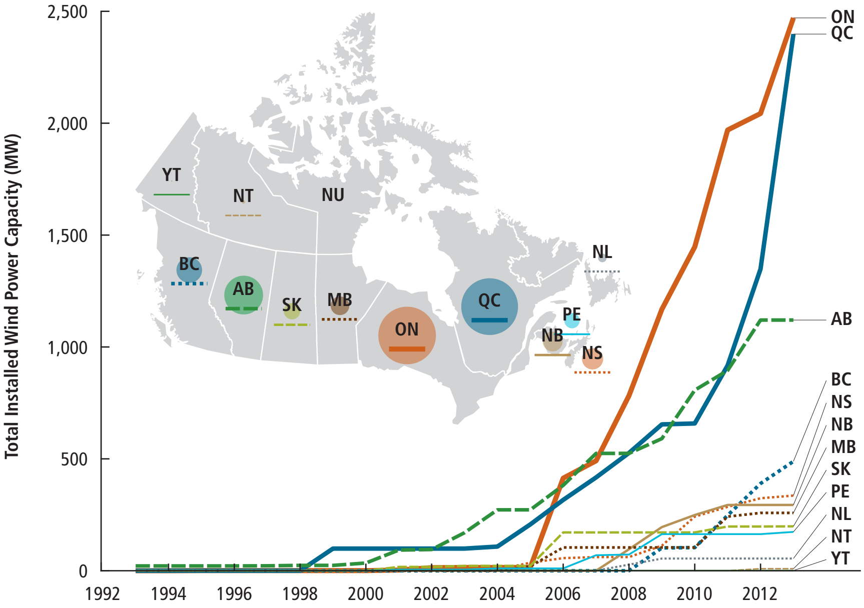
Figure 2.3

Total Installed Wind Energy Capacity Worldwide, 2013

The total height of the bars indicates the cumulative installed capacity for wind energy at the end of 2013, with the blue section at the top of each bar indicating the amount of wind energy capacity installed (and coming online) during 2013. Canada ranks ninth in the world in terms of total wind energy capacity in 2013, but was fifth in terms of newly installed capacity that year.

As of the end of 2013, 77% of Canada's installed wind energy capacity was in Ontario, Quebec, and Alberta, but these provinces have had differing histories of wind energy development (Figure 2.4). The first wind project in Canada was installed in Alberta in 1993, and consisted of a single 150 kW turbine (CanWEA, personal communication, 2014; Ferguson-Martin & Hill, 2011). Wind capacity in Alberta has grown slowly but steadily since 1998, whereas capacity in Ontario expanded rapidly after 2005. As a result, Ontario has quickly become the province with the most installed capacity in Canada (Figure 2.4). In Quebec, wind energy was introduced in 1998, and capacity increased sporadically, roughly keeping pace with Alberta, until 2013, when capacity increased by 78%.

Wind energy development across Canada is determined only in part by how windy an area is — that is, by the availability of wind resources. Wind energy projects are generally not pursued unless they are both economically viable and socially acceptable (Toke *et al.*, 2008; Ferguson-Martin & Hill, 2011). Development appears to depend on a combination of institutional factors



Data Source: CanWEA, personal communication, 2014

Figure 2.4

Installed Capacity for Wind Power by Province, 1992–2013

The size of the circles on the inset map is proportional to the total installed capacity in each province or territory at the end of 2013. As of 2013, Ontario, Quebec, and Alberta together account for 76.8% of Canada's total installed wind energy capacity. Although Alberta and Quebec have historically had the greatest installed capacity for wind power, Ontario's capacity has grown rapidly since 2005, exceeding that of other provinces since 2008. In contrast, installed capacity in Alberta has grown slowly over a longer period of time, while capacity growth in Quebec has been intermittent but has accelerated in recent years.

such as how the landscape is valued by stakeholders (for alternative uses) and whether there are government policies (e.g., incentive programs, processes for planning and approval of projects) (see Ferguson-Martin & Hill, 2011).

Wind facilities also have to be able to sell their electricity to a nearby electricity grid that is physically compatible. The grid must be able to accept the multiple smaller and variable inputs generated by wind turbines, in contrast to the fewer large inputs from nuclear plants, hydroelectric dams, or other traditional sources of electricity. The structure of the electricity market affects how competitive wind energy is relative to alternatives such as nuclear, hydroelectric, or coal sources. If a government offers tax incentives, or requires utilities to buy wind energy at a minimum price, such factors can make wind energy more viable.

The regulatory frameworks of federal, provincial, and municipal governments encompass several of these factors, and can therefore affect both the economic viability and social acceptability of wind energy development.

Wind energy in Alberta has grown despite grid limitations and a lack of explicit government incentive programs. Growth in wind power capacity appears to have been driven by market and consumer demand, supported by green energy marketing programs of private electrical utilities and municipalities, with the provincial government taking no official position on wind or renewable energy (Ferguson-Martin & Hill, 2011). This contrasts with Ontario, where the provincial government has had explicit policies in support of wind energy development, including capacity targets, economic incentives, and streamlined approval processes. Despite these government policies, public attitudes towards wind energy in Ontario have become sharply polarized, with many grassroots organizations supportive of, or opposed to, wind energy development (Ferguson-Martin & Hill, 2011).

2.3 HEALTH SURVEILLANCE

Like development of all energy sources and utilities, effects of wind energy development on the health of workers and nearby residents are regulated; they fall within the purview of public health. Surveillance of any health effects is complicated by the fact that responsibility for public health is divided among various jurisdictions in Canada. The federal government has powers over spending (e.g., provincial transfers and research funding), and various aspects of public health and safety, whereas provinces have jurisdiction over the provision of health care services, hospitals, and matters of a local nature. The Public Health Agency of Canada (PHAC) was established in 2004 in part as a response to the 2002 SARS outbreak, which highlighted the need for better surveillance, data sharing, and collaboration within and between jurisdictions (Health Canada, 2003b; PHAC, 2008). Health surveillance gathers critical information about trends in the general population, often providing early warning signs of public health emergencies, and of the effects of various factors on public health.

Health surveillance can be passive or active. Passive surveillance in Canada often takes the form of compiling health records, reports, and vital statistics (births and deaths) at the local level, by local and regional health units, which are reported up to a provincial agency, and then shared at the national level through agencies such as PHAC. Passive surveillance can capture high-level trends in the population but is often poorly suited to tracking rare conditions or to establishing a causal link to a novel factor in the environment. Active surveillance, through information-gathering approaches such as surveys, requires more resources but can better target specific conditions or factors that might influence health. Canada's passive health surveillance system does not collect information about exposure related to wind turbines, such as sound levels, distance, or visual presence. The Panel also found no active surveys in Canada that could be used to compare the prevalence of health conditions associated with wind turbines to the prevalence in the general population, or to the prevalence in different regions, in Canada or internationally (see Chapter 5).

2.4 NOISE LIMITS AND SETBACKS

The wind energy industry in Canada operates in a regulatory context involving multiple orders of government. The federal government has limited jurisdiction over the energy sector but has supported wind energy development nationally through direct funding, such as the ecoENERGY for Renewable Power program (CanWEA, 2011). Health Canada is responsible for regulating devices emitting radiation, which includes acoustical waves (sound and noise), under the *Radiation Emitting Devices Act* (GoC, 2004). As a result, Health Canada has expertise in measuring noise and assessing health impacts of noise (Health Canada, 2012). Because electricity falls under provincial jurisdiction, provincial government policies have the most effect on market structure, grid infrastructure, financial incentives, and the planning and approvals processes for wind energy projects (see CanWEA, 2011 for a list of initiatives). Most provincial approval processes also require an environmental impact assessment. Provincial governments have primary jurisdiction over wind turbine noise regulations, although individual projects must follow local municipal regulations when applicable, including zoning, building permits, and noise limits. Regulations covering wind turbine noise vary across Canada, in the absence of a national standard or criteria for noise exposure from wind turbines. The variation in wind turbine noise regulations in Canada, and internationally, also reveals the diversity of approaches and socially acceptable exposure levels. Common policy tools for regulating the placement of wind turbines are *setbacks* and *noise limits.*

A *setback* is the minimum distance between a wind turbine and the closest building or residence, intended to limit nearby residents' exposure to various safety hazards, including ice thrown from wind turbines, mechanical failure, and noise. In Ontario, wind turbines with a capacity over 50 kW require a setback of at least at 550 metres from dwellings (Ontario Regulation, 2012). New Brunswick, Manitoba, and Quebec also impose setbacks from residential areas, with distances ranging from 500 to 550 metres (Haugen, 2011). These setbacks are similar to those applied in other countries.

Noise levels can also be regulated by specifying limits on sound pressure levels, as measured at nearby residential buildings, irrespective of distance. Such levels are defined so that the majority of the population is not disturbed by noise exceeding the limit defined by the regulation (EPA, 2011). *Noise limits* vary between and within provinces, and are sometimes specified in relation to background noise, wind speed, rural/residential areas, or time of day (Haugen, 2011). Manitoba has adopted a noise limit scale that ranges from 40 decibels (A) (dB(A)) at wind speeds of 4 m/s to 53 dB(A) at 11 m/s. Ontario has sound level limits in rural areas that range from 40 to 51 dB(A) at wind speeds of 4 to 10 m/s. In New Brunswick, noise limits range from 40 dB(A) at wind speeds below 7 m/s to 53 dB(A) at wind speeds above 10 m/s. The Alberta Utilities Commission requires that night-time noise limits fall between 40 and 56 dB(A), while the daytime noise limits are 10 dB(A) above night-time limits (Haugen, 2011). Absolute noise limits across provinces are comparable to those in Denmark, Netherlands, Sweden, Australia, and New Zealand.

2.5 CHAPTER SUMMARY

Wind energy has been developed in Canada since 1993, but capacity has increased dramatically since 2006. The history of wind energy development has differed among provinces, not only because of differences in available wind resources, but also as a result of economic viability, electricity grid infrastructure, social acceptability, and government policies and regulations at all levels. Ontario and Quebec have dramatically increased capacity in recent years, while capacity in Alberta has grown steadily over a longer period of time. Canadian capacity is expected to increase further, with the industry estimating that it could satisfy 20% of electricity demand by 2025, although National Energy Board estimates are more conservative. In 2013, Canada ranked fifth in the world in terms of newly installed wind energy capacity, and ninth in terms of total installed capacity. However, this fast growth has created new social situations. Wind turbines have a visual and auditory presence in some rural areas, and are a divisive and polarizing issue in some communities. Uncertainty around their benefits and impacts, and how to measure them, has contributed not only to public unease, but also to a lack of consistency in noise regulations. Sound levels from wind turbines are regulated by setbacks and noise limits, which vary across jurisdictions in Canada. This new energy source in the Canadian economy thus creates novel challenges for the energy industry, regulatory organizations, and communities.

3

Wind Turbine Acoustics

- Fundamentals of Acoustics
- Sources of Sound from Wind Turbines
- Wind Turbine Sound Levels and Spectra
- Chapter Summary

3 Wind Turbine Acoustics

Key Findings

- Wind turbines produce sound through multiple mechanisms with varying characteristics. These signals are then modified as they travel through the environment.
- Measuring sound from any source is complex, involves many dimensions (e.g., sound pressure level, frequency, frequency weighting, time weighting), and requires special equipment and procedures.
- Wind turbines are a particularly complex and distinctive source of sound, which can span a wide range of frequencies including low-frequency tones. These in turn can travel longer distances and are less impeded by building materials than higher-frequency sound. Turbine sound is also characterized by amplitude modulation, often described as a "swishing" or "thumping" sound.
- Low-frequency components may not be captured properly by standard frequency-weighted measurements (e.g., dB(A)), and amplitude modulation is not captured by time-averaged measurements (e.g., L_{eq}). It is also difficult to separate out other background sound such as the wind itself.
- Simple metrics of sound are an important first step in determining audible sound exposure in most cases, but more detailed measurements may be necessary in order for researchers to fully investigate the potential health impact of specific wind turbine noise sources.

In any discussion about evidence of wind turbine noise affecting human health, it is helpful to describe the characteristics of the sound produced by such technology. These characteristics underlie the possible effects of sound from wind turbines on the human body, which will be explored further in later chapters.

This report provides only a brief overview of wind turbine acoustics, and readers interested in additional details or technical aspects of the issues presented in this chapter may refer to the sources cited. The information presented is current as of this writing, but the pace of technology development in the wind energy industry is rapid, and some details or design aspects may change over the coming years. Although fundamental aspects of acoustics and sound measurement are likely to stay the same, research into the mechanisms of sound production by wind turbines continues to try to address many knowledge gaps, including some identified in this report.

3.1 FUNDAMENTALS OF ACOUSTICS

Sound is a pressure wave that travels through a medium; in the case of sound from wind turbines, the medium is air (ANSI/ASA S1.1, 2013). As a pressure wave, sound consists of tiny alternating increases and decreases around atmospheric pressure, which travel (propagate) through the air. Sound is described by several features, such as the frequency of pressure oscillations that make up the wave, and the amplitude of the oscillations (sound pressure), both of which can change over time. *Noise* is often used to describe sound that is unwanted, for a variety of reasons, depending on the context in which it is perceived (see Chapter 4).

Measuring exposure to sound from wind turbines is complex because it is challenging to (1) detect and record sound at low frequencies, (2) summarize information about sound pressure levels over a period of time and a range of frequencies, and (3) isolate acoustic signals from wind turbines in an environment with many other sources of sound. Measurements must take all three challenges into account to provide information that is relevant to potential health impacts, although, for some health effects, the important characteristics remain uncertain (see Chapters 6 and 7).

3.1.1 Sound Pressure Level, Sound Power, and the Decibel Scale

Sound power indicates the total amount of sound being produced by a given source, measured in watts (W, the standard unit of power). *Sound pressure*, on the other hand, indicates the amplitude of pressure fluctuations in a sound wave travelling through air at a particular location, called the *receiver*, and is measured in standard units of Pascals (Pa). Sound power represents the acoustic output from a source in all directions, whereas sound pressure describes only the portion that reaches the receiver. Therefore, sound pressure is a relevant measure of exposure to sound. Sound pressure depends in part on sound power, although other factors in the environment play a role, as will be discussed in the next section.

Although the two concepts are related, it is important to keep in mind the differences between sound power and sound pressure, particularly since both are typically converted to levels measured in decibels (dB). The decibel scale is used for many measures that are expressed as a level, by taking a measurement relative to a reference value and converting it to a logarithmic scale. The reference value is always in the same units as the raw measurement, and therefore different measures have their own reference values. For sound pressure levels in air, the reference value of 20 μPa (2×10^{-5} Pa) is equivalent to 0 dB, which is close to the limit of normal human hearing at a frequency of 1 kHz. The reference value for sound power levels is 1×10^{-12} W, which is equivalent to 0 dB.

The decibel scale is logarithmic, compressing large linear ranges into smaller numerical differences. A doubling of sound pressure translates to a 6 dB increase in sound pressure level. When sound measurements from different sources are combined, the resulting dB value is not a simple sum of the two values; each must be converted to linear units before applying calculations, then converted back to dB (see Crocker, 2007; Leventhall, 2011). In general, non-coherent sounds (those that are not in perfect phase with each other) behave as follows:

- Combining two sounds of equal pressure level (dB) increases the sound pressure level by 3 dB.
- If the difference between pressure levels of two sounds is greater than 15 dB, adding the lower level has a negligible effect on the higher level.

(Manwell *et al.*, 2010)

Sound pressure level is calculated as an average level over a time interval and integrated over a specific range of frequencies. This produces a single number, which can be convenient for comparing sounds with similar frequency components and variation in time. However, information about frequency and time can be measured and described a number of different ways, leading to different conclusions when comparing sound exposure. Not all decibel values are comparable; some methods might provide similar values for sounds that actually have very different qualities. The challenge of any measurement technique is identifying which characteristics are important and capturing and highlighting the important information.

The sound power level of a wind turbine is estimated using measurements under controlled conditions, including distance and wind speed, specified by the International Electrotechnical Commission (IEC) 61400-11 standard (Hessler, 2011). The sound power level of utility-scale wind turbines is typically between 95 and 110 dB(A),[2] depending on the size and design of the turbine (van den Berg *et al.*, 2008; Leventhall, 2011; Møller & Pedersen, 2011). Wind turbines with a larger rotor diameter or rated power generally have a higher sound power level, but there is variation among designs and models. Furthermore, overall sound power levels have decreased in newer generations of wind turbines of the same size (Hau, 2006); as wind turbine design and construction evolves, larger turbines produce sound power levels similar to older, smaller turbines. There is some evidence that sound produced by larger turbines has more low-frequency components, but, again, this varies among designs and manufacturers (Møller & Pedersen, 2011).

---

[2] See Section 3.1.3 for an explanation of A-weighted sound pressure levels (frequency weighting).

The sound pressure level at a receiver ultimately depends on how this overall sound emission changes while travelling, or propagating, through the environment between the source and the receiver. There are currently no international standards for measuring sound from wind farms at a receiver, although there are many technical considerations to take into account (Hessler, 2011).

3.1.2 Sound Propagation

The pathways of transmission between a source and receiver can modify the sound characteristics in a variety of ways. Therefore, the movement of sound in the environment is affected by the properties of the medium (air) as well as by physical structures in the path between the source and receiver.

Under ideal, theoretical conditions, sound from a point source spreads out in all directions, like the surface of an expanding sphere, with the sound pressure declining by 6 dB for every doubling of distance (Bullmore, 2011). This assumes that sound is emitted equally in all directions, that the air is of uniform density, and that nothing will absorb or reflect the sound waves. In reality, the propagation of sound depends on several factors, including:

- distance between the source and receiver: this determines the extent to which other factors influence sound during propagation;
- meteorological conditions: wind speed, direction, wind shear, turbulence, and temperature gradients;
- air density, which is affected by air temperature and humidity; and
- ground characteristics: topography, surface features, and other factors that may absorb or reflect sound.

(Hau, 2006; Crocker, 2007; Manwell *et al.*, 2010; Bullmore, 2011)

A source of sound can be described by its sound power level as a function of frequency or over a frequency range. However, sound power level and frequency range are modified by transmission, absorption, reflection, or refraction of sound travelling to the receiver. Many of these factors depend on distance and frequency, and they can interact.

As sound travels through air, some acoustical energy is absorbed by the atmosphere. Higher frequencies are absorbed much faster than lower frequencies over the same distance (Bullmore, 2011). Higher frequencies are also reflected or absorbed to a greater degree by surfaces in the environment, including the ground. Low frequencies, however, are diffracted to a greater degree around barriers (Bullmore, 2011). Therefore, the sound pressure level of low-frequency sounds declines less with distance than the level of high frequencies.

Furthermore, gradients in air density or wind speed create small local changes in the speed of sound, causing sound waves to be refracted (Jakobsen, 2005; Crocker, 2007; Bullmore, 2011). For example, high wind shear occurs when wind speed increases quickly with height above the ground; with such a strong gradient in wind speed, sound is refracted upwards at locations upwind of the source, and down towards the ground at locations downwind of the source. This leads to lower sound pressure levels at locations on the ground upwind, and higher levels downwind of a source such as a wind turbine. At the same time, wind speeds at ground level are very low, and do little to mask other sounds.

Building construction and materials also heavily modify sounds. Most residential building materials, including windows and walls, affect the transmission of high-frequency sound, causing declines in sound pressure level. However, such materials transmit low-frequency sound to the interior with little loss in pressure level (HGC Engineering, 2010; Madsen & Pedersen, 2010; Søndergaard, 2011). Sound waves can also induce vibrations in structures if the frequency of the sound matches the fundamental acoustic resonance frequency of the materials. Sound frequency is inversely related to wavelength (the distance between pressure fluctuations), and wavelengths can be more than 10 metres long for frequencies below 30 Hz. Sounds interact with physical structures, such as a house, very differently when the wavelength exceeds the size of the structure. Rather than acting as a barrier to sound, a structure smaller than the wavelength is effectively surrounded by oscillating pressures, which can induce vibrations and sound within the structure at the same frequency as the sound (Findeis & Peters, 2004).

Low-frequency indoor sound can resonate depending on the condition of building materials, such as size and shape. This resonance creates a “standing wave” with alternating areas of amplified and muted sound pressure levels within a room (Hubbard, 1982; Findeis & Peters, 2004). Because sound levels can vary within different areas of a room or dwelling, particularly when such resonance occurs, it is difficult to predict or even measure average indoor sound levels to which a resident might be exposed (Pedersen *et al.*, 2007b).

In general, distance also results in a decline in sound pressure levels, which involves higher frequencies more than lower frequencies. This effect is not unique to wind turbine sound, but accentuates the low-frequency components of any source indoors and over longer distances. However, distance alone is a poor predictor of overall sound pressure levels (see Tachibana *et al.*, 2014).

Current knowledge about the characteristics of sound emitted by wind turbines, and the environment through which those sounds travel, can be combined to build models of how sound from wind turbines travels to receivers, such as neighbouring residents. Models are used to predict outdoor sound pressure levels for planned wind turbines before they are built, in order to identify and avoid potential cases of unacceptably high sound pressure levels at nearby residences (Box 3.1).

Box 3.1
Models of Exposure to Sound from Wind Turbines

Mathematical models can use information about a sound source, such as sound power level, for a range of frequencies and environmental factors in order to predict the propagation of sound and resulting sound pressure levels across a landscape. When planning a wind energy project, developers use such models to predict sound levels and identify potential noise problems before the turbines are built, as well as to select locations that would minimize sound exposure for nearby residents. Planning must involve models, because actual measurements cannot be taken until a turbine is built and installed, which is an expensive endeavour.

Standard modelling approaches have been developed to predict sound propagation in general (e.g., ISO 9613-2, Nord 2000, HARMONOISE 2002), and specifically for wind turbines (e.g., VDI 2714, Concawe, DIN 45645-1) (Wagner *et al.*, 1996; Hau, 2006; Bullmore, 2011; Burton *et al.*, 2011; Evans & Cooper, 2012). These models vary in levels of detail, in their reliance on empirical data, and in analytical approaches that take into account aspects of turbine design (Wagner *et al.*, 1996; Oerlemans & Schepers, 2009; Evans & Cooper, 2012). Models may not be appropriate if they are based on data from older designs for wind turbines. Most prediction methods are specific to outdoor sound levels, with indoor levels often estimated by adjusting predicted outdoor levels. The greater challenge, however, is accounting for the large degree of variability in wind and atmospheric conditions, which affect sound emission and propagation and add uncertainty to models.

Models of sound exposure are also used in many studies of health effects (Pedersen & Persson Waye, 2007; van den Berg *et al.*, 2008; Pedersen *et al.*, 2009). Taking measurements across hundreds of survey respondents is expensive and requires special expertise, whereas models can provide a more relevant measure of exposure than distance alone, by taking into account source characteristics and propagation in the environment.

3.1.3 Sound Measurement

Standard methods for measuring and representing sound have affected research and knowledge in acoustics relevant to wind turbines and are detailed here to provide background information for the following chapters.

Sound is generally measured using sound level meters, standard devices that use a microphone to convert acoustic signals into electrical signals, which are analyzed to provide various measures of sound. Different microphones are sensitive to different ranges of frequencies and sound pressures. Infrasound poses a particular challenge because of the long wavelengths. Specialized equipment, such as a large underground shielded microphone, is needed to measure infrasound accurately (HGC Engineering, 2010). Furthermore, humans have a relatively high hearing threshold for infrasound (typically 80 to 110 dB); see Chapter 4. For these reasons, infrasound is sometimes omitted from standard measurements of audible sounds, although it is a component of various sounds in the environment, including wind turbines, diesel engines, wind, and ocean surf.

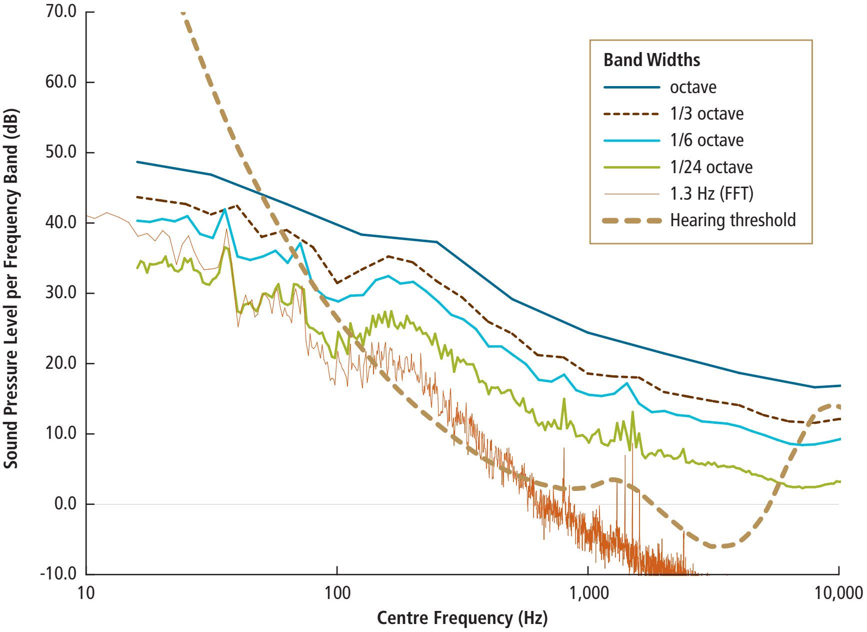
A microphone responds to all sounds that reach it, so establishing the characteristics of a particular source requires measurements under controlled conditions in which other sources are minimized. For wind turbines, this often involves measuring sound at a location while turbines are operating and while turbines are off, under similar wind conditions. The difference between such measurements provides an estimate of the sound levels produced by wind turbines relative to other background noise. Wind itself poses additional challenges to measuring sound outdoors, by creating turbulence around the microphone as well as false signals (HGC Engineering, 2010).

Once an acoustic signal is captured by a microphone, the information in that signal must be described using a relevant summary of the physical properties of the signal. The fundamental properties of sound are the pressure (amplitude) and frequency, both of which vary over time at any given location. Summarizing the information in an acoustic signal involves a trade-off between simplicity and complexity. Simple metrics are useful for highlighting specific characteristics of a sound while overlooking others. In cases where the relevant sound characteristics are unclear, including both acoustics and health research, more detailed measurements and analyses are often necessary to identify which characteristics are the most important. Measuring sound is therefore a complex, multi-dimensional challenge.

Frequency Components of Sound ("Frequency Spectra")

The *frequency* of sound refers to the number of pressure waves per second (measured in Hertz), which determines a sound's tone or pitch. A sound measurement can be broken down into intervals, called frequency bands, within the overall range captured by a sound level meter. Measurements over a range of adjacent frequency bands are collectively called a frequency spectrum. In acoustics, frequency bands are typically labelled by the centre frequency, exactly halfway between the upper and lower limits of a band on a logarithmic scale (the geometric mean of the upper and lower limits). A musical octave is an example of a frequency band, where a note is double the frequency of a note exactly one octave lower. One-third octave bands follow a similar principle, except that the ratio between centre frequencies is two and one-third, instead of double.

Narrower frequency bands (e.g., one-third octave bands vs. one-octave bands) provide more detail about the frequency components of a sound, but also capture less acoustical energy within each band. As a spectrum describing a signal is split into narrower bands, the sound pressure level of each band is typically lower than wider bands around the same centre frequency, as shown in Figure 3.1. Peaks in a spectrum of narrower bands indicate possible tones at those frequencies.



Reproduced with permission from Madsen & Pedersen, 2010

Figure 3.1

Example Frequency Spectra of Sound from a Wind Turbine

The spectra in this figure are based on sound from a 1.3 MW wind turbine, measured at 70 metres. The overall sound pressure level of the sound is 33 dB(A). A spectrum of narrower frequency bands shows more detail, with spikes indicating possible tones at those frequencies. The hearing threshold shown is for an average person responding to tones in a quiet room with no background noise. Unlike the logarithmic scale of octave bands, narrow-bands are the same width along the entire frequency range (1.3 Hz, in this case, analyzed using a form of narrow-band frequency analysis called fast Fourier transform (FFT)) and provide highly detailed information about the frequency components of a sound measurement.

The frequency spectra presented in Figure 3.1 are based on real measurement data for a wind turbine, but are representative of the conditions specific to that measurement. As discussed in Section 3.1.1, many factors affect the frequency spectra and overall sound pressure level at a given location, including the characteristics of the source (turbines), distance from the source, atmospheric conditions, and terrain. Therefore, different conditions and turbines might lead to slightly different frequency spectra (see Section 3.2 for more examples).

Comparing frequency spectra to the threshold of human hearing is not always straightforward, as suggested by Figure 3.1. Standard hearing thresholds for humans are based on measurements made under highly controlled conditions and may not reflect audibility in real-world conditions. These thresholds are also median values for a population sampled, and there is individual variation at all frequencies (see Section 4.3).

This report refers to frequencies between 200 Hz and 2 kHz as mid-range, while high-frequency sound includes frequencies between 2 and 20 kHz. Sound frequencies above 20 kHz are known as ultrasound and are generally inaudible to humans, due to the sharp drop in sensitivity of the human ear to these frequencies.

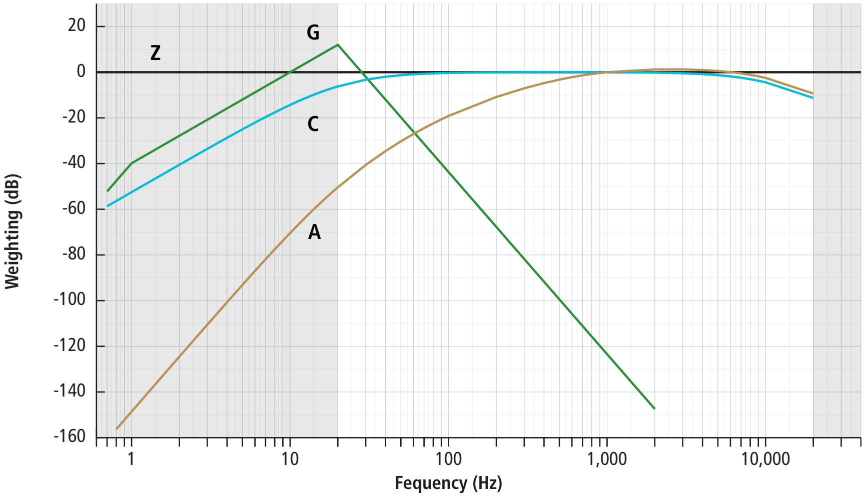
At the low end of the frequency range, sound at frequencies below 20 Hz is typically referred to as *infrasound*. Infrasound is often described as “inaudible,” although, as discussed above, measurements indicate that it can be heard at sound pressure levels above 70 to 100 dB by an average person (Watanabe & Møller, 1990). Although human hearing does respond qualitatively differently to infrasound (<20 Hz) and ultrasound (>20,000 Hz), the boundaries between these and other frequency ranges are arbitrary, as the changes in hearing thresholds occur over a range of frequencies around these boundaries (see Section 4.3).

Low-frequency sound has different meanings, depending on the context and application, and has no standard definition. The upper limit ranges from 100 to 250 Hz or sometimes even 500 Hz (Berglund *et al.*, 1996; Persson Waye, 2005), while the lower limit ranges from 20 Hz (the upper limit of infrasound) to 10 Hz or even 5 Hz (Leventhall, 2009). In this report, low-frequency sound refers to sound in frequencies between 20 and 200 Hz, acknowledging that the exact range may vary in individual studies.

Frequency Weighting

Sound levels are often summarized across the range of frequencies measured. This value can be adjusted, within sound measurement equipment or after recording, to provide greater weight to certain frequencies of interest. An overall sound pressure level trades off the complexity of frequency components for the simplicity of a single value. Simpler metrics make it easier to compare different sounds, but comparisons based on a frequency-weighted value cannot take into account any differences in frequency components. The choice of frequency weighting is a function of both the characteristics of the source and the effects being studied.

The weighting profiles of common methods used to measure sounds from wind turbines and other environmental sources are shown in Figure 3.2. A- and C-weighting give less weight to low-frequency and very high-frequency (>10 kHz) sounds. A-weighted sound pressure levels are indicated dBA or dB(A). G-weighting gives greater weight to low-frequency sound and infrasound between 10 and 30 Hz. Unweighted measurements are called Z-weighted (for “zero”) to explicitly indicate an absence of any frequency weighting. Z-weighting may also be labelled dB SPL (decibel sound pressure level) or dB alone. However, specifying the weighting avoids possible confusion. The same sound can have different dB(Z), dB(A), or dB(G) values, depending on the levels of different frequency components of the sound.



Data Source: IEC 61672:2003 (A and C-weighting); ISO 7196:1995 (G-weighting)

Figure 3.2

Common Weighting Methods for Sound Pressure Level Measurement

Positive values on the vertical axis indicate that sound levels at that frequency are increased (up-weighted) at the indicated frequency; negative values mean that sound levels at that frequency are reduced (down-weighted) by the amount indicated on the vertical axis. Shaded areas indicate infrasound (frequencies below 20 Hz) and ultrasound (frequencies above 20 kHz). Z-weighting indicates linear, unweighted measurements in which sound levels are not adjusted based on frequency. A- and C-weighting were originally intended to mimic the response of the human ear, by down-weighting low-frequency sounds and infrasound. G-weighting emphasizes sound frequencies between 10 and 30 Hz. The G-weighting curve shown is an approximation on a log-scale.

A-weighting was originally intended to mimic human perception of loudness at low sound pressure levels, and C-weighting was similarly intended for higher sound levels. In practice, this distinction has been abandoned, and both are used at all levels (Leventhall, 2011). A-weighted measurements are commonly provided by sound level meters, and specified in regulations and guidelines, for all types of environmental noise (Colby *et al.*, 2009; Leventhall, 2011). As a result, it has become standard practice to report environmental noise levels using A-weighted measurements, which makes measurements comparable across studies in a way that is relevant to human hearing responses. Comparisons based on A-weighted measurements may not be valid, however, for sounds with markedly different frequency components, especially low-frequency components that are down-weighted.

Time Weighting

In addition to frequency weighting, all sound measurements are averaged over a given time interval. Even when sound is measured over long periods, such as several hours or days, measurements are often recorded over many regular intervals, typically 1 second (slow) or 1/8 of a second (fast). A series of measurements can then be processed to calculate different metrics and analyze how sound levels change over time. Some common indicators of environmental noise exposure are described in Table 3.1.

Table 3.1

Sound Pressure Level Indicators and Their Notation

L_{eq}, L_{Aeq}	Equivalent continuous sound level: A steady sound pressure level that would produce an equivalent level over the period of measurement. There is no weighting given to any portion of the time period measured, which is indicated in the subscript after a comma. Frequency-weighting is indicated by the appropriate subscript (A, C, G, etc.). E.g., $L_{Aeq,1hr}$ is the equivalent continuous A-weighted sound pressure level over 1 hour.
L_f	"Fast" measurements, integrated over one-eighth of a second.
L_s	"Slow" measurements, integrated over one second.
L_{dn}	An average A-weighted sound pressure level over a year ($L_{Aeq,1yr}$), where 10 dB(A) is added to night-time levels. Night-time is usually defined as 11 pm to 7 am, or 10 pm to 6 am.
L_{den}	Similar to the L_{dn}, except that 5 dB(A) are also added to levels during evening hours, 6 to 10 pm or 7 to 11 pm.
$L_{night,outside}$	A yearly average of night-time sound pressure levels ($L_{Aeq,night}$ over a typical year), measured outside. This is often used as a long-term indicator for night noise levels in Europe.
L_{max}	The maximum sound pressure level observed over the measurement period.
L_{10}, L_{50}, L_{90}	The level exceeded during a percentage of the measurement period, indicated by the subscript number. For example, L_{10} indicates the sound level exceeded 10% of the time and gives an idea of the upper extremes over this period.

(WHO, 2009; Münzel *et al.*, 2014)

The time interval of a measurement has several implications for the way it is interpreted and compared with other measurements. Long-term averages can be useful indicators of sound exposure relevant to health (WHO, 2009), but shorter intervals can provide much more detail about how sound varies over time. In general, shorter measurement intervals capture larger variations. However, longer intervals such as L_{eq} are often used, and these fail to capture short-term effects such as amplitude modulation (see Figure 3.6).

3.2 SOURCES OF SOUND FROM WIND TURBINES

Wind turbines produce sound primarily from two sources:

- **Mechanical**, produced by physical movements of the gearbox, generator, and other components in and around the nacelle, which is mostly tonal in character (dominated by a narrow range of frequencies), but can also have a *broadband* character, meaning it is composed of sound over a wide range of frequencies.
- **Aerodynamic**, caused by air flowing over the blades, usually producing broadband sound at levels proportional to the relative velocity of the air flow.

(Hau, 2006; Manwell *et al.*, 2010; Oerlemans, 2011)

Appropriate design and manufacturing have reduced sound levels from mechanical sources; as a result, aerodynamic noise from the blades is the dominant type of sound for modern utility-scale wind turbines (Hau, 2006; Oerlemans, 2011). Low-frequency tones associated with mechanical sources are distinctly audible for some turbines, however (Søndergaard & Madsen, 2008; Madsen & Pedersen, 2010).

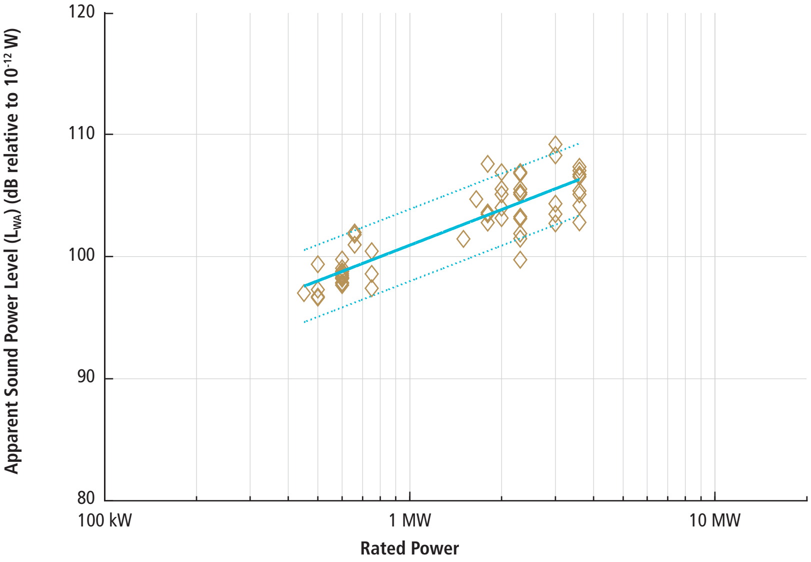
The aerodynamic mechanisms that produce sound from wind turbines involve interactions between air flow and different parts of the blade. These interactions depend on the speed and turbulence of the incoming wind, the shape of the blade (in cross-section and outline), the angle between the blade and the relative wind velocity flowing over the blade (the angle of attack), and the distance from the hub (Wagner *et al.*, 1996; Oerlemans, 2011). In particular, parts of the blade closer to the tip are moving faster than those closer to the hub, leading to faster relative air velocities. Higher relative velocities typically lead to higher sound levels, especially at higher frequencies (Oerlemans, 2011). Therefore, most aerodynamic sound is produced near (but not at) the blade tips (Oerlemans & Méndez López, 2005; Oerlemans, 2009). This is partly why turbines with longer blades have a higher sound power level: longer blades mean higher relative velocities near the blade tips for the same rotation rate.

Different aerodynamic mechanisms produce sounds with different characteristics, however. *Low-frequency sound* may be created as a result of inflow turbulence in the wind along the leading edge of the turbine blade (Oerlemans, 2011). This varies considerably from site to site, depending on local conditions. For example, turbines located in the wake of another turbine are particularly likely to experience inflow turbulence. Sound produced by air flow at the blade tip (tip noise) is generally broadband with high-frequency components, but only in some cases contributes to overall sound emissions (Wagner *et al.*, 1996; Oerlemans, 2011). Sound produced by air flow at the trailing edge of the blade is usually the dominant source of sound from wind turbines, and has an overall broadband character (Oerlemans, 2011).

As blades degrade because of erosion and buildup of debris, however, they can produce more sound than normal, due to turbulence created by air flow over a blade surface that is not as smooth as intended for the blade design (Oerlemans *et al.*, 2007).

Aerodynamic sources of sound from wind turbine blades also have a strong directional component, radiating mainly downwind, upwind, or even perpendicular, depending on the dominant mechanism (Oerlemans, 2011). Therefore, the amplitude of the acoustic signal at a particular location, measured by the sound pressure level, can vary depending on the direction, speed, and turbulence of the wind. Furthermore, as the rotor turns, the orientation of each blade changes from the perspective of a stationary receiver. As a result, the pressure level of sound from a given turbine reaching a receiver also varies as the blades rotate, resulting in periodic *amplitude modulation* — regular changes in sound pressure level over time (van den Berg & Bowdler, 2011; RenewableUK, 2013).

Since aerodynamic mechanisms account for the majority of sound emissions from wind turbines, sound power levels increase with wind speed up to the maximum sound power level at the rated wind speed (Wagner *et al.*, 1996; Søndergaard, 2011). Furthermore, the relevant wind speed affecting sound power levels is that at the height of the blades, which can differ from that at ground level. Given rotor diameters of 50 to 100 metres or more, uneven wind speeds within the swept area of the wind turbine rotor can also add to sound production, as well as to amplitude modulation of emitted sound.



Reproduced with permission from Møller & Pedersen, 2011; Møller *et al.*, 2011

Figure 3.3

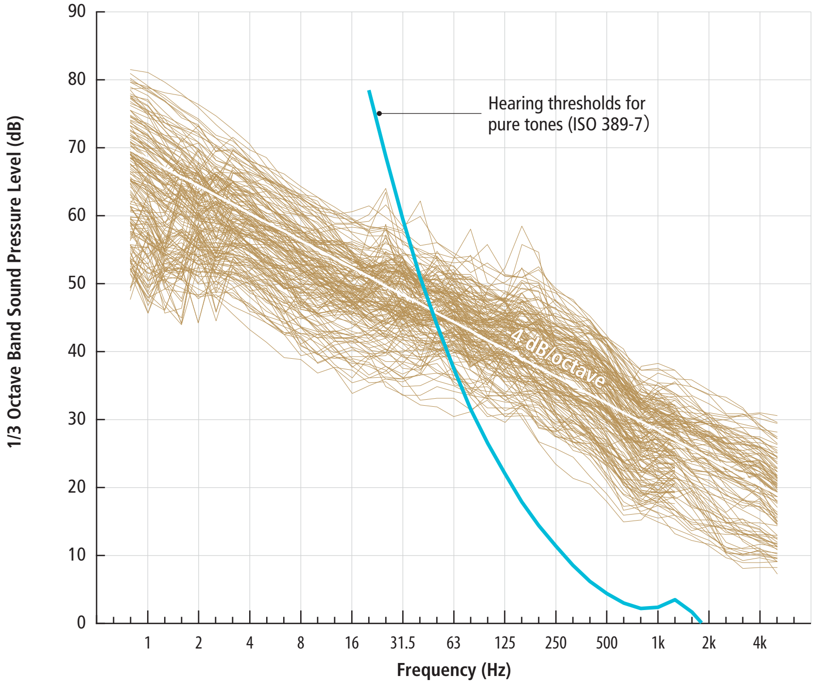
Apparent Sound Power Level (LWA) of Wind Turbines as a Function of Rated Power

These data are based on the measurements of 61 wind turbines from a range of models in Europe, downwind at 8 m/s, according to IEC 61400-11 standards. Each turbine is shown as a diamond symbol. A regression line is shown, with 90% confidence intervals shown as dashed lines. Turbines with a higher rated power tend to have a higher sound power level, but there is variation in sound power level among models of the same rated power. The slope is close to 10 dB per decade (9.7) corresponding to equal acoustic power per electrical power.

3.3 WIND TURBINE SOUND LEVELS AND SPECTRA

Characterizing wind turbine sound is complicated by the variation in mechanisms that produce sound, the changes that occur during transmission across a range of distances, and a lack of measurement standards (Hessler, 2011). See Figure 3.3 for the sound power level of wind turbines as a function of rated power.

Although there is a standard method for measuring the sound power level of wind turbines (IEC 61400-11), methods for measuring the sound pressure level (exposure) at a receiver must be tailored to individual circumstances and technical factors. Questions such as “how loud are wind turbines?” are difficult to answer, because the response depends on local wind and atmospheric conditions, distance to the turbine, and intervening topography. Large numbers of measurements in recent years, however, have started to shed light on the range of variation and the characteristics of sound emissions from wind turbines.



Adapted with permission from Tachibana *et al.*, 2014 and INCE/USA

Figure 3.4

One-Third Octave Band Unweighted Sound Pressure Level Measurements Around 29 Wind Facilities in Japan

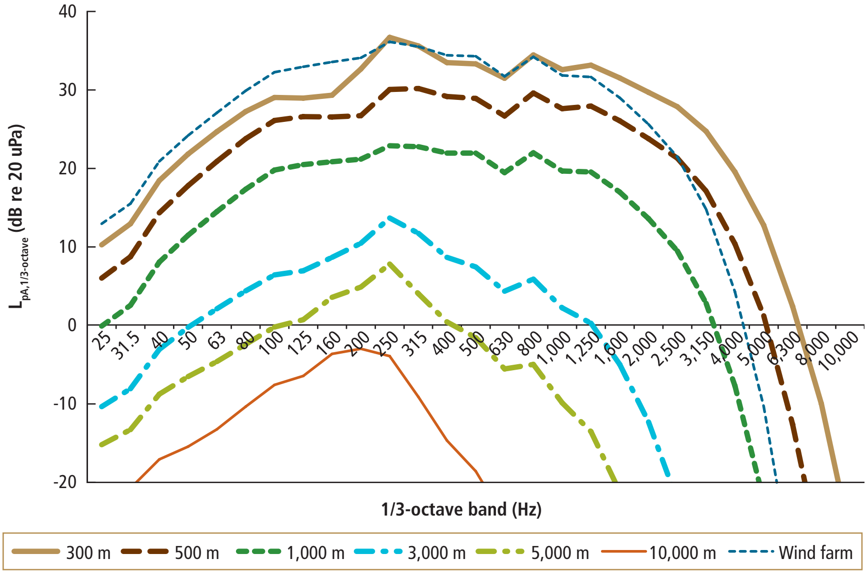
One-third octave band spectra are overlaid for 164 outdoor locations around 29 wind facilities across Japan, from about 100 to 1,000 metres from the nearest wind turbine. Each spectrum is based on a 10-minute measurement period at night, and sound pressure levels are unweighted (dB(Z)). Data from four coastal sites were excluded because wind turbine sounds could not be detected above background noise from waves and wind. Spikes in individual spectra suggested the presence of low-frequency tones in some cases. These unweighted spectra corresponded to average night-time levels between 25 and 50 dB(A), with most being between 35 and 45 dB(A). Levels of infrasound appeared to be below the median threshold of human hearing (based on laboratory experiments); infrasound was measured at a range of 46 to 75 dB(G), with the peak of the distribution around 61 to 65 dB(G). Hearing thresholds (ISO 389-7:2005) are shown for comparison, but this threshold is based on measurements using pure tones and varies among people; frequency components above this line are not necessarily audible, nor are frequencies just below this line necessarily inaudible.

Tachibana *et al.* (2014) report outdoor measurements from multiple locations around 29 wind facilities, ranging from 100 to 1,000 metres from the nearest wind turbine. The combined spectra are presented in Figure 3.4, which shows some variation in levels at all frequencies, but an overall consistent shape, with levels dropping by about 4 dB per octave. Peaks in the low-frequency and infrasonic ranges (<250 Hz) suggest low-frequency tones present in a few cases. The average level for 10-minute night-time periods ranged between 25 to 50 dB(A) across all outdoor measurements, with most being between 36 and 45 dB(A) (Tachibana *et al.*, 2014).

Other sounds with similar A-weighted levels include an average living room, quiet office, light car traffic more than 20 m away, an air conditioning unit more than 60 m away, or the wind itself (Wagner *et al.*, 1996; Colby *et al.*, 2009; Fortin *et al.*, 2013), although these sounds may vary over time in different ways than wind turbines, or have different frequency components. In some cases, background noise from wind and waves can be at similar or higher levels, making it difficult to isolate the sound from wind turbines (Hepburn, 2006; Tachibana *et al.*, 2014). Two sounds with the same A-weighted overall pressure level may not be associated with the same health effects, however, as other characteristics may be more relevant, such as maximum levels, long-term exposure, or interpretation of the sound by its hearer.

Although pressure levels of sound from wind turbines tend to decline with increasing frequency, the mid-range and high frequencies are often the most audible, due to the sensitivity of the human ear. As mentioned above, assessing audibility based on spectra such as those in Figure 3.5 is difficult because of differences in the way the sounds and hearing threshold are measured (see Chapter 4 for additional details). Infrasound (<20 Hz) levels in the Japanese measurements were below human hearing thresholds, based on laboratory studies using recordings of the sounds (Tachibana *et al.*, 2014). Above 20 Hz, the same lab studies found that the recorded sounds from these wind turbines were indeed audible. This is consistent with many other studies that have concluded that average infrasound levels from modern wind turbines at outdoor locations are below the human hearing threshold, even as close as 100 m from the turbine (Jakobsen, 2005; HGC Engineering, 2010; Madsen & Pedersen, 2010). Hepburn (2006) found that infrasound levels were not significantly above background levels at 1,000 metres from wind turbines at the Castle River Wind Farm in Alberta; infrasound levels ranged from 53 to 62 dB(Z) in low wind conditions to 76 to 82 dB(Z) in high wind conditions, which is consistent with the measurements by Tachibana *et al.* (2014).

The general spectra shown in Figure 3.5 include measurements at a range of distances. The spectrum from an individual turbine is expected to shift toward dominance of lower frequencies at increasing distance, combined with an overall decline in sound pressure level, as discussed in Section 3.1.2. Figure 3.5 shows predicted A-weighted spectra at increasing distance from a wind turbine, based on a measured overall sound pressure level of 45 dB(A) at 300 metres. At further distances, the frequencies likely to dominate what is heard (i.e., A-weighted) shift towards lower frequencies, while the overall sound pressure level decreases.



Data Source: Søndergaard, 2011. Reproduced with permission from Multi-Science Publishing Company

Figure 3.5

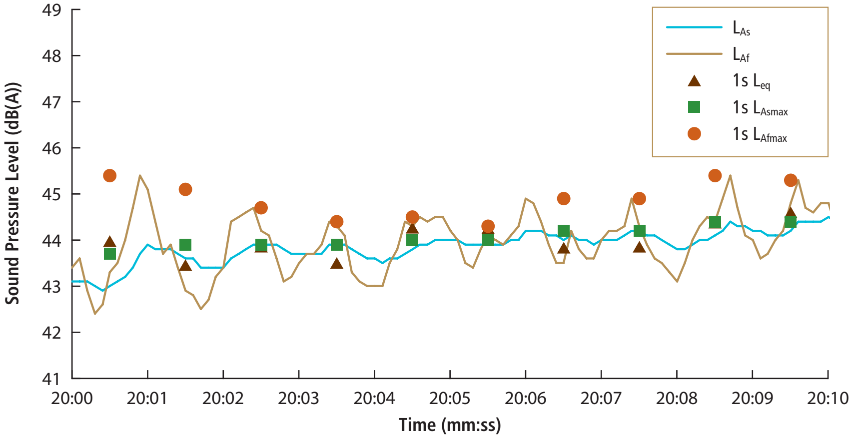
Predicted Sound Spectra at Various Distances from a Wind Turbine

Estimated sound spectra were generated using the Nord2000 turbine, assuming flat farmland and a wind speed of 8 m/s. Predictions were based on a measured sound spectrum of 45 dB(A) at 300 m from a "typical" wind turbine with a hub height of 90 m (solid bold line in the figure). The dotted line labelled "Wind farm" shows a spectrum from a wind facility with multiple turbines that also has an overall sound pressure level of 45 dB(A). These model predictions show how dominant A-weighted frequencies tend to shift toward lower frequencies at increasing distance from a wind turbine.

As described in Section 3.2, the rotating blades on a wind turbine can lead to sound emissions at levels that fluctuate periodically from the perspective of a stationary observer — a phenomenon called periodic *amplitude modulation*. Amplitude modulation is described by modulation depth, the difference between the lowest and highest sound pressure levels, and the modulation *frequency*, which is the rate at which the sound pressure level alternates between the lowest and highest levels. Modulation frequency should not be confused with the frequency range of the sound in which pressure levels are changing. Although both may be described in Hz, amplitude modulation typically fluctuates at a similar rate to the blade-pass frequency, which is around 1 Hz (meaning there is one second between each blade passing the same point), whereas such amplitude modulation can affect a range of sound frequencies produced by wind turbines. While other sources of environmental noise, such as road traffic, also exhibit amplitude modulation (the sound pressure level changes over time), sound from wind turbines is distinct in that the amplitude modulation repeats regularly with the rotation of the blades — it is periodic and often described as "swishing" or "thumping," depending on the sound frequencies involved.

There are few published measurements of amplitude modulation from wind turbines, and modulation depth is sometimes measured using different metrics (RenewableUK, 2013; Tachibana *et al.*, 2014) (see Figure 3.6). Available data suggest that modulation depth ranges from non-existent to about 5 dB, with most being between 2 and 3 dB (Oerlemans & Schepers, 2009; van den Berg & Bowdler, 2011; Tachibana *et al.*, 2014). A modulation depth of 2 dB or more is considered audible (van den Berg & Bowdler, 2011), so amplitude modulation in wind turbine sounds is likely perceptible in many cases, but not all. Most amplitude modulation occurs at mid-range sound frequencies between 200 and 1,000 Hz, which is often described as a "swishing" sound (Bowdler, 2008; van den Berg & Bowdler, 2011; RenewableUK, 2013).

RenewableUK — a not-for-profit energy trade association for renewable energy companies in the United Kingdom — has published a collection of research reports that distinguish between normal and enhanced or other amplitude modulation, which exhibits greater modulation depth, lower frequencies, or other characteristics outside the normal range (RenewableUK, 2013). Normal amplitude modulation can be explained by air flow at the trailing edge and blade movement, as described above, and tends to be strongest perpendicular to the wind direction, in the same plane as the wind turbine rotor (Oerlemans & Schepers, 2009; van den Berg & Bowdler, 2011; RenewableUK, 2013). Other amplitude modulation is thought to be due to wind gusts, local turbulence, or other non-uniform wind conditions that interact with turbine blades rotating in a periodic manner (RenewableUK, 2013). Enhanced amplitude modulation tends to occur for brief periods, but the modulation depth can approach 10 dB, often at low frequencies (1 to 2 kHz), and the sound can travel for longer distances downwind than normal amplitude modulation (Bowdler, 2008; van den Berg & Bowdler, 2011; RenewableUK, 2013). Enhanced amplitude modulation is sometimes described as “thumping,” and distinguished from “swishing” by greater modulation depth and lower frequency components. The causes and types of amplitude modulation are a topic of ongoing research, including investigation into how the modulation character is propagated outdoors (van den Berg & Bowdler, 2011; RenewableUK, 2013).



Data Source: Kaliski, 2014. Reproduced and adapted with permission from RSG, Inc., (funded by MassCEC and co-managed with MassCEC by MassDEP)

Figure 3.6

A-Weighted Sound Metrics for a Wind Turbine Over a 10-Second Period

This graph shows several metrics for the same sound measured 260 metres crosswind from a single wind turbine (size or model not specified). All metrics are A-weighted. L_{As} indicates slow measurements, integrated over one second intervals, whereas L_{Af} indicates fast measurements integrated over one-eighth second intervals: these intervals overlap, so that there is more than one instantaneous L_{As} measurement per second of observation (each L_{As} measurement integrates over the previous second). The major difference is that fast measurements respond to shorter changes in sound pressure level. The L_{eq} and maximum levels for L_{As} and L_{Af} are also indicated for each one-second interval over the measurement period. These values illustrate the ability of shorter intervals (L_{Af}) to capture larger variations and therefore affect the magnitude of other metrics, such as L_{Amax}, for the same sound. The time series also shows regular amplitude modulation of wind turbine sound, which appears to be more extreme when using fast measurements (L_{Af}) but would not be apparent to short- or long-term equivalent averages (L_{eq}).

3.4 CHAPTER SUMMARY

Wind turbines produce sound through multiple mechanisms with varying characteristics. These signals are then modified during propagation in the environment. Sound from wind turbines is therefore highly complex and variable, but has some characteristics that are similar to other sources of community noise, such as road and airport traffic noise:

- It is broadband, composed of sound over a range of frequencies, with levels typically dropping by about 4 dB per octave (HGC Engineering, 2010; Tachibana *et al.*, 2014).
- The overall sound pressure levels outdoors vary greatly depending on distance, wind speed, and transmission from the source to the receiver (Tachibana *et al.*, 2014).
- Higher frequencies tend to be reduced indoors and with increasing distance, leading to an emphasis on lower frequencies (HGC Engineering, 2010; Søndergaard, 2011). Low-frequency sound can cause acoustic resonance within structures.
- It is amplitude modulated, with sound levels changing over time.

Wind turbines also emit sound with the following characteristics that are less common to 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 (Søndergaard & Madsen, 2008; HGC Engineering, 2010; Madsen & Pedersen, 2010; Tachibana *et al.*, 2014).
- The sound power level increases with the wind speed, up to the rated wind speed of the turbine, at the height of the blades, which is often 60 to 100 metres or more above ground level (Wagner *et al.*, 1996; Søndergaard, 2011).
- Sound from wind turbines can have periodic amplitude modulation, fluctuating regularly at the same rate as the blade pass frequency (around 1 Hz), which gives it a “swishing” or “thumping” character, depending on the dominant sound frequencies at which modulation occurs. Modulation depth is less than 5 dB in most cases, but in rare cases may approach 10 dB (van den Berg & Bowdler, 2011; RenewableUK, 2013; Tachibana *et al.*, 2014).

Sound measurement is limited by available equipment and methods, but typically includes sound pressure level and frequency components. These measurements are often weighted by frequency to reflect human hearing responses (A-weighting), and are summarized by an average over a period of time (equivalent sound pressure level, L_{eq}).

The Panel acknowledges that a standard A-weighted average sound level (L_{Aeq}) is not intended to capture the full complexity of sound, but often provides a useful first approximation of long-term sound exposure. Comparisons based on such overall average levels, however, can fail to take into account important differences in frequency content or amplitude modulation. When sound conditions are unusual or of particular concern, more detailed measurements may be needed to identify problems. The most appropriate sound metric is a function of both the source and the sound characteristics of interest.

4

Hearing and Perception of Sound

- The Auditory Pathway
- Non-Auditory Pathways
- Basic Auditory Perception and Mechanisms
- Sound Perception
- Chapter Summary

4 Hearing and Perception of Sound

Key Findings

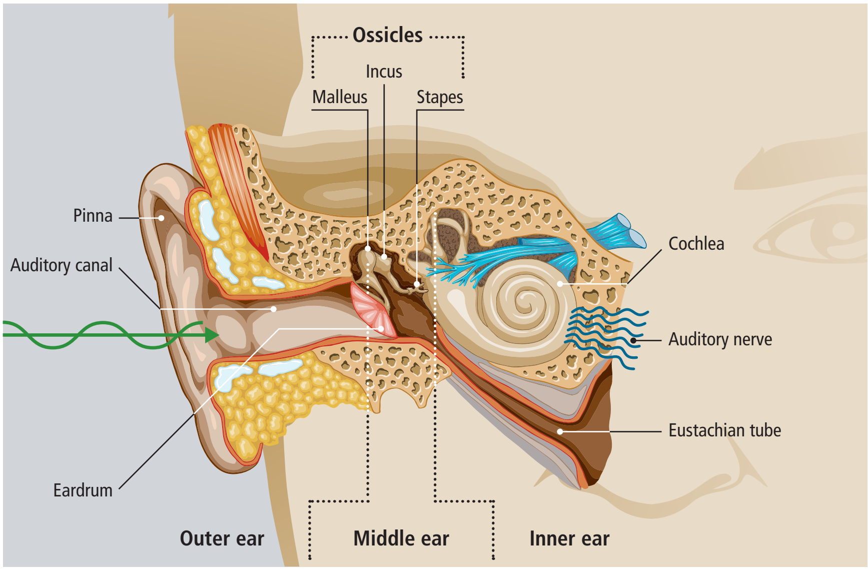
- Sound can affect the human body through auditory and non-auditory pathways. The auditory pathway involves sounds reaching the cochlea through air and bone conduction, where they are converted into neural signals by the hair cells. Sounds can also stimulate the vestibular system and/or cause whole-body vibration under certain conditions. At commonly specified setback distances from wind turbines, the dominant sound pathway is through air conduction.
- Absolute hearing thresholds have been standardized for a reference population of young adults. These represent the lowest sound pressure levels at which the average young adult with normal hearing can hear a pure tone sound signal at different frequencies in controlled quiet conditions. However, hearing thresholds can vary widely in the general population as a result of age, prior exposure to loud sounds or ototoxic agents, medical conditions, and many other factors.
- In everyday environments where there are background noise signals, the detection of sounds also depends on the levels of competing masking sounds. In the context of wind turbine noise, it is appropriate to consider masked hearing threshold. This is the sound pressure level at which a sound can be heard in the presence of other sound (competing acoustic signals). The perceptual attributes of sounds heard in the environment depends on their spectral content (e.g., tonal versus broadband), temporal characteristics (e.g., continuous or modulated), loudness (subjective perception of sound intensity), and many other factors.
- Sound may have emotional and psychological effects that also need to be taken into account.

To explore how sound from wind turbines can affect individuals, it is important to understand how it is processed by the human body and how the same sound may affect people differently depending on physiological and psychological factors or pre-existing medical conditions. This chapter describes how sound is processed by the body through the auditory pathway, and how it can activate non-auditory body structures such as the vestibular system. Finally, the chapter explores how individuals may be affected differently by sound and provides an overview of non-acoustic modifiers of sound perception.

4.1 THE AUDITORY PATHWAY

In order to be processed by the brain, sound has to reach the inner ear, which converts sound into neural signals (Figure 4.1). The human ear can be divided into three main sections:

- The outer ear, composed of the pinna and the auditory canal, directs airborne acoustic signals to the tympanic membrane (eardrum).
- The middle ear, including the eardrum and delicate ossicular chain (ossicles or tiny bones), converts acoustic vibrations into mechanical vibrations that are transmitted to fluid-filled chambers in the inner ear.
- The inner ear is composed of the cochlea and vestibular end-organs. Hair cells in the cochlea detect waves created by the mechanical signals from the middle ear, and convert them into electrical signals that are transmitted to the brain via the cochleovestibular (VIIIth) cranial nerve.



Reproduced with permission from the University of Ottawa/Université d'Ottawa

Figure 4.1

Sound Pathway from the Environment to the Brain

Airborne sound enters the ear through the outer ear and vibrates the tympanic membrane of the middle ear. The ossicular chain transmits the mechanical vibrations into fluid-filled chambers of the inner ear. Hair cells in the cochlea of the inner ear convert vibrations in the fluid into electrical signals that are carried to the brain by the auditory nerve. Mechanical vibrations in the middle ear can also result from skull vibrations conducted by bone from other parts of the body.

Airborne sound causes vibration of the eardrum and ossicles in the middle ear. In the inner ear, the fluid within the cochlea moves in response to these vibrations. The sound pathway described is called *air conduction* but is not the only pathway for a sound to be perceived by the brain. Acoustic signals can also cause vibrations that are conducted to the inner ear through bones. This *bone conduction* pathway is also involved in hearing; when we speak, we hear our own voice largely through bone-conducted sound (Hansen & Stinson, 1998). Bone conduction is an important pathway when the head (or body) is connected to a vibrating object, either internally (e.g., vocal apparatus) or externally (e.g., mechanical stimulator placed on the skull). By contrast, in response to external sounds, bone conduction is 40 to 60 dB lower than airborne conduction in normal-hearing individuals (Berger *et al.*, 2003). As a result, bone conduction is a significant pathway for external sounds only when the airborne pathway is blocked (e.g., by use of a high-attenuation hearing protector). These conditions do not apply to sound exposure from wind turbines.

Auditory signals are processed at many levels in the auditory pathway, including at the brainstem and midbrain levels, but are not perceived consciously as sound until there is activation of the auditory cortex.

4.2 NON-AUDITORY PATHWAYS

Sound may also activate other parts of the body that are not part of the auditory pathway, such as the vestibular system, or cause whole-body vibration through direct mechanical stimulation of tissues.

4.2.1 Vestibular System

The vestibular system is part of the inner ear that contributes to balance and spatial orientation. It may be activated by certain sound signals and is therefore relevant in the context of possible effects of sound. The vestibular system is composed of semicircular canals, which detect rotational movements (angular accelerations) of the head, and the otoliths, which detect gravitational pull and linear movements of the head. The vestibular system has some very important functions that we rarely notice until things go wrong. For example, the stability of the eyes is controlled by detection of head movements via the semicircular canals. Balance is achieved in large part by input signals from the vestibular system, which are combined with visual inputs and signals from the somatosensory system to allow us to stand upright and generally orient ourselves in space. In their normal balance function, the hair cells of the vestibular system are typically activated by much slower movements of inner ear fluids than hair cells in the cochlea. As a result, the vestibular hair cells are generally sensitive to relatively low vibration frequencies. For example, the otolith organs are most sensitive to acoustic signals around 100 Hz (Todd *et al.*, 2008). The input from the vestibular system is transmitted to the vestibular cortex of the brain, which processes the information.

4.2.2 Whole-Body Vibration

Typically, to achieve whole-body vibration, direct mechanical stimulation from a vibratory source (e.g., working with power tools) is required. However, acoustic exposure at high sound pressure levels can also induce some amount of whole-body vibration (Takahashi, 2011). The levels of acoustic energy generated by wind turbines, at commonly specified setbacks and/or sound levels (see Chapters 2 and 3), are much lower than typically needed to affect body tissues.

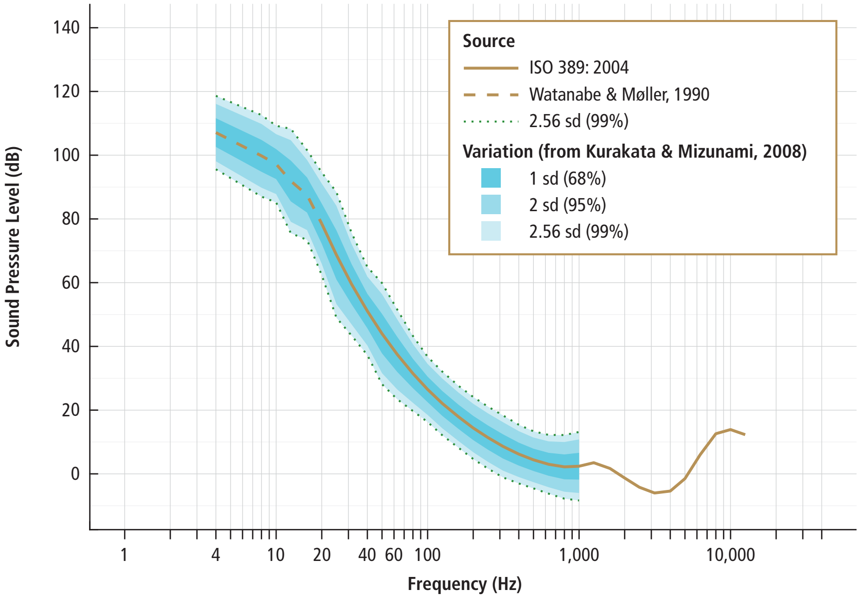
4.3 BASIC AUDITORY PERCEPTION AND MECHANISMS

Perception of sound depends on many factors, including not only physiological sensitivity but also psychological and external factors. Basic auditory perception can be described by the following critical components:

- Auditory sensitivity
- Masked hearing threshold
- Loudness

4.3.1 Auditory Sensitivity

Hearing thresholds reflect the combined sensitivity of a person's ear and the person's ability to notice an environmental sound. (Other factors affecting perception of sound are discussed in Section 4.4.) The *absolute hearing threshold* is the lowest sound pressure level of a pure tone that a person can hear in a very quiet environment with focused concentration. This threshold varies depending on the frequency of the tone. Determining this threshold is one way of measuring auditory sensitivity across frequencies in human subjects. The healthy human ear is most sensitive between 2 and 5 kHz (roughly the highest octave on a piano; middle C is 261 Hz), and is less sensitive to very low and very high frequencies. Figure 4.2 shows the absolute hearing threshold curve in a reference population of young adults with normal hearing. It shows the differences in threshold as a function of sound frequency. For example, at 1,000 Hz, the average threshold level is 4 dB, whereas at low frequencies (<20 Hz), sound is perceived only at sound pressure levels above 90 to 100 dB. Note that, even within this reference population of young normal-hearing adults, hearing thresholds typically vary by approximately 20 dB between individuals, as indicated in Figure 4.2 by the variance plots.



Data Source: ISO 389: 2004; Watanabe & Møller, 1990; Kurakata & Mizunami, 2008

Figure 4.2

Absolute Human Hearing Thresholds

The central solid or dashed line indicates the sound pressure level (dB SPL) at which a typical young adult can hear a pure tone under controlled conditions, at the frequency along the bottom axis. The line indicates the median threshold: half of the population are more sensitive and can hear sounds at lower pressure levels, while the other half are less sensitive and can hear sounds only at higher pressure levels. The shaded blue bands around the line indicate the amount of variation: the darkest blue band indicates the range of sound pressure levels at which approximately 68% of people can hear a tone at a given frequency (one standard deviation) (see Leventhall, 2009). The lower the frequency, the higher the sound pressure level needed for the sound to be heard. For example, infrasound (typically a sound at a frequency under 20 Hz) can be heard only above 70 to 100 dB (Watanabe & Møller, 1990).

In the general population, hearing thresholds vary considerably and can be much higher than the reference audiometric thresholds in Figure 4.2 as a result of aging, prior exposure to loud sounds or ototoxic agents, medical conditions, and a wide range of other factors. In audiological practice, the hearing level of individual patients is expressed as the amount of threshold elevation (measured in decibels hearing level [dB HL]) with respect to the reference absolute threshold curve. For example, an individual with a hearing level of 40 dB HL has absolute hearing thresholds that are 40 dB above that shown in Figure 4.2. The amount of threshold elevation often varies with frequency. There are various schemes to classify the severity of a threshold elevation or hearing loss. Under the classification of the American Speech and

Hearing Association, normal hearing corresponds to hearing levels equal to or below 15 dB HL, while hearing loss is classified on a scale ranging from mild loss (16-25 dB HL) to severe loss (91+ dB HL) (ASHA, 1981). Box 4.1 provides details on particular conditions affecting auditory sensitivity.

Box 4.1
Sensitive Groups and Pathologies

When considering the effects of acoustic signals through hearing or vestibular pathways, it is important to be aware that certain individuals may have a lower hearing threshold than normal and may thus be more sensitive to sound. As noted above, even among people with normal hearing, thresholds can vary by as much as 20 dB.

There are also some conditions involving a heightened sensitivity to sound and a lowering of hearing thresholds. For example individuals with hyperacusis can have an "unusual intolerance to ordinary environmental sounds" that are normally tolerated by the majority of people (Baguley, 2003). This condition may be relatively common, with prevalence estimates ranging from 8 to 15% of the population. In regard to possible sound activation of the vestibular system, some pathological conditions are known to lower vestibular activation thresholds (e.g., enlarged vestibular aqueduct, perilymphatic fistula, or superior semi-circular canal dehiscence). However, even in these cases, the sound pressure level required for vestibular system activation is much higher than that present in wind turbine noise (Harrison, 2014).

4.3.2 Masked Hearing Threshold

An absolute hearing threshold is rarely appropriate in the context of environmental sound, as other sounds and noises prevent detection of sounds at pressure levels near that threshold. Thus, in considering environmental sound, the *masked hearing threshold* is often used. This is the sound pressure level at which a sound can be heard in the presence of other sound (competing acoustic signals). In the context of wind turbine noise, it is appropriate to consider masked hearing threshold.

Box 4.2
Sound, Noise, and Loudness

Sound pressure is an objective measure of the amplitude of a sound wave. *Loudness* is the subjective perception of the intensity of a signal after it has been detected by the ear and processed in the auditory system. *Noise* can be described as an unwanted sound. It may be a competing acoustic signal in the environment that masks a sound of interest, or it can be a sound percept that individuals are trying to separate out or ignore. In this respect, noise is subjective, and depends on the individual and the context.

4.3.3 Loudness

When a sound or noise reaches the human ear and is above the masked hearing threshold, the magnitude of the sensation in response to that sound is termed *loudness*. Hence, loudness is the intensity of an auditory sensation; it is related to, but distinct from, the physical acoustic signal that generated it. In everyday terms, sounds are usually ordered on a scale extending from soft to loud (Olson, 1972). Loudness is a subjective perception of the intensity of a signal and depends not only on the characteristics of sound but also its duration, its perception by the brain, and the presence of other sounds. Like variations in the threshold of hearing, perception of loudness also varies from person to person.

4.4 SOUND PERCEPTION

Sound may have an effect on the brain through direct and indirect mechanisms. The primary auditory pathway projects to the core auditory cortex and is responsible for hearing (i.e., the percept of sound). The indirect or non-primary pathway is a parallel ascending system mainly activating cortical association areas and the limbic system (e.g., amygdala). This pathway is responsible for the emotional response to sound stimuli. When defining the impact of exposure to a sound, and the subsequent physiological stress reactions, both mechanisms must be considered. The physical acoustic signal characteristics, such as spectral (e.g., tonal versus broadband) and temporal (e.g., continuous or modulated) characteristics, are perceived via the direct pathway, and the emotional content of sounds activating the limbic system through non-primary pathways (Spreng, 2000; Babisch, 2002; Münzel *et al.*, 2014). When a sound is perceived as unpleasant, intrusive, or disturbing, it is sometimes referred to as *noise*.

4.5 CHAPTER SUMMARY

Sound reaches the inner ear through air conduction and bone conduction. Signals are then converted into neural signals by hair cells in the inner ear and are processed by different parts of the brain, both consciously and subconsciously. Acoustic signals, especially those at low frequencies, can also stimulate the vestibular system, and this stimulation occurs at lower levels for people with certain conditions. Direct contact with a vibratory source or higher sound pressure levels are typically needed to induce significant amounts of whole-body vibration.

Auditory perception can be described by auditory sensitivity, masked hearing threshold, and loudness. Hearing thresholds reflect a person's auditory sensitivity and ability to notice a sound in the environment. Absolute hearing thresholds (in quiet surroundings with focused concentration) vary greatly in the general population, by as much as 20 dB. Masked hearing thresholds tend to be higher than absolute thresholds, and reflect the ability of people to notice a particular sound in the presence of other competing sounds. Loudness is the intensity of the auditory sensation, and its perception varies from one individual to another. Some people may be more sensitive to sound than the general population, either due to higher auditory sensitivity (lower hearing threshold) or sound perception.

Sound signals are processed in various parts of the brain, through direct and indirect mechanisms. In reviewing the evidence regarding potential health effects of wind turbine noise, the Panel was informed by a schema proposed by Babisch (2002) suggesting that both the direct and indirect effects of noise lead to physiological arousal (see Chapter 5).

5

Assessment of Evidence

- Recent Reviews of Wind Turbine Noise and Health
- Proposed Adverse Health Effects
- Prevalence of Reported Health Effects and Noise Complaints in Canada
- Conceptual Framework for Hypothesized Health Effects
- Evidence Regarding Sound from Wind Turbines and Human Health
- Weighing and Summarizing Evidence
- Chapter Summary

5 Assessment of Evidence

Key Findings

- The Panel identified 32 reported symptoms and health conditions attributed to exposure to sound from wind turbines, based on a broad survey of peer-reviewed and grey literature, web pages, and legal decisions.
- The adverse health effects most widely attributed to wind turbine sound are annoyance, sleep disturbance, and stress-related symptoms. This does not provide evidence of causation, but does indicate a level of concern related to these possible health effects.
- The empirical research available to assess the support for a causal relationship between wind turbine noise and adverse health effects is composed of a great variety of sources, including peer-reviewed articles, conference papers, a graduate thesis, a book, and grey literature.
- More than 300 publications were found through a comprehensive search, and these were narrowed down to 38 relevant studies.

To respond to the Charge, the Panel developed an approach based on the concepts of evidence-informed public health proposed by the National Collaborating Centre for Methods and Tools at McMaster University in 2008 (Ciliska *et al.*, 2008). Broadly speaking, when considering a public health issue, existing evidence concerning the problem and its solution is found and weighed according to the strength of its methods and findings; conclusions are based on the weight of evidence. In using this approach, the Panel followed three major steps:

- Define the issue: The Panel began by compiling, from a broad range of sources, a list of health effects that have been attributed to wind turbines. The health effects identified provided key terms used to search for relevant empirical research.
- Search and appraisal: The Panel searched for and appraised empirical research papers discussing the effect of wind turbine noise on human health.
- Synthesis: The Panel used Bradford Hill's guidelines as a basis to weigh the body of evidence and screen for plausibility of causation between exposure to sound from wind turbines and specific health effects (Bradford Hill, 1965). In addition to empirical research specific to wind turbines, review articles and results from research on other environmental noise sources were used when appropriate, and when empirical evidence from wind turbines was lacking. The Panel's findings concerning causation, and the state of evidence in each case, were summarized using standard language (HCN, 1994; IARC, 2006). Figure 5.1 illustrates the major steps of the review process undertaken by the Panel.

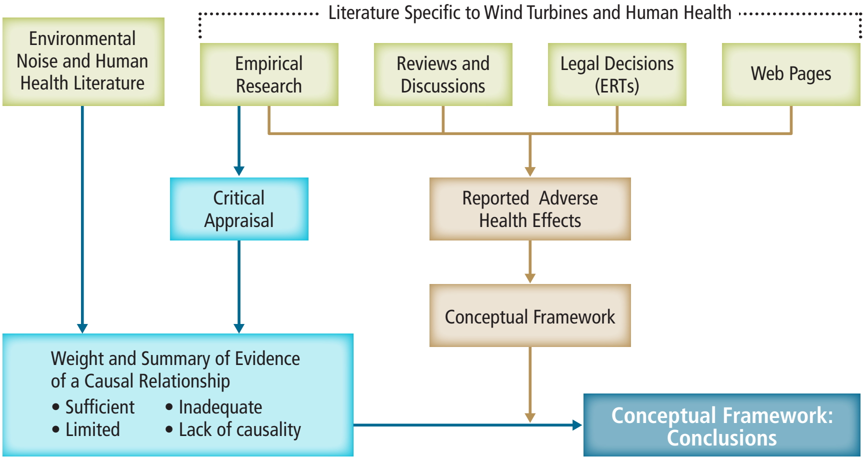


Figure 5.1

Evidence Assessment Process

Brown lines show information used in defining potential health outcomes and in building models of pathogenic mechanisms; blue lines show the literature review process with reference to causal associations between wind turbine noise and each potential health effect. Empirical research, grey literature, and sources such as legal decisions and web pages guided the Panel in listing health effects possibly linked to wind turbine noise. Consideration of these health effects served the development of a conceptual framework and search for empirical research specific to the effect of wind turbine noise on human health. The empirical evidence resulting from this search was critically appraised and constituted along with broader literature on the health effects of environmental noise. The body of evidence for each proposed adverse health effect was reviewed based on Bradford Hill's guidelines. Findings were summarized in the report using language adapted from the International Agency for Research on Cancer (IARC). The conceptual framework was updated, taking into account these findings, and presented in Figure 7.1.

5.1 RECENT REVIEWS OF WIND TURBINE NOISE AND HEALTH

Many reviews have been published on wind turbines and health, several in the past five years alone. Among these recent reviews are those commissioned by various orders of governments (HGC Engineering, 2010; NHMRC, 2010, 2014; Masotti & Hodgetts, 2011; Ellenbogen *et al.*, 2012; Rod, 2012; Brisson *et al.*, 2013; Hodgetts & O'Connor, 2013; Merlin *et al.*, 2013), non-profit organizations (e.g., Sierra Club Canada, 2011), and industry organizations (e.g., Colby *et al.*, 2009). Other reviews were either published in peer-reviewed journals (e.g., Roberts & Roberts, 2013) or self-published online (e.g., Frey & Hadden, 2012). In general, these reviews were inconsistent with regard to their findings on the effects of wind turbine noise on human health and were not used in the critical evaluations. However the Panel used them to help guide and frame issues in the current context and in ensuring that key findings were communicated clearly.

5.2 PROPOSED ADVERSE HEALTH EFFECTS

The Panel began by identifying health conditions and symptoms that have commonly been attributed to wind turbine noise. The Panel took a broad approach to assembling such a list, including a review of the scientific peer-reviewed literature related to wind turbine noise, as well as a sample of lay literature such as web pages, self-published reports or books, and legal decisions. Each source was scanned for mentions of symptoms attributed to wind turbine noise. These documents were not assessed by the Panel, and the evidence supporting claims of association was not evaluated at this stage.

Twenty internet sites (36 web pages) were identified from references in recent reviews, empirical literature, and a bibliography compiled from submissions to Health Canada during consultations on the design of a wind turbine noise and health study (Health Canada, 2013a). The Google search engine was used to search each site (web domain) for pages published since 2009 that discuss wind turbine sound and human health.[3] These pages included blog posts, individual accounts, and other types of web documents. Some sites also had pages devoted primarily to summarizing health effects of wind turbines, easily identifiable from the home page, and those were also scanned as part of the process. In addition, decisions from Environmental Review Tribunal (ERT) hearings in Ontario, Canada, were scanned for health effects claimed by appellants or described by expert witnesses.

Only health effects attributed to wind turbines reported in the last five years (from 2009 to 2014) were included, to ensure that they are current and relevant to modern utility-scale wind turbines. Older wind turbine models and designs produce higher levels of sound, including infrasound and low-frequency sound, than modern wind turbines (see Section 2.1). In addition, sound propagation factors differ between the new and old turbines owing to the height of the wind turbines.

---

[3] Search terms used: ("wind turbine*" or "wind farm*") and (sound or noise) and (health or sick or symptom*). If no results were found, a second search was attempted using the terms: "wind turbine" noise health.

Table 5.1 presents 32 health conditions that have been attributed[4] (proposed but unconfirmed) to wind turbine noise in various types of sources (e.g., self-reported individual case, compiled list). This list was the starting point for the Panel to assess the evidence for causal relationships between these outcomes and wind turbine noise but does not constitute in any way evidence for causal relationship.

Table 5.1

Proposed, but Unconfirmed, Adverse Health Effects Attributed to Wind Turbine Noise in at Least Three Documents Reviewed

Condition or Symptom	Peer-Reviewed Study	Peer-Reviewed Review	Conference Proceedings	Grey Literature	Legal Decision	Web Page
Number of Sources Reviewed	20	5	6	13	5	36
Annoyance	●	●	●	●	●	●
Sleep disturbance	●	●	●	●	●	●
Stress, tension	●	●	●	●	●	●
"Health-related quality of life"	●	●	●	●	●	●
"Vibroacoustic disease"		●	●			●
Cardiovascular System						
Cardiovascular disease			●	●		●
High blood pressure (hypertension)		●		●	●	●
Irregular heartbeat (cardiac dysrhythmia, tachycardia)	●	●	●	●	●	●
Endocrine System						
Diabetes		●	●	●	●	●
Immune System						
Impaired immunity				●		●
Musculoskeletal System						
Back pain	●				●	
Joint pain	●					●
Muscle pain (myalgia)	●				●	●
Shaking (palsy)	●			●	●	

continued on next page

---

[4] This list is not exhaustive and is meant to capture the major issues only. A single source document may contribute to multiple conditions and symptoms (dots) in the table.

Condition or Symptom	Peer-Reviewed Study	Peer-Reviewed Review	Conference Proceedings	Grey Literature	Legal Decision	Web Page
Nervous System (General)						
Cognitive or task performance	●	●	●	●	●	●
Disturbances of skin sensation	●			●	●	
Fatigue	●	●	●	●	●	●
Headache	●	●	●	●	●	●
Nausea	●	●	●	●	●	●
Pressure in the chest	●					●
Sensation of internal vibration	●			●	●	●
Vertigo, dizziness	●	●	●	●	●	●
Vision problems			●	●	●	●
Nervous System (Auditory)						
Communication interference			●		●	●
Ear pressure or pain	●	●	●	●	●	●
Hearing loss			●	●		●
Tinnitus	●	●	●	●	●	●
Psychological Health						
Anxiety	●	●		●	●	●
Depression	●	●	●	●	●	●
Irritability		●	●	●	●	●
Psychological distress	●	●	●	●		●
Respiratory System						
Nosebleed				●	●	●

This list was used as a starting point for the Panel to assess the evidence for causal relationships between these health outcomes and wind turbine noise. It includes health effects attributed to wind turbine noise, without assessing the strength of evidence. It includes self-reported individual reports and compiled lists from various sources such as web pages, and grey and peer-reviewed literature. A dot corresponds to one or more mentions for the given type of document, but only symptoms mentioned in at least three separate documents of any type are presented. Symptoms associated with "wind turbine syndrome" (Pierpont, 2009) are considered individually in the list above.

5.3 PREVALENCE OF REPORTED HEALTH EFFECTS AND NOISE COMPLAINTS IN CANADA

The Panel's ability to assess the prevalence of adverse health effects related to wind turbine noise in Canada was limited by a lack of available data. Public health surveillance for chronic diseases falls under the responsibility of federal, provincial, and territorial governments (Health Canada, 2003a). However, no formal processes or surveillance programs exist in Canada to capture potential health outcomes resulting from wind turbine noise. Neither did the Panel identify, through its literature review, research studies in Canada or internationally that had estimated prevalence. In the absence of such data, estimates of disease burden attributable to wind turbine noise could be derived from data on (1) the diseases causally associated with wind turbine noise; (2) the incidence of each such disease in the general population; (3) the proportion of the population exposed to wind turbine noise; and (4) the incremental risk of developing the disease associated with exposure to wind turbine noise. However, calculating such estimates is currently challenging because of a paucity of data with respect to all four of the necessary parameters.

In 2013, the Pembina Institute studied documented formal noise complaints concerning wind turbines in Alberta made to various authorities. This study includes noise complaints to regulatory bodies, municipalities, and wind farm operators, covering approximately 90% of the wind energy capacity in the province (Thibault *et al.*, 2013). This study found five noise complaints related to wind turbine operations between 2007 and 2011 across Alberta. They concluded that noise complaints to authorities related to wind turbines had been infrequent and measurably fewer than complaints related to conventional energy activities such as oil and gas operations (Thibault *et al.*, 2013).

There are limitations to using complaints to estimate prevalence of health outcomes. Alberta may not represent the whole of Canada, and the situation may be different in other parts of the country. For example, there are likely many more noise complaints in Ontario, given the many cases before the Environmental Review Tribunal. No systematic review by independent parties of noise complaints across jurisdictions in Canada has been performed, likely because of the lack of consistency in reporting mechanisms for such complaints or health reports, the collection of complaint information, and whether complaints are even related to health (as opposed to economic disparity or visual impacts, for example). However, there are studies of noise complaints in other countries, such as Australia, where policies require that noise complaints made to wind project developers are collated and made available to the public. Such policies allow for an analysis of these complaints, showing uneven patterns of complaints focused on specific projects within the country, several years following initial construction. In Australia, from 2006 to 2012, 129 complaints were received by wind turbine developers corresponding to about 0.4% of the population living within 5 km of a wind turbine (Chapman *et al.*, 2013). However, conclusions on the probability of complaints in Canada cannot be reached based on other countries' studies of complaints.

5.4 CONCEPTUAL FRAMEWORK FOR HYPOTHESIZED HEALTH EFFECTS

The Panel developed a framework (Figure 5.2) that included the proposed but unconfirmed adverse health effects of wind turbine noise described in Table 5.1, as well as possible mechanisms relating noise and health to the various component characteristics of wind turbine noise. This framework was used to guide the search for, and evaluation of, relevant evidence concerning these causal relationships between wind turbine noise and the health outcomes in Table 5.1. The analysis is presented in Chapter 6, and an updated figure (after review of the evidence and the final conclusion of the Panel) can be found in Chapter 7.

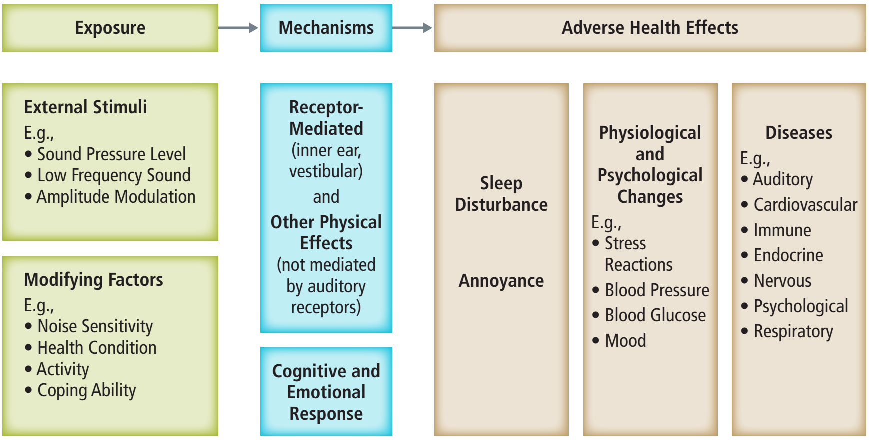


Figure 5.2

Proposed Elements of Potential Relationships Between Wind Turbine Noise and Adverse Health Effects

This framework includes proposed physical mechanisms, some of which are mediated by effects on auditory and vestibular receptors, as well as proposed effects mediated by a person's cognitive and emotional response to sound.

5.5 EVIDENCE REGARDING SOUND FROM WIND TURBINES AND HUMAN HEALTH

The empirical research used to assess causal associations between exposure to sound from wind turbines and the development of adverse health effects was found in peer-reviewed literature and conference papers. The Panel also considered relevant grey literature, such as technical reports, and reports published by not-for-profit organizations. All documents presenting results of empirical studies were reviewed (see Appendix B), and only studies assessing the effects of modern utility-scale wind turbines[5] (500 kW or more) were considered.

5.5.1 What Can Scientific Studies Tell Us About Causality?

The ability to draw valid conclusions from a health study depends largely on the quality of that study. In an experimental study, all aspects of the study are controlled by the researcher and are thus modifiable and reproducible. In most population health studies, such control is not possible. Factors such as people's location, age, when the wind turbine is installed, and exposure to noise cannot be controlled. This does not mean that observational studies (as epidemiologists call studies of people in the "real world") are necessarily of a lower quality than experimental studies. Carefully designed, well-executed studies that consider the impact of all factors that may influence relationships between an exposure and outcome are very powerful (Howick *et al.*, 2009). High-quality observational studies have informed many of the major public health advances in the past century, such as the link between lung cancer and smoking, and asbestos and mesothelioma.

Few if any studies are perfect, meeting every test of quality, but that does not mean they are without value. It does mean, however, that a determination of causality is more reliable when that determination is based on the "weight of evidence" provided by multiple studies, because of factors such as consistency of findings across studies of different designs, different analysis techniques, different populations, etc. A consistent finding of a relationship across several studies strengthened the Panel's confidence that the observed relationship is causal and not a simple association.

---

[5] All wind turbines in Canada are modern (in the last 20 years) and few (1.6%) are not utility-scale (<500 kW). See Figure 2.1.

5.5.2 Assessing the Methodological Quality of a Study

Study validity is threatened by poor design, errors in measurement, or failure to take into account confounders (i.e., factors that muddy the relationship between a cause and effect, such as between wind turbine noise and sleep). Below is a brief review of some of the main issues (or biases) that commonly affect overall methodological quality and study validity:

Study Design

Study design strongly influences methodological quality (see Appendix A). A randomized controlled trial or experiment is generally considered to be the highest-quality study design, but these are rarely feasible in population-based studies. Two types of longitudinal study designs — cohort and case-control studies —follow a study population over time. These designs analyze “natural experiments,” since the researcher does not control the conditions under which the study population lives. Cohort and case-control studies may use sophisticated design and analysis tools to improve validity. At the other end of the spectrum are case reports; while these have some usefulness in initial identification of associations between exposures and diseases, they are prone to many forms of bias, affecting validity.

Sample Size

To reduce the impact of random differences between disease risk in exposed and unexposed groups, a certain number of participants or study subjects is required. Generally, studies of larger groups have more statistical power than those of smaller groups to detect effects that are less pronounced (i.e., larger studies increase confidence that any observed difference in outcome between two groups is real, and not just random chance). If studies are also looking at exposed sub-groups (e.g., males and females, several age groups) and also multiple confounders, then study size may need to be very large.

Confounding Factors

Scientists are always concerned that, when they identify a possible relationship between an exposure and an outcome, the relationship might have been caused by some other unknown factor. For example, if it were found that gamblers were more likely to get lung cancer, researchers would be cautious to label this a causal relation, because casinos are smoky places; perhaps it is smoking, and not gambling, that is to blame for the excess rate of lung cancer in the subject population. These factors are called confounders. However, there are several techniques scientists can use to control the impact of confounders on a study.

Misclassification of Exposure or Outcome

The quality of the measurement of the exposure (such as sound from wind turbines) or the outcome (such as blood pressure) is very important to the quality of a study and to its validity. If a study does not accurately measure these two variables, then it may misclassify exposed subjects as being unexposed and *vice versa*. Similarly, without a good measure of an outcome, a study may be lumping people who do not have a disease in with those who do, thus "diluting" the study group. In both examples of misclassification (of exposure or of outcomes), the apparent relationship between exposure and outcome may be diminished relative to the true relationship, which thus becomes obscured.

In reviewing studies, a key concern is how accurately the study measures exposure. Studies on noise, for instance, can be highly complex because noise has several parameters (amplitude, frequency, variation in time) that make up the acoustic signal to which a subject is exposed. In the case of an outcome or disease, a *case definition* ("standard criteria for deciding whether a person has a particular disease" or condition (Columbia University, n.d.)) that is systematic and ideally based on an unbiased test, such as a blood pressure examination, is needed. Self-reported outcomes are generally considered more prone to misclassification or bias.

Selection Bias

Scientists must be very careful in deciding how individuals are recruited into studies to avoid biases that could skew the results. Ideally, a study includes a random selection of individuals who are either exposed or unexposed (for a cohort study), or those with a disease and those in whom the disease is absent (in a case-control study). Self-selection bias may occur if, for example, a scientist asks for volunteers to participate in a study; volunteers are often those with a special interest in the subject, and may differ in important ways from the general population. A biased selection of subjects is not representative of the general population, and the study results may therefore be skewed away from the "truth."

Summary

Observational epidemiological studies can be very powerful tools in discovering and explaining causal associations — that is, does a specific exposure cause a certain disease outcome? However, most studies have strengths and weaknesses, and must be reviewed carefully in order to identify problems that may affect the study's validity, to assess the body of knowledge (i.e., multiple studies), and to consider the weight of evidence. Other factors such as biological plausibility and experimental evidence must be looked at, too, when assessing causality. A short summary of the evidence reviewed is given in Appendix B, which is intended to be used as a supplement to Chapter 6.

5.6 WEIGHING AND SUMMARIZING EVIDENCE

5.6.1 Searching for Empirical Research

The aim of the search for evidence was to be as comprehensive as possible. The Panel searched the SCOPUS and PubMed databases using keywords related to wind turbines, general health, and specific health conditions attributed to wind turbine noise (see Appendix B). Search results from both databases were combined and duplicates removed, producing over 300 articles published in peer-reviewed journals and conference proceedings between 1966 and 2014. Abstracts and titles of papers from all of these sources were scanned to ensure relevance, which narrowed the number of articles and reports to 33. The Panel also considered evidence submitted to Health Canada during consultation on the design of a wind turbine noise and health study (Health Canada, 2013b), literature cited in key reviews, and Panel members' input. Through this process, eight additional studies, including a graduate thesis, a book, and grey literature, were added to the evidence base. In total 38 studies were therefore included and critically appraised. No time limitation was applied to studies for inclusion; however, the relevance of the wind turbine design was verified. The quality and weight of the evidence presented in an empirical study was critically reviewed using a questionnaire based on assessment factors used by the U.S. Environmental Protection Agency (EPA, 2003). This critical review informed the Panel in describing the evidence.

The Panel also extended the search for empirical literature discussing the health effects of specific sound characteristics produced by wind turbines, such as infrasound, low-frequency sound, and amplitude modulation. This was undertaken to look for additional evidence on the possible mechanism that could cause adverse health effects, where evidence was lacking. The Panel also used additional evidence from peer-reviewed environmental noise literature.

5.6.2 Assessing Causality

Epidemiological studies cannot determine the cause of an outcome in a given individual, or even the mechanism responsible, but they can establish an association between a given exposure and the frequency of an outcome in a population (e.g., many epidemiological studies assessed the association between smoking and lung cancer). Causation can be inferred, usually based on several factors, such as the strength and consistency of the association, mechanistic plausibility, as well as the temporal sequence and biological gradient — or dose-response relationship — of the exposure and the outcome (Bradford Hill, 1965; Howick *et al.*, 2009). Along with coherence, specificity (a reliable association between exposure and a line of outcomes), and evidence from experiments and analogy, these guidelines were proposed by Bradford Hill (1965) for evaluating the plausibility of causal relationships based on observational studies, even in the absence of randomized controlled experiments.

A critical appraisal guided the Panel in assessing and assigning weight to the evidence linking wind turbine noise to health effects. The Bradford Hill guidelines were used to guide Panel deliberations and to structure the summaries of evidence (Chapter 6), keeping in mind that they are not intended to be strict guidelines, and should be applied to a body of evidence rather than to individual studies. The final determination of causality was ultimately based on the Panel's judgment of the findings.

5.6.3 Summarizing Findings

The Panel further adopted standard language to summarize the findings of causal relationships, following a framework similar to that used by the International Agency for Research on Cancer (IARC, 2006), also adopted by the Health Council of the Netherlands (HCN, 1994). According to this scheme, the overall strength of evidence for a causal relationship falls into one of four categories:

- **Sufficient evidence of a causal relationship:** A relationship was observed between exposure to sound from wind turbines and a specific health effect in studies in which chance, bias, and confounding factors can be ruled out with reasonable confidence.
- **Limited evidence of a causal relationship:** An association was found between exposure to sound from wind turbines and a health effect for which causal interpretation is considered by the Panel to be plausible, but for which chance, bias, and confounding factors cannot be ruled out with reasonable confidence.
- **Inadequate evidence of a causal relationship:** The available studies are of insufficient quality, or lack the consistency or statistical power to permit a conclusion about the presence or absence of a causal relationship.
- **Evidence suggesting lack of causality:** Several adequate studies covering the full range of exposure are available that are mutually consistent in not showing a positive association between exposure and effect at any observed level of exposure.

5.7 CHAPTER SUMMARY

The Panel considered a range of evidence sources in various ways:

- to identify health outcomes that have been attributed, claimed, or reported to be linked to wind turbine noise;
- to develop a conceptual framework of hypothesized pathways linking wind turbine noise to the identified outcomes; and
- to weigh evidence for these causal relationships.

The Panel identified 32 potential adverse health effects attributed to wind turbine noise, with sleep disturbance, annoyance, and stress effects being mentioned the most often in the sources reviewed. Literature on the outcomes identified was searched and reviewed systematically. A total of 38 empirical studies were selected and assessed for methodological quality, and these were supplemented by relevant peer-reviewed articles from the environmental noise literature. The Panel used the causation guidelines of Bradford Hill to inform and structure the review, and a framework adapted from the International Agency for Research on Cancer to summarize the findings for evidence of causal relationships.

6

Current Evidence Related to Adverse Health Effects of Wind Turbine Noise

6 Current Evidence Related to Adverse Health Effects of Wind Turbine Noise

Key Findings

Primary evidence is available for some, but not all, health effects attributed to wind turbine noise. The following findings are based on available primary evidence, mainly from population-based studies and in some cases experimental studies:

- The current state of the evidence is ***sufficient*** to conclude that a causal relationship between exposure to wind turbine noise and annoyance can be established; however, knowledge gaps remain with regard to the influence of specific sound characteristics, such as amplitude modulation, low frequency content, or visual aspects of wind turbines, which are difficult to study in isolation.
- The current evidence is ***limited*** with regard to the relationship between exposure to wind turbine noise and sleep disturbance. The available evidence suggests that a direct or indirect mechanism might exist, but confounding factors cannot be ruled out with reasonable certainty.
- The available evidence is ***inadequate*** to establish the presence or absence of a causal relationship between exposure to wind turbine noise and stress. Similar to sleep disturbance, available evidence suggests that a direct or indirect mechanism might exist; however, the evidence lacks methodological and statistical strength.
- The Panel concluded that there is ***evidence of no causal relationship*** between exposure to wind turbine noise and hearing loss.
- While statistically significant associations between exposure to wind turbine noise and diabetes and tinnitus have been found, these associations are not consistent across studies and evidence remains ***inadequate*** to determine the presence or absence of causal relationships.
- Primary research has also addressed cardiovascular diseases, effects of non-audible sound, cognitive and mental performance, psychological health, and general quality of life; however, evidence remains ***inadequate*** to determine the presence or absence of causal relationships between exposure to wind turbine noise and any of these health effects.

Using its search and assessment process (Chapter 5), the Panel reviewed evidence on adverse health effects, and assessed and summarized the current body of evidence. This chapter reviews the potential health effects identified in the preliminary scan of health outcomes (Table 5.1) and offers the Panel's conclusions about the state of the evidence regarding each outcome. Table B.2 (in Appendix B) summarizes the evidence from empirical research on health impacts of wind turbine noise. The Panel identified the datasets that have been used in the papers reviewed in this report and gave each dataset a code identifying the country of a study and the year the study was undertaken (e.g., NL-07), as presented in Table B.2. This table also provides an overview of the key methodological aspects of each study. The following sections provide a detailed review of the evidence for all health outcomes that have been the subject of population-based studies or laboratory experiments. The Panel's findings with regard to these outcomes are summarized in Chapter 7. The Panel also considered possible causal mechanisms linking exposure to wind turbine noise and other health outcomes that have been mentioned in case series or other sources, but have not yet been the subject of empirical research.

6.1 ANNOYANCE

Noise annoyance can be defined as "a feeling of displeasure evoked by a noise" and "any feeling of resentment, displeasure, discomfort and irritation occurring when a noise intrudes into someone's thoughts and moods or interferes with activity" (Passchier-Vermeer & Passchier, 2006). Annoyance is the most common and most studied effect of noise on individuals. Whether a person becomes annoyed may depend on the sound's characteristics (e.g., how intense it is, how it varies with time, and what frequencies it contains), and on factors related to the individual (e.g., noise sensitivity, attitude towards the noise source, physiological and psychological state), and on situational or contextual factors (e.g., activities performed or intended to be performed, expectations of disturbance, noise source-related factors such as controllability of the noise source, fear, and permanence). The Panel used this broad descriptive definition, but stresses that in most studies described below, researchers used questionnaire data in which respondents replied based on their own perception and recollection of annoyance.

Pedersen's (2011) re-analysis of three study datasets (SWE-00, SWE-05, NL-07) showed a statistically significant association between exposure to wind turbine noise and annoyance. Pedersen found that an increase in the estimated A-weighted sound pressure level was associated with an increased proportion of participants being annoyed. In these three datasets, the proportion of respondents annoyed outdoors ranged from 5 to 20% at 35-40 dB(A) and from 10 to 45% at 40-45 dB(A) (Persson Waye, 2009). Annoyance was the only health effect of wind turbine noise that was consistently associated with estimates of A-weighted sound levels in all three datasets. Preliminary analyses of studies in Poland (POL-13) and Japan (JAP-10) found similar exposure-response relationships between A-weighted sound levels and annoyance (Kuwano *et al.*, 2013; Yano *et al.*, 2013; Pawlaczyk-Łuszczyńska *et al.*, 2013; Pawlaczyk-Łuszczyńska *et al.*, 2014). In the Polish study (Pawlaczyk-Łuszczyńska *et al.*, 2013), the percentage of respondents who were annoyed (i.e., those who reported being "rather annoyed," "annoyed," or "extremely annoyed" on a five-point verbal scale) by exposure to wind turbine noise outdoors increased from 27.1% at 35-40 dB(A) to 63.6% at 45-50 dB(A). Similarly, the percentage of subjects annoyed by exposure to wind turbine noise indoors increased from 18.6% at 35-40 dB(A) to 23.4% at 40-45 dB(A), but decreased to 18.2% at 45-50 dB(A). In the Japanese study (Yano *et al.*, 2013), the share of respondents who were "very" or "extremely" annoyed increased from 9.7% to 22.6% as night-time exposure levels increased from 30 to 45 dB(A).[6]

To date, few studies have used actual measurements of noise exposure rather than estimated exposure levels. Sound measurements in the field are costly, time-consuming, and difficult to conduct consistently across large population groups. Therefore, studies using sound measurements have been field experiments rather than population-based studies. Bockstael *et al.* (2012) conducted regular sound measurements at eight households located between 270 metres and approximately 750 metres from the closest of three wind turbines. The authors found that noise exposure and annoyance depended on wind speed, wind direction (i.e., angle of the rotating turbine to the exposed households), as well as the energy output of the wind turbines. Magari *et al.* (2014) conducted short-term indoor and outdoor sound measurements at 52 households located approximately 400 to 800 metres from the closest turbine of a large wind park. Average L_{Aeq} measures were 47 dB(A) (standard deviation: 11.5 dB(A)) indoors and 45.3 dB(A) (standard deviation: 8.2 dB(A)) outdoors. The researchers also surveyed residents, and their survey results did not support an exposure-response relationship between short-term indoor or outdoor noise exposure and self-reported annoyance. However, the data did show correlations between measured noise exposure and concern about health effects, and between noise exposure and the prevalence of sleep disturbance and stress. The authors noted that larger cohort studies with sound measurements taken indoors and outdoors are necessary to verify the divergent results from studies using calculated exposure measures. Zajamsek *et al.* (2014) presented a method to simultaneously record time-series noise data and corresponding annoyance ratings submitted by exposed subjects. The authors tested the method at two homes at a distance of 2.5 km and 8 km from the nearest wind turbine. While the recordings showed sound patterns that correlated with the wind turbines' energy output, the overall noise level and annoyance of residents at these

---

[6] Although all studies used a five-point verbal scale, the terminology used is different among papers. For example "extremely" and "very" annoyed in Yano *et al.* (2013) corresponds to "extremely annoying" and "annoying" in Zajamsek *et al.* (2014) and "very annoyed" and "rather annoyed" in Pedersen (2011). There are therefore differences due to language but the results are considered comparable.

distances were better explained by the prevailing wind speeds at the residences (Zajamsek *et al.*, 2014). In population-based studies with large sample sizes included in this review, the relative risk of being annoyed by wind turbine noise increased with estimated outdoor sound pressure levels, suggesting that annoyance follows an exposure-response relationship (see Figure 6.1).

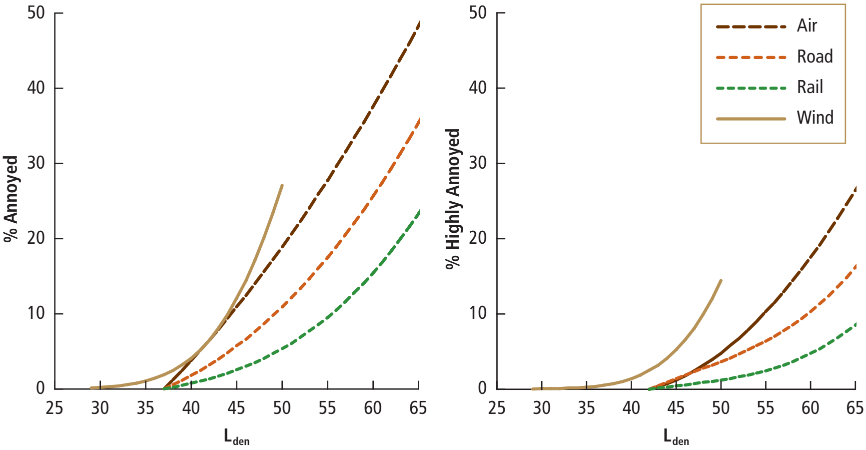
Similar exposure-response relationships based on sound pressure level were also found in laboratory experiments involving humans. Among these, Lee *et al.* (2011) conducted an experiment to identify the role of amplitude modulation on annoyance, using recorded samples of sound from wind turbines to simulate amplitude modulated exposure with modulation depth between 5 and 12 dB at equivalent sound pressure levels between 35 and 55 dB(A). The results showed that annoyance increased with both the equivalent sound pressure level of exposure and the amplitude modulation depth of wind turbine sound. Seong *et al.* (2013) investigated annoyance using sound samples representing exposure at different distances and angular positions relative to the direction of the wind hitting a wind turbine, with L_{Aeq} ranging approximately from 25 to 50 dB(A). Maffei *et al.* (2013) and Ruotolo *et al.* (2012) used audio-visual simulations of distance, including recordings of real-world exposure, as auditory stimuli. Fastl and Menzel (2013) showed that annoyance decreased with sound pressure level in subjects exposed to amplitude modulated sound stimuli between 50 and 38 dB(A). While none of these experiments (Ruotolo *et al.*, 2012; Fastl & Menzel, 2013; Maffei *et al.*, 2013) were specifically designed to investigate the exposure-response relationship, the results consistently showed that increasing levels of sound from wind turbines are associated with higher levels of annoyance among those exposed.

Annoyance can be caused by a multitude of factors, including several that often occur together with exposure to wind turbine noise, such as visual impacts of wind turbines. The studies reviewed by the Panel controlled for different combinations of contributing factors, including self-identified noise sensitivity (Pedersen & Persson Waye, 2004, 2007; Pawlaczyk-Łuszczyńska *et al.*, 2013); background noise from road traffic (Bakker *et al.*, 2012); possible masking of wind turbine noise from other noise sources (Pedersen *et al.*, 2010; Van Renterghem *et al.*, 2013); self-identified personal attitudes (Pedersen & Persson Waye, 2004; Pawlaczyk-Łuszczyńska *et al.*, 2013); the influence of background sound on annoyance from wind turbine noise (Bolin *et al.*, 2012), participation in economic benefits from wind turbine operation (Pedersen & Persson Waye, 2004; Janssen *et al.*, 2011); and characteristics of living environments (Pedersen & Larsman, 2008). The observed association between wind turbine noise and annoyance generally remained after controlling for these factors. Regardless, while cross-sectional studies can control for these factors when assessing the relationship between wind turbine noise and annoyance, they suffer from an inability to determine the temporality of the relation (i.e., whether exposure to wind turbine noise leads to negative attitudes or whether negative attitudes affect noise perception).

A factor in perception of and annoyance due to wind turbine noise is the visual impact of turbines. In several studies, residents in direct line of sight of a wind turbine were more likely to be annoyed than those who could not see a wind turbine (Pedersen & Persson Waye, 2004; Pawlaczyk-Łuszczyńska *et al.*, 2013). Similarly, residents who valued the visual appeal and quietness of rural landscapes were more likely to be annoyed than those who viewed the countryside as a place for economic opportunity (Pedersen & Persson Waye, 2004; Mulvaney *et al.*, 2013). Laboratory experiments using short-term exposure to infrasound have shown that positive and negative expectations can influence self-reported symptoms and impacts on mood in positive and negative directions, respectively (Crichton *et al.*, 2014a, 2014b). Bockstael *et al.* (2013) found that subjects who could recognize sound from wind turbines among other types of environmental sound were more likely to be annoyed than subjects who noticed the sound without recognizing its source. The authors suggested these results could support a hypothetical causal pathway in which noticing a wind turbine is followed by an appraisal step, the outcome of which influences the degree of annoyance (Bockstael *et al.*, 2013).

Pedersen *et al.* (2009) noted that their study design could not exclude the possibility that negative attitudes to wind turbines are caused in part by noise exposure or that annoyance is more strongly associated with visual intrusion than with sound exposure (see also Ellenbogen *et al.*, 2012). Pedersen and Larsman (2008) used a series of models to simultaneously account for different aspects of attitude including visual attitude and other impacts of wind turbines, and found that the association between wind turbine noise and annoyance is significant even when other factors are considered, but that a negative visual attitude would enhance the risk for noise annoyance for people living on flat terrain.

Janssen *et al.* (2011) used the responses from the Swedish and the Dutch studies (SWE-00, SWE-05, NL-07) to compare the exposure-response relationship for annoyance from wind turbine noise with annoyance associated with air, road, and rail transportation noise. The authors found that annoyance from wind turbine noise occurred at relatively low sound pressure levels of 40 to 45 dB(A). The model predicted that the percentage of persons annoyed by wind turbine noise indoors was higher than the percentage annoyed by other sources of sound at the same sound pressure level and grew faster when sound pressure levels increased (Figure 6.1).



Reproduced with permission from Janssen, S. A., Vos, H., Eisses, A. R., & Pedersen, E. (2011). A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. The *Journal of the Acoustical Society of America*, 130, 3746-3753. Copyright 2015, Acoustical Society of America

---

Figure 6.1

Comparison of Annoyance Due to Wind Turbine Noise and Transportation Noise

Comparison of the percentage of residents annoyed (left) or highly annoyed (right) indoors due to wind turbine noise (wind) and due to traffic noise (air, road, rail), based on data from datasets SWE-00, SWE-05, and NL-07. For comparison, sound exposure measures are expressed as L_{den} values calculated using the A-weighted immission levels determined in the original studies in accordance with the European Union environmental noise guidelines. L_{den} (day/evening/night sound level, also referred to as community noise equivalent level or CNEL) expresses the average sound level over a 24-hour period with a penalty of 5 dB added for the evening hours (7 pm to 10 pm) and a penalty of 10 dB added for the night-time hours (10 pm to 7 am). The calculation of L_{den} is based on a complex protocol that includes correction factors for specific conditions affecting noise exposure at the location of each respondent, such as prevailing wind speeds and direction or topography.

Earlier research suggested that the higher risk of annoyance was related to the specific sound characteristics of wind turbine noise, including amplitude modulation and tonality. For example, participants in an experimental study described wind turbine noise as “lapping,” “swishing,” or “whistling,” and perceived these sound characteristics as annoying (Persson Waye & Öhrström, 2002). In another experiment, Lee *et al.* (2011) used stimuli based on recorded sound samples that were processed to simulate sounds with different levels of modulation depth. They showed that the amplitude modulation of sound from wind turbines is perceived as more annoying than continuous sound with the same frequency and average sound level. Based on a similar experiment, Seong *et al.* (2013) suggested that a measure of weighted maximum sound level that captures the peaks of amplitude modulation (L_{AFmax}), rather than daily averages (L_{Aeq}), is the best predictor for the risk of annoyance. A recent report prepared by the University of Salford for RenewableUK, a wind energy industry group, included a series of listening tests with 20 participants using sound stimuli from real-world recordings of wind turbine noise with increasing modulation depth at constant L_{Aeq} (RenewableUK, 2013). The objective was to explore how much higher the level of an unmodulated sound would have to be in order to be perceived as equally annoying to a modulated sound. The results showed that increasing modulation depth led to increasing annoyance ratings. On average, the adjustments necessary to express the perceived difference in loudness of a sound with amplitude depth varying from 0 dB to 12 dB were 3.5 dB for a 30 dB(A) test sound and 1.7 dB for a 40 dB(A) test sound. In other words, a modulated sound of L_{Aeq} of 30 dB(A) was perceived to be as loud as an unmodulated sound of 33.5 dB(A) (von Hünerbein *et al.*, 2013).

A similar study by Yokoyama *et al.* (2013) used 52 low-frequency (1-250Hz) stimuli with amplitude modulation that was generated with sound recordings from wind turbines, in order to test the subjective noise perceived by 10 subjects. This study found that perceived noise increased with increased amplitude modulation depth, although the time-averaged sound pressure level remained the same (Yokoyama *et al.*, 2013). While the samples in these experiments were too small to generalize the findings, the results suggested that amplitude modulation may lead to higher annoyance than an unmodulated sound at the same equivalent sound pressure level. Furthermore, higher annoyance ratings could be linked to modulation depth in an exposure-response relationship (Yokoyama *et al.*, 2013). Von Hünerbein *et al.* (2013) also noted that, in real-world conditions, spectral characteristics (tonality) vary along with amplitude, with both effects likely to affect annoyance. These findings are consistent with results of studies on other types of noise with amplitude modulation, such as exhaust noise (Kantarelis & Walker, 1988), or noise from heating, venting, and air-conditioning systems (Bradley, 1994).

Some researchers have suggested that the higher degree of annoyance associated with wind turbine noise could be related to its low-frequency components. Earlier research showed that low-frequency noise produced by fans was perceived as more annoying than other types of sound at reference levels over 40 dB(A) (Persson Waye & Björkman, 1988). However, to date no population-based studies have been conducted to measure exposure to low-frequency sound, mainly because taking appropriate measures of low-frequency sound is costly and technically challenging (see Chapter 3 for more information on the adequacy of sound measurements).

Annoyance is the most prevalent community response to environmental noise (Basner *et al.*, 2014). The evidence for annoyance from wind turbine noise shows findings consistent with those from research on other types of environmental noise. Strong associations between traffic or aircraft noise and annoyance based on exposure-response relationships have been established in numerous studies (Babisch *et al.*, 2003; Bakker *et al.*, 2012). Annoyance response to noise from other sources has also been shown to depend on sound characteristics of the source in question, including frequency, complexity, and duration of sound, and its meaning to the subject (Stansfeld, 2003). Different noise sources have been shown to elicit different levels of community response: at equivalent sound levels, aircraft noise, for example, has been shown to be more annoying than road traffic noise, while railway noise was associated with less annoyance than road traffic (Miedema & Oudshoorn, 2001; Yano *et al.*, 2012). Like annoyance from wind turbine noise, annoyance from other sources is also influenced by individual traits, such as noise sensitivity, which can moderate the perception of annoyance independently of the sound pressure level of noise exposure (van Kamp *et al.*, 2004).

6.1.1 Summary of the Evidence on Annoyance

The Panel determined that the evidence available is ***sufficient*** to establish a causal relationship between exposure to wind turbine noise and annoyance. The evidence linking annoyance and wind turbine noise consistently showed an association between annoyance and wind turbine noise exposure that follows an exposure-response relationship: higher sound pressure levels lead to an increasing risk of being annoyed. The findings from several cross-sectional studies with large sample sizes were consistent across different environments and exposure conditions and supported by evidence from other types of research designs (e.g., short-term laboratory studies).

A large body of research has established an exposure-response relationship between sound levels of various sources of community noise, such as road and rail traffic, and airports. The evidence for annoyance from wind turbine noise showed similar types of exposure-response relationships and associations with these other sources of noise. Furthermore, wind turbine noise was more annoying than other types of noise at equivalent sound pressure levels. The specific response pattern appeared to correspond to the acoustic characteristics of wind turbine noise, including amplitude modulation, as well as to the particular factors that affected wind turbine noise perception, such as noise sensitivity, visual impact, and personal attitude.

Based on available evidence, the influence of confounding factors can be ruled out with reasonable certainty. Knowledge gaps remain with regard to the influence of visual impacts on the perception of sound from wind turbines. 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. Furthermore, little is known so far about the baseline prevalence of annoyance, the magnitude of the effect, and the thresholds for the perception of wind turbine noise under different environmental and topographic conditions.

6.2 SLEEP DISTURBANCE

Sleep disturbance may be defined as "any deviation, measurable or subjectively perceived, from an individual's habitual or desired sleep behavior" (Perron *et al.*, 2012). Indicators of sleep disturbance include the following: sleep quality, sleep medication taken, total sleep time and time spent in specific sleep stages, sleep stage changes, arousal, and awakenings (Perron *et al.*, 2012). As stated by the WHO, "sleep is a biological necessity, and disturbed sleep is associated with a number of adverse impacts on health" (WHO, 2009). Despite the established importance of sleep, sleep disturbance is a common phenomenon in all populations. In an international survey, only 43% of Canadians stated that they have "a good night's sleep" every or almost every night, while 23% said so rarely or never (NSF, 2013).

The auditory system is never completely disengaged. As a result, noise can have a direct effect on sleep (Griefahn, 2002; Persson Waye *et al.*, 2003; WHO, 2009). Sleep disruption can also occur in an unconscious state, without the subject noticing the disturbance (Basner *et al.*, 2011), for example by activating the autonomic nervous system (Mathias *et al.*, 2008). This is in contrast to annoyance, which is caused only by consciously perceived noise. However, most studies on environmental noise and sleep disturbance that were assessed by the Panel relied on self-reported sleep impacts (namely, awakenings or daytime sleepiness linked to perceived reduction in sleep quality).

Sleep disturbance can negatively affect physiological functions. The circadian rhythm — a key mechanism that regulates daily rhythms, activities, and rest cycles — can be affected by sleep disturbance, and its disruption by external influences (e.g., jet lag or shift work) can cause sleep problems (Persson Waye *et al.*, 2003). Environmental noise can disrupt regular sleep cycles and cause arousals, which include vegetative arousal and the release of stress hormones such as cortisol (Maschke & Hecht, 2004). Acute activation, or full awakening, represents a major physiological response, but increased cortisol levels have also been found in individuals who have been exposed to increased noise during sleep without conscious awakening (Ising *et al.*, 1999). Similarly, the effects of noise on sleep can lead to the stimulation of the sympathetic nervous system (a division of the autonomic nervous system), an unconscious response that may not be noticed by the person experiencing the disturbance. This can result in the release of hormones such as adrenaline (epinephrine), noradrenaline (norepinephrine), and cortisol, and can precipitate further sleep disturbance in the long run (Maschke & Hecht, 2004). Long-term daytime noise exposure, for example, leads to an increase in night-time minimum levels of cortisol, which means a reduction in sleep quality (time spent in deep sleep) and increases the chance of night-time arousal (Fruhstorfer *et al.*, 1985). The term "sleep disturbance" thus describes two different mechanisms: the acute awakening caused by noise exposure, which is accompanied by night-time release of stress hormones; and long-term effects of daytime or night-time noise exposure that change the pattern and intensity of stress hormone release, and thus affect sleep quality even in the absence of acute disturbance at night.

Two out of the three data sets analyzed in Pedersen's (2011) re-analysis (SWE-00 and NL-07) showed a statistically significant association between exposure to sound from wind turbines and self-reported incidences of sleep interruption. All three studies also showed a significant association between annoyance and sleep interruption. Furthermore, sleep interruption was associated more strongly with annoyance due to noise experienced indoors across the three studies (Pedersen, 2011). Study SWE-05, in which the turbines were not always visible as a result of differentiated topography, showed a weaker increase in annoyance with increasing sound pressure levels outdoors, but a stronger increase in annoyance with increasing sound pressure levels indoors, as well as a stronger association between sleep interruption and annoyance indoors (Pedersen, 2011). These findings suggested that sleep interruption was related to annoyance rather than exposure to the sound from wind turbines directly. Thus, sleep disturbance could both be a cause and a consequence of annoyance related to exposure to sound from wind turbines.

Using data from the Dutch study (NL-07), Bakker *et al.* (2012) found that one-half of the respondents reported sleep disturbance at a sound pressure level of 45 dB(A) and above. Pedersen (2011) and Bakker *et al.* (2012) both noted that it was unclear whether sleep disturbance was a direct consequence of exposure to wind turbine noise, or an indirect consequence of the state of annoyance caused by exposure to wind turbine noise and other contributing factors in the vicinity of a subject's dwelling.

Nissenbaum *et al.* (2012) used the Pittsburgh Sleep Quality Index (PSQI) and the Epworth Sleepiness Score (ESS) to investigate whether there was an association between the residence distance from wind turbines (<1.5 km vs. >3-7 km) and sleep quality or daytime sleepiness. While the authors concluded that the sleep of residents living closer to wind turbines was negatively affected, other researchers have suggested that the study's limitations, including possible *selection bias*, small sample size, and poor exposure data, did not allow for such a conclusion (Ollson *et al.*, 2013). Bearing these limitations in mind, the Panel noted that the study did show an association between the exposure to sound from wind turbines and impacts on sleep in a different region from the Dutch and Swedish studies, and using a different methodology. The Panel found one study (unpublished at the time of writing) investigating the impact of exposure to wind turbine noise on a population in rural Ontario. Based on sleep diaries and actigraphy-derived measures of sleep quality, the study found that residents living between 474 metres to 1085 metres from the closest wind turbine had slightly lower sleep efficiency, longer sleep onset latency, and longer wake after sleep onset; however, none of these differences was statistically significant. The study was limited by small sample size (23 participants and 110 person-night observations) and relatively low wind speeds and wind turbine performance during the observation period (Lane, 2013). The WindVOiCe self-reported survey reported what the authors described as a "moderately significant" association (p-value = 0.0778, which is greater than conventional statistical significance where p = 0.05) between sleep disturbance and distance to wind turbines (Krogh *et al.*, 2011).

The Panel found no sleep studies or experiments that measured the effect of wind turbine noise on sleep physiology using standard methods such as brain wave measurements (electroencephalography or EEG).

Other types of environmental noise have been linked to impacts on sleep. For example, sleep disturbance has been shown to be a direct consequence of exposure to traffic and aircraft noise (Öhrström & Rylander, 1982; Öhrström, 1989; Perron *et al.*, 2012). In a review of existing evidence, WHO (2009) found that exposure to sound pressure levels as low as 32 dB(A) had biological effects on sleep quality. In a review of noise and sleep, Muzet (2007) noted that external sound stimuli triggered autonomic responses, such as heart rate change and vasoconstriction, even when the person remained asleep. In a laboratory study, Basner *et al.*, (2011) (N=72 participants) showed that exposure to rail, road, and air traffic noise led to statistically significant changes in sleep continuity (measured as a combination of time to sleep onset, number of arousals, number of awakenings, and number of sleep state changes). Furthermore, there was a difference in measured impacts on sleep structure and continuity and subjective evaluations of different types of traffic noise on sleep quality. “While road traffic noise led to the most prominent changes in sleep structure and continuity, air and rail traffic noise exposure” at night were perceived to be more disturbing (Basner *et al.*, 2011). In research on the effect of the temporal variability of environmental noise, continuous noise was found to have a statistically smaller effect on sleep quality than intermittent noise (Öhrström & Rylander, 1982; Persson Waye *et al.*, 2003). Intermittent noise mainly affects deep sleep, while continuous noise at exposure levels between 36 and 55 dB(A) has been shown to decrease the time spent in REM sleep (Eberhardt *et al.*, 1987).

As noted above, there are currently no studies that have investigated the specific impacts of exposure to low-frequency sound emitted by wind turbines. The Panel found two field studies in the context of other environmental noise that have explored whether exposure to low-frequency sound leads to specific impacts on sleep (Nagai *et al.*, 1989; Persson Waye & Rylander, 2001). Nagai *et al.* (1989) described effects on people exposed to low-frequency sound from road traffic at levels between 72 and 85 dB(A). Subjects were also exposed to shaking and rattling windows caused by a superhighway. The combination of these disturbances led to insomnia and excessive tiredness (Nagai *et al.*, 1989). Another study showed that people who were exposed to sound from heat pump or ventilation installations in their homes (26-36 dB(A), corresponding to 49-60 dB(C)) were significantly more likely to report annoyance and experience disturbed concentration and rest than residents exposed to noise from similar sources but without the low-frequency components (Persson Waye & Rylander, 2001).

6.2.1 Summary of the Evidence on Sleep Disturbance

An association between wind turbine noise and sleep interruption or reduced sleep quality has been found in some observational studies, but not consistently across all studies reviewed. A direct association between exposure to wind turbine noise and sleep disturbance was observed in only two population-based studies, whereas sleep disturbance was consistently associated with annoyance due to noise exposure in three studies. Furthermore, the exposure-response relationship is currently unclear. The Panel therefore concluded that the current evidence for a causal relationship is ***limited***. The evidence related to wind turbines is generally in line with findings from studies on the impacts of other sources of noise on sleep. While sleep disruption has been investigated in several studies, the resulting evidence base is smaller (fewer and less consistent studies, fewer participants per study) than for the relationship between wind turbine noise and annoyance.

The main knowledge gap concerns the nature of the mechanism. It is unclear whether sleep disruption can result directly from exposure to wind turbine noise, and what proportion of the observed sleep disruption is an indirect consequence of annoyance. There are currently no experiments or sleep studies available that demonstrate the impact of sound from wind turbines on the brain physiology of sleep, as gauged by traditional sleep measures such as EEG. Further knowledge gaps include the impact of specific characteristics of sound emitted by wind turbines, such as low-frequency components or periodic amplitude modulation, on sleep.

6.3 STRESS

The term *stress* is broad and generally includes conditions of a physical, biological, or psychological nature that strain the adaptive capacity of a person up to or beyond his or her limits (Welford, 1974; Gemmert & Van Galen, 1997). Stress conditions for humans include factors such as extreme temperatures, heavy workloads, noise, or social pressures (Broadbent, 1971; Van Gemmert & Van Galen, 1997). These stressors are typically classified as emotional (caused by emotions or relating to personality traits), cognitive (related to mental load when the person is faced with complex tasks), or physical (related to physical loads originating in the physical environment) (Van Gemmert & Van Galen, 1997). The same stressor can have multiple effects. For example, noise may interfere with cognitive activity and trigger an emotional response to the source of noise.

Environmental noise is a common physical stressor for people in urban areas or in other areas exposed to high levels of community noise (Van Gemmert & Van Galen, 1997). Noise exposure can lead to stress directly as a physical effect, or indirectly as a consequence of annoyance. Babisch (2002) provided a comprehensive review of a direct mechanism for a stress response to noise. Noise exposure activates the sympathetic nervous and endocrine systems, resulting in increased levels of stress hormones such as epinephrine, norepinephrine, and cortisol. These hormones affect metabolism and antibody immunity, and act as mediators along the pathway from noise to stress-related disease (Babisch, 2002). Changes in levels of these hormones also result in physiological effects, including changes in blood pressure or blood clotting factors (see Babisch *et al.*, 2003 for a summary of research on the general stress model).

Noise can also cause stress indirectly through annoyance. Kalveram *et al.* (1999) suggested that noise, in combination with information about the noise source, leads to annoyance. This can convey a “possible loss of fitness signal,” signifying fitness would decline if the individual stays in the same situation

(Kalveram *et al.*, 1999). Such a signal can motivate retreat, aggression, stand-by, or coping behaviour. While stress responses are normal and generally beneficial, they are thought to become pathological if chronic or frequently repeated, especially without appropriate resolution. In line with this model, Babisch (2002) suggested that noise annoyance leads to physiological arousal and stress.

None of the three datasets analyzed by Pedersen (2011) showed a statistically significant association between exposure to estimated A-weighted sound pressure levels of wind turbine noise and self-reported perceptions of stress; however, all three studies reported a positive association between annoyance from wind turbine noise outdoors and stress (Pedersen, 2011). The study designs did not allow conclusions about cause and effect: annoyance may be a consequence of stress, or vice versa. Using data from the Dutch study (NL-07), Bakker *et al.* (2012) found that psychological distress was indirectly correlated with sound exposure in respondents who noticed wind turbine noise, with "noise annoyance acting as a mediator."

In a review article, Baqtasch *et al.* (2006) noted that stress related to wind turbines was among the variables related to annoyance. Growing turbine sizes have also raised concerns that the sound spectrum emitted has shifted toward lower frequencies (Møller & Pedersen, 2011); however, Shepherd *et al.* (2011) also highlighted links among turbine noise, stress, and annoyance, speculating that these links were exacerbated because chronic noise exposure is a potent psychosocial stressor, leading to chronic stress (Shepherd *et al.*, 2011).

Pedersen (2011) suggested that cognitive stress theory could explain the association between annoyance from wind turbine noise and stress, (see also Lazarus & Folkman, 1984). According to this theory, an individual in an already stressful situation would evaluate wind turbine noise as an additional threat to restoration. Since the source of the noise is beyond the individual's control, the response is manifested as annoyance. It is worth noting, however, that people who reported being annoyed by wind turbine noise also reported more symptoms related to stress and resulting secondary effects, such as feeling less well-rested, and considered their environment as less suited to rest and restoration (Pedersen *et al.*, 2007a; Pedersen & Persson Waye, 2008).

While the association between annoyance from wind turbine noise and stress has been found consistently in all studies that investigated stress-related variables, stress has not been associated directly with exposure to wind turbine noise. The Panel did not find any studies or experiments that explored whether stress can result directly from the specific characteristics of wind turbine noise.

Indirect stress response via annoyance has also been studied in the context of other sources of environmental noise, namely traffic noise exposure. Annoyance and chronic stress have been linked in numerous studies (most often involving occupational environmental noise or traffic noise); however, a causal relationship has not been shown. Rylander's (2004) review noted, for instance, that there are no data available on the relationship between annoyance and cortisol in saliva (an indicator of stress) under conditions of either acute or chronic environmental noise exposure.

6.3.1 Summary of the Evidence on Stress

The Panel found no evidence of a direct association between wind turbine noise and stress. However, several studies showed indirect associations between annoyance due to wind turbine noise and stress. Stress was associated with annoyance due to wind turbine noise exposure outdoors in three studies, but due to wind turbine noise exposure indoors in only one study. Furthermore, stress has not been the main outcome investigated by existing studies. The datasets that presented results related to stress (SWE-00, SWE-05, NL-07), and the resulting studies that investigated the relationship with stress (Pedersen & Persson Waye, 2008; Pedersen, 2011; Bakker *et al.*, 2012), were limited to self-reported data, which are treated inconsistently across different studies. Available studies are of insufficient quality with regard to stress and lack the statistical power to permit a conclusion regarding the presence or absence of a causal relationship between wind turbine noise and stress. The Panel therefore concluded that the current state of the evidence of a causal relationship is ***inadequate***.

The Panel noted, however, that the patterns of self-reported stress reactions are generally consistent with associations between stress reactions observed in a large body of research on the impacts of other environmental noise. These associations have not yet been tested for wind turbine noise using comparable methods. It is therefore unknown whether wind turbine noise has effects on stress comparable to those of other types of noise. Further knowledge gaps involve the nature of the underlying mechanism, in particular whether stress can be caused directly through exposure to wind turbine noise or whether it is an indirect consequence of annoyance, sleep disturbance, or both.

6.4 CARDIOVASCULAR DISEASES

Cardiovascular diseases are a group of conditions affecting the heart and blood vessels (e.g., coronary artery disease). Cardiovascular diseases also result from multiple causes related to risk factors such as diet, physical inactivity, tobacco use, the environment, or hereditary preconditions (WHO, 2013). These diseases have high prevalence in the general population. For example, cardiovascular diseases were responsible for 32% of all premature deaths across Canada in 2004, and were the second largest contributor to health care costs in 2000 (PHAC, 2009). The complex relationship between multiple risk factors and effects makes it difficult to associate the risk of cardiovascular disease with a single cause such as wind turbine noise. No high-quality studies designed to examine cardiovascular disease outcomes and their relationship to exposure to wind turbine noise have been conducted to date.

It is known that noise can act on individuals as a physiological stressor, “inducing a vegetative response (such as blood pressure elevations), causing somatic (such as hypertension) and psychosomatic responses, which in turn, may affect the risk of disease” (van Kempen & Babisch, 2012). However, evidence from studies of road traffic noise showed that there appeared to be no increased risk of cardiovascular disease resulting from exposure to sound pressure levels below 60 dB(A) during the day (Babisch, 2008) or 55 dB(A) at night (Babisch, 2011).

Research on other types of environmental noise has shown that cardiovascular disease might also be indirectly linked to noise exposure via chronic annoyance and stress. For instance, chronic annoyance has been used as an indicator of increased risk for persistent imbalance in the physiological stress system (Barregard *et al.*, 2009; Pedersen, 2011). This imbalance can lead to high blood pressure and other manifestations of cardiovascular disease if the exposure is prolonged (Barregard *et al.*, 2009). The pathway through which noise affects blood pressure is not yet fully understood. Stansfeld (2003) proposed that the effect could be mediated through an intermediate response such as noise annoyance; however, current evidence is insufficient to support this pathway. Willich *et al.* (2006) found an association “between chronic noise burden and the risk of myocardial infarction.” They noted that this finding was consistent with a causal mechanism based on a conceptual stress model in which “sound pressure levels and/or annoyance by noise may enhance psychological stress.” Suls (2013) reviewed evidence for an association between annoyance and anger or hostility, which are known risk factors for stress.

Furthermore, there is evidence that sleep disturbance caused by traffic noise can lead to cardiovascular effects. For example, a laboratory experiment (number of participants =38) simulating freight train noise exposure (at 40 dB(A) and 50 dB(A)) showed that railway noise at night had an effect on the cardiovascular system of sleeping subjects (Tassi *et al.*, 2010; Croy *et al.*, 2013).

Pedersen (2011) found no statistically significant association between wind turbine noise exposure or annoyance and either self-reported high blood pressure or self-reported cardiovascular disease in any of the three studies that she re-analyzed. Using the two Swedish studies (SWE-00, SWE-05), Pedersen and Persson Waye (2008) examined the relationship between noise annoyance from wind turbines and cardiovascular disease. Their findings suggested no differences in self-reported rates of cardiovascular diseases between respondents reporting that they were annoyed by wind turbine noise and other respondents (Pedersen & Persson Waye, 2008). The sample sizes of the studies analyzed in Pedersen (2011) and Pedersen and Waye (2008) are relatively small, given the need to examine what would be expected to be minor increases in relative risk, and potentially large misclassification errors and other sources of bias.

The cardiovascular effects of various sources of noise, such as road traffic noise, community noise, and occupational noise, have been extensively researched (Babisch, 2008; van Kempen & Babisch, 2012). A meta-analysis of 43 epidemiologic studies published between 1970 and 1999 investigating the relationship between noise exposure and blood pressure or ischemic heart disease found small increases in blood pressure as a result of occupational noise exposure (van Kempen *et al.*, 2002). The review also showed a significant association between exposure to either occupational or air traffic noise at 45 to 75 dB(A) ($L_{Aeq,16hr}$) and hypertension (van Kempen *et al.*, 2002). Another meta-analysis of effects of road traffic noise on annoyance and health found "a positive and significant association between noise annoyance and the risk of arterial hypertension" (Ndrepepa & Twardella, 2011).

Studies by Bakker (2012) and Shepherd *et al.* (2011) suggested that annoyance acts as a mediator or pathway in a causal chain between exposure to wind turbine noise and impacts on health or quality of life. This is supported by the finding that annoyance was a significant effect modifier with respect to the association between aircraft noise and hypertension (Babisch *et al.*, 2003). Sound pressure level and noise annoyance were found to be equally good predictors of the impact of aircraft noise on health. Another related study suggested that sound pressure level and noise annoyance may both serve as explanatory variables for the link between chronic noise exposure and cardiovascular disease, although sound pressure level is often a stronger predictor (Babisch *et al.*, 2013). Annoyance and disturbance due to road traffic noise have also been associated with a higher incidence of ischemic heart disease; however, when study subjects had conditions predisposing them to cardiovascular disease, noise exposure did not change the risk of ischemic heart disease (Babisch *et al.*, 2003).

Chronic environmental noise exposure in general has been associated with an increased risk of myocardial infarction, consistent with the hypothesis that there is an association between long-term noise exposure and risk of cardiovascular disease. Willich *et al.* (2006) suggested that chronic noise exposure is "the equivalent of an exogenous risk factor contributing to the development of cardiovascular disease."

Although low-frequency sound is a common component of wind turbine noise, little is known about its specific effects on cardiovascular disease, especially in comparison with other types of noise exposure with complex and difficult-to-measure characteristics, such as impulse noise (e.g., explosions and gunshots) (Berglund *et al.*, 1996). Schust (2004) reported a study by Danielsson and Landstrom (1985) that showed the effects of infrasound ranging in frequency (6, 12, or 16 Hz) and sound pressure level (95, 110, or 125 dB(Z)) on blood pressure, pulse rate, and serum cortisol levels. This study showed an induced peripheral vasoconstriction with increased blood pressure and concluded that "environmental infrasound may be of importance for the development of essential hypertension in predisposed individuals" (Danielsson & Landstrom, 1985). However, exposure levels reported were much higher than those observed in the context of wind turbine noise. A Portuguese research group has argued that infrasound and low-frequency noise from wind turbines may cause "vibroacoustic disease," a hypothesized syndrome including cardiovascular effects such as increased risk of coronary artery surgery, which may be associated with long-term exposure to sound with high sound pressure levels and low-frequency components (Alves-Pereira & Branco, 2007). To date, independent research has failed to support the existence of "vibroacoustic disease" (Kåsin *et al.*, 2012). Furthermore, there is no evidence that wind turbines emit infrasound or low-frequency sound at pressure levels comparable to those studied in the context of "vibroacoustic disease" (Bolin *et al.*, 2011).

6.4.1 Summary of the Evidence on Cardiovascular Disease

The Panel found no evidence suggesting a direct association between exposure to wind turbine noise and cardiovascular disease. Several of the studies reviewed used case definitions of specific cardiovascular diseases in self-reported data, but none of these revealed a statistically significant association. Therefore, the Panel concluded that available evidence is ***inadequate*** to permit a conclusion regarding the presence or absence of a causal relationship. Prior research on other sources of environmental noise has repeatedly found associations between noise exposure and cardiovascular effects, but at exposure levels that are much higher than those encountered in the context of wind turbine noise.

6.5 DIABETES

Diabetes is a chronic disease in which the body either cannot produce (type 1 diabetes) or properly use (type 2 diabetes) insulin, a hormone that controls the amount of glucose in the blood. Type 1 diabetes develops in early childhood or adolescence and is generally thought to be the result of a hereditary genetic predisposition. Type 2 diabetes develops mainly in adults and is associated with a number of risk factors, including stress, sleep disturbances, high body weight and physical inactivity (Sørensen *et al.*, 2012; WHO, 2014).

Researchers have investigated whether exposure to traffic noise is associated with a higher risk of incidence of type 2 diabetes. Similar to research on cardiovascular disease, research on diabetes is challenged by the multitude of risk factors associated with this disease. Furthermore, diabetes develops only after long-term exposure to those risk factors.

None of the studies reviewed by the Panel focused on diabetes mellitus; however, the three studies analyzed in Pedersen (2011) did record self-reported cases of diabetes among the study populations. One study (SWE-05) showed a statistically significant association between A-weighted sound pressure levels at participants' homes and cases of diabetes. The study did not record the duration of exposure, however, nor was it designed to control for confounding factors specific to diabetes, such as the rate of pre-existing or type 1 diabetes, diet, physical activity, current and previous smoking, work strain, or general health status.

Two recent studies have investigated whether road traffic noise or long-term exposure to aircraft noise affect the incidence of type 2 diabetes in exposed residents. Sørensen *et al.* (2012) used data from a cohort study on road traffic noise exposure for 57,053 subjects who were followed for an average of 9.6 years. During the follow-up period, 2,752 cases of diabetes were recorded. The study showed that a higher average exposure of 10 dB at the time of diagnosis was associated with a higher risk of diabetes with an incidence rate ratio (IRR) of 1.11[7] (95% confidence interval (CI) 1.03 to 1.19), whereas exposure in the five years preceding diagnosis was associated with an IRR of 1.14 (95% CI 1.06 to 1.22) after adjusting for confounding factors. Eriksson *et al.* (2014) investigated the "effects of long-term aircraft noise on body mass index (BMI), waist circumference, and type 2 diabetes using data from a cohort study with 5,156 participants. The results did not show a significant association between noise exposure (based on an ordinal-scale noise variable) and either BMI or type 2 diabetes." A 5 dB increase in aircraft noise level was associated with a greater-than-average increase in waist circumference of 1.51 cm (95% CI 1.13 to 1.89).

---

[7] This means that for every 100 cases that would be expected in the general (unexposed) population based on the average rate of type 2 diabetes cases, there were 111 actual cases found in the exposed group.

Both studies used exposure assessment scales that considered residents to be unexposed if L_{den} was <50 dB(A) for road traffic noise and <42 dB(A) for aircraft noise. The highest associations occurred at sound level categories >60 dB (road traffic) and >55 dB (aircraft). These exposure levels are generally higher than those that have been measured for the subjects considered in studies of wind turbines (see Chapter 3).

6.5.1 Summary of the Evidence on Diabetes

The Panel found only one study that showed an association between wind turbine noise and cases of diabetes; however, the study design did not identify the timeframe over which these cases developed or whether other factors may have confounded the association. Therefore, the Panel concluded that available evidence is ***inadequate*** to permit a conclusion about the presence or absence of a causal relationship. Studies have found that diabetes may be related to other sources of environmental noise; however, knowledge gaps persist regarding the exposure levels and duration of exposure that lead to increased incidence of type 2 diabetes. With regard to wind turbine noise, there is a general knowledge gap concerning the effects of long-term exposure. This gap is partly due to the fact that wind turbine noise is a fairly recent phenomenon.

6.6 EFFECTS ON HEARING

Noise-induced hearing loss is a partial or total inability to hear caused by sensorineural damage affecting the inner ear (e.g., hair cells) or the auditory nerve, leading to higher thresholds for detecting sounds or permanent and irreversible loss of hearing. Exposure to noise at high sound pressure levels in the short term can result in reversible "temporary threshold shift" (Nelson *et al.*, 2005). However, permanent noise-induced hearing loss is common, for example, in those who have long-term occupational exposures to broadband noise with a sound pressure level over 80 to 85 dB(A) that leads to damage of outer hair cells.

No studies or experiments have been conducted to date to specifically investigate whether exposure to wind turbine noise can lead to hearing loss. Noise-induced hearing loss generally only occurs at exposure levels above those observed in the proximity of wind turbines. Exposure to environmental noise at levels of 75 dB(A) or lower is not expected to lead to hearing loss, even after a lifetime of exposure (WHO, 2011).

6.6.1 Summary of the Evidence on Hearing Loss

Previous research on noise-induced hearing loss provides ***evidence of no causal relationship*** between exposure to broadband noise at sound pressure levels associated with wind turbines at any distance and hearing loss. Previous studies of other sources of noise are mutually consistent in failing to show a positive association between human exposure to sound at pressure levels associated with wind turbines and any symptom of hearing loss.

6.7 TINNITUS

Tinnitus is the "general term for perceived sound perception (for instance, roaring, hissing, or ringing) that cannot be attributed to an external source" (WHO, 2011). Previous research has identified a wide range of possible causes of tinnitus, including noise-induced hearing loss, neurological disorders, stress, metabolic disorders, and psychiatric disorders. The specific pathways that lead to tinnitus are not yet fully understood, despite relatively high prevalence in many populations (Henry *et al.*, 2005).

One of the three studies analyzed in Pedersen (2011) showed a statistically significant association between exposure to wind turbine noise and self-reported cases of tinnitus (SWE-00). No association was found with annoyance due to wind turbine exposure outdoors or indoors. In research on other sources from environmental noise, approximately 10% of patients with tinnitus recorded in the Oregon Tinnitus Clinic Database self-reported long-duration noise as the cause of their tinnitus (Henry *et al.*, 2005). The WHO (2011) suggests that, globally, 3% of the population could suffer from tinnitus caused by environmental noise exposure. Tinnitus is also associated with hearing loss. In one study conducted in Britain, 16.1% of men who reported severe difficulties in hearing also reported having tinnitus, compared with 5% in those with slight or no difficulties in hearing. The respective numbers among women were 33.1% and 2.6% (Palmer *et al.*, 2002). In a literature review, Henry *et al.* (2005) showed that the majority of tinnitus patients are also affected by some degree of hearing loss, with rates ranging from 50 to 80% depending on study design and age of the subjects studied. On the other hand, tinnitus is also common among people who do not have any measurable hearing loss (Eggermont, 2005).

Most studies of noise-induced tinnitus have focused on impulse noise (e.g., explosions or gunshots) or short-term exposure to intense sound (e.g., loud music, occupational noise), which are at much higher sound pressure levels than wind turbine noise. No studies could be found of associations between tinnitus and low-frequency noise or infrasound.

6.7.1 Summary of the Evidence on Tinnitus

The Panel concluded that the state of evidence is ***inadequate*** to determine the presence or absence of a causal link between wind turbine noise and tinnitus. The Panel noted considerable uncertainty over the general causes of tinnitus and knowledge gaps with regard to associations between long-term exposure to environmental noise and tinnitus.

6.8 EFFECTS OF NON-AUDIBLE SOUND ON THE INNER EAR

Several reports have suggested that symptoms, such as vertigo, nausea, ear pressure, or vision problems, could be caused by non-audible sound emitted by wind turbines, such as infrasound and low-frequency sound below a person's hearing threshold (Pierpont, 2006; 2009; Jeffery *et al.*, 2013; Ambrose *et al.*, 2012).

The Panel found no evidence from epidemiological studies or experiments that specifically investigated impacts of non-audible sound emitted by wind turbines on the ear. However, research has explored possible pathways through which infrasound or low-frequency sound might affect the ear, including damage to the inner ear, stimulation of the cochlea, or stimulation of the vestibular system.

Stimulation of the Cochlea

The hair cells of the cochlea are the main organ of human sound perception. Sound waves stimulate the inner hair cells, which transform the sound into a neural signal that is perceived by the brain as sound. The inner hair cells are known to be less sensitive to infrasound (≤ 20 Hz) or low-frequencies, and rather high sound pressure levels are needed to provoke a sensation especially for the infrasound range (see Chapter 4); however, it is unclear whether there are other pathways of stimulation.

Using cochlear monitoring, Hensel *et al.* (2007) showed that cochlear processing was altered after exposure to infrasound of 6 Hz at a sound pressure level of 130 dB. Based on this and other research, Salt and Hullar (2010) suggested that low-frequency sound can stimulate the outer hair cells at sound pressure levels 40 dB below the threshold of hearing, when the inner hair cells are not stimulated. The study showed that cochlear potentials generated by hair cell transduction in guinea pigs can be recorded in response to 5 Hz infrasound, although these potentials are not perceived by the brain as sound because they are transmitted via a different neural pathway. In a subsequent animal study, Salt *et al.* (2013) showed that infrasound at 5 Hz can produce an electrical response in the cochlea larger than that produced by tones at other frequencies between 50 and 1,000 Hz at levels as low as 60 to 65 dB. Based on these results, the authors argued that the apical region (tip) of outer hair cells may be more sensitive than previously estimated and could provide a mechanism through which infrasound stimulates the brain that does not involve hearing. They further suggested that "some clinical conditions, such as Ménière's disease, superior canal dehiscence, or asymptomatic cases of endolymphatic hydrops" could further increase this sensitivity (Salt & Hullar, 2010). This would imply that some individuals may be hypersensitive to infrasound. In an earlier paper, Salt and Kaltenbach (2011) also speculated that infrasound could lead to perceptions of fullness, ear pressure, or tinnitus. This work suggests that there may be a response of the cochlea to suprathreshold levels of infrasound, but the effect on the brain remains unknown (see Ellenbogen *et al.*, 2012).

Stimulation of the Vestibular System

The vestibular system is the apparatus that helps a person maintain balance, spatial orientation, and visual fixation (see Chapter 4). No epidemiological studies or experiments that investigated the activation of the human vestibular system through *air-conducted* non-audible sound were found. The evidence is currently limited to studies of human subjects using acoustic stimulation through *bone conduction* and of animal subjects using exposure to air-conducted low-frequency sound.

In an experiment using mice, Tamura *et al.* (2012) showed that low-frequency sound of 100 Hz at 70 dB caused impaired balance due to partial loss of hair cells and increased levels of oxidative stress in the vestibule. The authors noted that "it is unclear how this level of sound exposure can directly cause loss of hair cells," but that the finding "indicates that further study is required including an extrapolation to humans." In human studies, Todd *et al.* (2008) showed that acoustic signals transmitted by bone conduction can activate the otolith organs of the inner ear. The threshold for triggering the vestibulo-ocular reflex, a reflex in which the head movement is compensated by a change of position of the eyes, was lowest at a frequency of 100 Hz. Acoustic stimulation is a well-established technique for testing vestibular system function (vestibular evoked myogenic potential (VEMP)) (e.g., Colebatch & Halmagyi, 1992; Colebatch *et al.*, 1994; Robertson & Ireland, 1995; Curthoys *et al.*, 2006; Zhang *et al.*, 2012).

These studies suggest that air-conducted sound at sound pressure levels below 100 dB are unlikely to stimulate the otoliths (the most sensitive part of the vestibular end organs) in a healthy person. There is evidence, however, that in some pathological conditions acoustic signals could activate the vestibular system at lower levels. Tullio syndrome (Tullio, 1929), characterized by vertigo or an abnormal vestibular ocular reflex, results from changes in the fluid pathways between the cochlear and vestibular parts of the inner ear caused by various anatomical abnormalities (e.g., enlarged vestibular aqueduct or perilymphatic fistula). *Superior* (semicircular) *canal dehiscence* syndrome (SCDS) (Minor *et al.*, 1998; Minor, 2000) is an observable fenestration (opening) of a semicircular canal, which is correlated with sound-induced vestibular activity (see Chapter 4). Under these pathologic conditions, acoustic signals can be more effective in activating the vestibular system. A number of studies have used VEMP testing to compare the sensitivity of the vestibular system to sound in patients with various degrees of canal dehiscence (Pfammatter *et al.*, 2010) or in patients before and after surgery to plug superior canal dehiscence (Welgampola *et al.*, 2008). These papers noted a 20 to 30 dB reduction in the sound stimulation threshold for patients affected by SCDS. Russo (2014) estimated that SCDS may affect up to 5% of the population. Other studies found that 1.2% of normal adults have definite or possible dehiscence (Erdogan *et al.*, 2011). Hagiwara *et al.* (2012) reported 3% prevalence in adults and 27% prevalence in children less than two years of age.

A relatively large number of adults, and many more infants, are more sensitive to acoustic activation of the vestibular system than the general population (Hagiwara *et al.*, 2012). But even these individuals are unlikely, in the Panel's opinion, to experience stimulation of the vestibular system by the acoustic signals from wind turbines. The normal threshold for sound activation of the vestibular system, as judged from VEMP testing, is a sound pressure level of around 110 dB. Subjects with a pre-existing condition such as canal dehiscence may be sensitive at 85 to 90 dB. However, at the standard 40–50 dB(A) noise level regulations commonly in place for wind turbine exposure, the broadband components of wind turbine noise do not approach levels high enough to activate the vestibular system (Harrison, 2014). If the reduced emphasis of low-frequency components by the use of A-weighted sound levels is taken into account, and signal levels of low frequencies are estimated based on sound spectrum data, peaks in low-frequency levels rarely exceed 70 dB. Therefore, based on the existing evidence, the Panel could not make conclusions about whether vestibular symptoms such as vertigo, dizziness, or nausea are the direct result of exposure to wind turbine noise (Harrison, 2014).

6.8.1 Summary of the Evidence on Effects of Non-Audible Sound

Based on the evidence reviewed above, the Panel found:

- Infrasound (5 Hz) can stimulate the outer hair cells of the cochlea at moderate sound pressure levels (>60 dB) in certain animal models; however, the effect on the brain remains unknown, and this research has not been extrapolated to humans.
- Infrasound can stimulate the human vestibular system at high sound pressure levels (>110 dB for a person with normal sensitivity and possibly >85 dB for a person with higher sensitivity).

- The thresholds for infrasound or low-frequency sound associated with damage to the inner ear and vestibular activation are far above the levels of exposure associated with wind turbines. The threshold for cochlear activation in animal models could be achieved by sound from wind turbines; however, since neither the threshold in humans nor the impact on the brain are known, it is not possible to associate health impacts with cochlear activation through infrasound.
- It is plausible that certain pre-existing clinical conditions could decrease the threshold of stimulation of the cochlear or the vestibular system and thus lead to higher sensitivities to non-audible sound in affected individuals, in particular young children; however, no specific thresholds have been established to date. It thus remains unclear whether wind turbine noise could exceed such thresholds.

In view of these findings, the Panel concluded that the current evidence is ***inadequate*** to determine the presence or absence of causal links between exposure to non-audible sound emitted by wind turbines and symptoms such as vertigo, nausea, ear pressure, or vision problems. Knowledge gaps include measurement and understanding of low-frequency sound from wind turbines, thresholds for stimulation or damage of the cochlear and vestibular systems in humans, and lower thresholds in sensitive populations.

6.9 COGNITIVE AND MENTAL PERFORMANCE

Cognitive abilities develop early in life (Diamond, 2002). Stansfeld *et al.* (2005) hypothesized that environmental noise could impact the mental performance of young children. As well, ambient environmental noise could distort awareness of speech sounds (Bryant & Bradley, 1985). Several early studies conducted by Hockey and colleagues identified other potential pathways through which noise exposure may influence cognitive performance in adults (Hockey, 1984; Robert & Hockey, 1997). These studies suggested that noise may affect the performance of specific tasks and that, while noise increases levels of alertness, it does not increase mental performance speed, but rather reduces cognitive performance accuracy and short-term memory performance.

The Panel found no epidemiological studies of impacts of wind turbine noise on cognitive performance. Evidence is currently limited to two laboratory studies. Ruotolo *et al.* (2012) showed that executive control and semantic memory deteriorate with auditory and visual stimuli that simulate increasing proximity to a wind energy facility. Visual features appeared to amplify the negative impact on executive control. No impact was found on short-term verbal memory. These results suggested that wind turbines may have selective effects on cognitive performance, with stronger impacts on tasks that demand high levels of executive control.

Alimohammadi *et al.* (2013) conducted an experiment to test whether low-frequency noise from different sources, including wind turbines, causes annoyance or has an impact on mental performance, and whether these impacts depend on personality type. Participants exposed to low-frequency noise had increased mental performance both with respect to speed and accuracy in the completion of tests designed to evaluate executive control. The results also revealed that introverted participants were significantly more annoyed and performed tests with less accuracy than extroverted participants. These results contradict research using higher-frequency sound from ventilation noise, which suggested that noise at levels above 51 dB(A) disrupted performance (Kjiellberg & Wide, 1988). But the literature on performance is very complex and the divergence in results indicates that the impact of noise on cognitive performance likely depends on the type of task subjects have to perform.

Past studies of environmental noise have shown that it can have an impact on cognitive performance and learning, particularly in children (Clark & Sörqvist, 2012; Klatte *et al.*, 2013). For example, Hughes and Jones (2001) presented a review of laboratory studies showing that sound affects cognitive processing and disrupts performance. Several studies have shown that children exposed to noise at school experience cognitive impairments (Clark & Stansfeld, 2007). Tasks that were impaired involve central processing and language, namely, reading comprehension, memory, and attention (Evans & Maxwell, 1997; Haines *et al.*, 2001). A set of key studies examined the impacts of the relocation of an airport in Munich, Germany, on children's cognition (Evans *et al.*, 1995, 1998). High noise exposure was associated with deficits in memory and reading comprehension, but after the noise exposure ceased, the deficits disappeared, indicating that effects may be reversible.

A large-scale study in the Netherlands, Spain, and the United Kingdom conducted by Stansfeld *et al.* (2005) found a linear exposure-effect association between chronic aircraft noise exposure and impairment of reading comprehension and recognition memory; the researchers highlighted aircraft noise as an auditory stressor that is detrimental to a healthy educational environment.

6.9.1 Summary of the Evidence on Cognitive and Mental Performance

To date no population-based studies and very limited experimental evidence are available on the specific impact of wind turbine noise on cognitive performance. Research on other sources of environmental noise has shown a possible link; however, the results are inconclusive, showing both beneficial and adverse effects on cognitive and mental performance. Therefore, the Panel found that the evidence is ***inadequate*** to determine the presence or absence of a causal relationship between wind turbine noise and cognitive and mental performance.

Knowledge gaps include clear-case definitions and measurements of mental performance under noise exposure; a lack of understanding of how noise characteristics may stimulate or adversely affect cognitive performance; and how these impacts are influenced by characteristics of the subjects exposed and the type of cognitive task performed.

6.10 PSYCHOLOGICAL HEALTH

Mental health refers "to a state of emotional and psychological well-being" (Van Kamp & Davies, 2008). In keeping with the definition of health used in this report, mental health means the absence of mental illness as well as unpleasant feelings or emotions (psychological distress) that may affect a person's level of functioning. Environmental noise exposure has been linked to effects on mental health under a variety of circumstances. However, in most cases environmental noise leads to psychological distress rather than produce serious mental illness (Van Kamp & Davies, 2008).

With regard to wind turbine noise, one study by Bakker *et al.* (2012) found a positive association between exposure and psychological distress, with annoyance appearing to act as an intermediary variable. The study further found that psychological distress is linked to sleep disturbance, regardless of exposure to sound from wind turbines.

Whether exposure to environmental noise can directly lead to mental illness is still unclear. In a literature review, Stansfeld *et al.* (2000) found that exposure to environmental noise did not appear to lead to diagnosed psychological disorders, but was sometimes associated with mental health symptoms such as depression or anxiety. The authors further noted that self-reported noise sensitivity did not appear to interact with noise exposure in leading to mental illness. Noise sensitivity was, however, associated with certain mental health symptoms. In the same vein, Stansfeld *et al.* (2009) noted that transport-related noise was unlikely to cause serious mental illness but may be responsible for psychological symptoms. Hardoy *et al.* (2005) found a relationship between exposure to aircraft noise and "generalized anxiety disorder" or "anxiety disorder not otherwise specified." In a study of road traffic noise, Sygna *et al.* (2014) found a positive association between noise exposure and psychological distress among subjects with poor sleep quality, but the association was not statistically significant.

6.10.1 Summary of the Evidence on Psychological Health

The current state of the evidence on noise exposure and mental health does not allow conclusions as to whether noise causes mental illness or whether it only contributes to psychological distress or exacerbates symptoms in people who already have a mental illness. Evidence reviewed by the Panel does not permit conclusions about whether there is a specific causal relationship linking psychological distress to exposure to wind turbine noise. The Panel found, therefore, that current evidence is ***inadequate*** to determine the presence or absence of a causal relationship. The Panel further noted that, given the inconclusive nature of the impact of noise on general mental health, knowledge gaps in this area are not specific to sound from wind turbines. A better understanding of the effect of general noise exposure on psychological disorders is needed, and the effects of specific characteristics of sound from wind turbines remain even more uncertain.

6.11 QUALITY OF LIFE

Two studies have investigated the impact of wind turbine noise on health-related quality of life. Shepherd *et al.* (2011) conducted a cross-sectional study with a control group in New Zealand using the short version of the WHO's quality of life survey. The results supported findings from cross-sectional studies of an exposure-response relationship between wind turbine noise and annoyance, and showed that several domains of quality of life were negatively affected for respondents living close to wind turbines (perceived sleep quality, energy levels, environmental quality of life, and amenity). A two-year follow-up study by McBride *et al.* (2013) showed that the difference in quality of life between the two groups remained stable over time. Mroczek *et al.* (2012) conducted a randomized cross-sectional study using the SF-36 General Health Questionnaire. The results of this study did not show a significant difference in health-related aspects of quality of life between residents living closer to wind turbines and those living further away. The authors noted, however, that the study design did not include a number of factors that influence quality of life, such as economic opportunity provided by wind turbines and socioeconomic differences between areas. Such omissions may lead to observed differences that are not related to wind turbine noise. The WindVOiCe self-reported survey did not find that quality of life was significantly altered for people living closer to wind turbines (Krogh *et al.*, 2011).

6.11.1 Summary of the Evidence on Quality of Life

To date, very limited evidence is available on the specific impact of wind turbine noise on quality of life. Moreover, the different studies available reach different conclusions. The Panel found, therefore, that current evidence is ***inadequate*** to determine the presence or absence of a causal link.

6.12 OTHER HEALTH IMPACTS

The previous sections in this chapter have discussed health outcomes that have been the subject of population-based studies or laboratory experiments. A number of other health impacts have been frequently attributed to exposure to wind turbine noise in case series, informal surveys, complaints, the media, and other sources.

In research on other environmental noise, some of these health outcomes were indirectly associated with noise via annoyance, but not directly associated with exposure to wind turbine noise. These outcomes included diabetes (see Section 6.5), chronic disease (unspecified), undue tiredness/fatigue, and headache. Fatigue and headache are very common, unspecific health outcomes that could be secondary impacts of annoyance, sleep disruption, or stress. They can also be a consequence of many other factors and influences that often co-occur with exposure to wind turbine noise and are therefore difficult to isolate.

For all other health outcomes considered (see Table 5.1), the Panel did not find any research involving population-based studies or experiments that could provide evidence of the presence or absence of causal links. In these cases, the Panel therefore considered the use of the IARC framework imperfect, as these specific health effects have not yet been the subject of primary empirical research. The Panel noted, however, that many of these health effects could be secondary consequences of other effects that have been addressed in primary empirical research related to wind turbines.

6.13 CHAPTER SUMMARY

The Panel reviewed the evidence selected according to the process outlined in Chapter 5, and reported on all health outcomes for which at least one population-based study found a statistically significant association or for which at least one laboratory experiment has been published. The main health outcomes that emerged were annoyance, sleep disturbance, and stress:

- The Panel concluded that the current evidence is ***sufficient*** to establish a causal relationship between exposure to wind turbine noise and annoyance.
- The Panel concluded that current evidence for a causal relationship is ***limited*** to establish a causal relationship between exposure to wind turbine noise and sleep disturbance.
- The current evidence of a causal relationship is ***inadequate*** to reach a conclusion concerning the presence or absence of a relationship between exposure to wind turbine noise and stress, although the effect may be indirect, via annoyance.
- The Panel concluded that there is ***evidence of no causal relationship*** between hearing loss and exposure to broadband noise at sound pressure levels associated with wind turbines, at any distance.

The Panel concluded that the current evidence is ***inadequate*** to determine the presence or absence of causal links between exposure to wind turbine noise and the other health outcomes listed in Table 5.1. A more detailed description summary is given in Chapter 7.

7

Overview of the Evidence, Knowledge Gaps, and Research Needs

- Summary of the Evidence
- Quality of the Evidence Reviewed
- Further Research
- Chapter Summary

7 Overview of the Evidence, Knowledge Gaps, and Research Needs

Key Findings

- Much of the evidence reviewed by the Panel suffered from methodological limitations: inadequate control for selection bias and confounding factors; small sample size that limited statistical power; lack of longitudinal studies; and lack of measurement to assess exposure.
- The Panel identified specific gaps in knowledge for each health condition studied, such as the visual impact of wind turbines on annoyance or the possible pathways leading to sleep disturbance or stress.
- There is a lack of longitudinal studies as well as a paucity of research on sensitive populations.
- In measurement of wind turbine sound, long-term equivalent A-weighted levels are most often used, but this measure fails to capture wind turbine sound characteristics such as amplitude modulation and low frequencies.

This chapter reviews the main findings related to wind turbine noise and health outcomes and describes the knowledge gaps and research needs for relevant adverse health effects. The Panel's findings with regard to each adverse health effect are summarized in Tables 7.1 and 7.2.

7.1 SUMMARY OF THE EVIDENCE

More than one pathway or mechanism might plausibly link exposure to wind turbine noise and the adverse health effects examined in this report. Figure 7.1 summarizes the most probable causal pathways linking exposure to sound from wind turbines to adverse health effects. The evidence is sufficient to establish a causal relationship between exposure to wind turbine noise and annoyance. However, knowledge gaps remain on the question of whether factors such as visual impacts and personal attitudes modify the noise-annoyance relation. Long-term annoyance resulting from other types of noise, such as road traffic noise, has been shown to be a potential precursor or contributing factor to other adverse health effects, including stress, sleep disturbance, and cardiovascular diseases, but the exact mechanisms are incompletely understood (Babisch, 2002, 2008; Persson Waye *et al.*, 2003; Barregard *et al.*, 2009; van Kempen & Babisch, 2012).

In addition, the Panel found no evidence that wind turbines routinely produce infrasound at levels significantly higher than other environmental sources, such as the wind itself, or at levels associated with the known health effects of infrasound. However, in some cases and in certain types of dwellings, low-frequency sound may be more pronounced indoors because low frequencies are less attenuated by walls and windows and because of structure resonance. The Panel also found that exposure to wind turbine noise is unlikely to cause hearing loss.

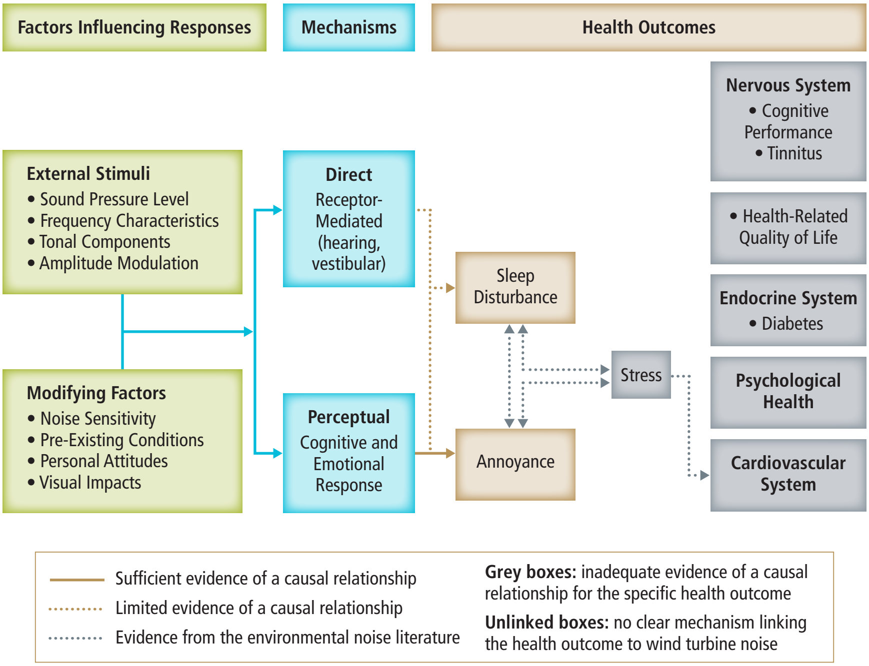


Figure 7.1

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

As discussed in Chapter 6, there is sufficient evidence to support a causal relationship for annoyance only. The current evidence is limited with regard to the relationship between exposure to wind turbine noise and sleep disturbance. The available evidence is inadequate with regard to stress; however, general evidence suggests that stress may be aggravated by annoyance and sleep disturbance. Research on the health effects of noise in general also suggests a strong relationship between long-term stress and cardiovascular or other diseases. Nevertheless, the causal mechanisms remain uncertain, particularly for wind turbine noise. Multiple pathways may be responsible for individual outcomes and population-level rates of adverse health effects. The absence of a causal relationship between wind turbine noise and hearing loss is not represented in this figure. See Table 7.1 for more information.

Knowledge gaps for the various conditions or symptoms discussed in Chapter 6 are listed in Table 7.1. Health effects that are not addressed in epidemiological studies or experiments specific to wind turbines and/or for which no plausible mechanisms can be suggested are listed in Table 7.2. Advancing understanding about whether or not these health effects are linked to noise exposure in general will also help determine if these are a concern in the context of wind turbine noise and if additional, more specific research is needed.

Table 7.1

Overview of Findings with Regard to Adverse Health Effects Addressed in Empirical Population-Based Research on Exposure to Wind Turbine Noise

Condition or Symptom	Level of Evidence (IARC)	Possible Pathways	Knowledge Gaps
Annoyance	Sufficient	Direct – exposure to wind turbine noise can lead to annoyance; however, the effect may be modified by factors such as visual impact and attitudes.	• Role of visual impact and attitudes on perception of wind turbines. • Prevalence of annoyance in exposed populations, gravity of effect, and thresholds under different conditions. • Role of specific sound characteristics (amplitude modulation, low frequency noise).
Sleep Disturbance	Limited	Direct and indirect (via annoyance or stress response or both) pathways are possible; however, wind turbine noise is likely only one among many factors affecting sleep quality.	• Nature of the mechanism (direct, indirect, or both) and the relative prevalence and magnitude of the effect for each. • Impacts of specific sound characteristics (including low-frequency sound) of wind turbine noise on sleep. • Long-term effects of wind turbine noise on sleep disturbance.

continued on next page

Condition or Symptom	Level of Evidence (IARC)	Possible Pathways	Knowledge Gaps
Stress	Inadequate	Direct and indirect (via annoyance or sleep disturbance or both) pathways are possible; however, no evidence for a direct association was found. Wind turbine noise could be one among many factors contributing to stress response.	• Nature of the mechanism (direct, indirect, or both) and relative prevalence and magnitude of the effect. • Unclear whether mechanism or stress response is comparable with other sources of environmental noise. • Impact of specific sound characteristics on stress. • Long-term effects of wind turbine noise on stress.
Cardiovascular System and Diseases (including hypertension, cardiac dysrhythmia, tachycardia)	Inadequate	Analogous research suggests that direct and indirect (via annoyance and stress or sleep disturbance or both) pathways are possible; however, no evidence for an association with wind turbine noise was found.	• Adequate epidemiological evidence. • Effects of long-term exposure. • Nature of the mechanism.
Diabetes	Inadequate	An indirect pathway (via stress, sleep disruption, or combinations) is plausible; however, the evidence linking these to noise from wind turbines was not consistent.	• Adequate epidemiological evidence. • Effects of long-term exposure. • Nature of the mechanism and comparability to the effect of other types of environmental noise.
Hearing Impairment	Evidence of no causal relationship	Sufficient evidence was found in research on other types of noise to conclude that permanent noise exposure below 75 dB(A) does not lead to hearing loss, even after lifelong exposure.	
Tinnitus	Inadequate	Research on tinnitus suggests that an indirect pathway via stress is possible.	• General uncertainty over the causes of tinnitus and links to other conditions such as impaired hearing.

continued on next page

Condition or Symptom	Level of Evidence (IARC)	Possible Pathways	Knowledge Gaps
Cognitive or Task Performance	Inadequate	Research on other types of noise suggests that noise exposure can affect cognitive performance; however, the character of the impact (positive or negative) and its strength vary with many factors, including sound characteristics and the type of task used to test cognitive performance.	• Understanding of how noise exposure affects different types of cognitive or task performance, including clear case definitions and measurement of cognitive performance.
Psychological Health (anxiety, depression, psychological distress)	Inadequate	Noise exposure could be a contributing factor to the development or aggravation of psychological disorders.	• General understanding of possible links between noise exposure and psychological disorders.
Health-Related Quality of Life	Inadequate	No mechanism identified or postulated. Exposure to wind turbine noise affects several categories that are used to measure quality of life, many of which overlap with the health impacts reviewed here.	• Research focusing on the relative impacts of wind turbine noise compared to other factors that affect quality of life.

The conditions and symptoms listed here are those attributed to wind turbine noise from various sources (see Table 5.1), for which the Panel found empirical research specific to wind turbine noise.

Table 7.2

Health Effects that Have Not Yet Been the Subject of Empirical Population-Based Research on Wind Turbine Noise

Condition or Symptom	Possible Pathways
Immune System	
Impaired immunity	An indirect pathway via stress response is possible; however, none of the studies assessed used variables that could test for associations between wind turbine noise and impaired immunity.
Musculoskeletal System	
Back pain Joint pain Muscle pain (myalgia) Shaking (palsy)	Indirect pathways via stress are possible; these symptoms could be caused by a large number of factors and medical conditions. No evidence regarding association with wind turbine noise exposure was found in the literature.

continued on next page

Condition or Symptom	Possible Pathways
Nervous System	
Disturbances of skin sensation	No pathways were described or proposed in the literature reviewed.
Effects of non-audible sound (inner ear, cochlea, vestibular system)	Within the normal hearing frequency range, sounds have to be at a very low level to be non-audible, and at those levels would not contribute to any type of known hearing dysfunction. For low-frequency signals, including infrasound, activation of the vestibular system is possible if the signal levels are at high intensity. For both normal subjects and even for individuals with certain medical conditions that result in lowered vestibular activation thresholds (e.g., Tullio syndrome, superior canal dehiscence, perilymphatic fistula, or enlarged vestibular aqueduct), wind turbine signals are unlikely to reach the activation threshold. It is therefore unlikely that wind turbine noise could directly cause any symptoms associated with vestibular dysfunction, such as vertigo, dizziness, vision problems, or nausea.
Fatigue	Daytime fatigue is a common consequence of sleep disruption.
Headache	Headaches are sometimes associated with noise annoyance, but not consistently in the available literature. Several pathways are possible (via annoyance, sleep disruption, or stress, or combinations); however, the symptom is associated with many possible causal pathways.
Nausea	A pathway based on stimulation of the vestibular system through non-audible sound in populations with certain medical conditions has been proposed; however, no evidence supporting its existence has been found.
Pressure in the chest	No pathways were described or proposed in the literature reviewed.
Sensation of internal vibration	No pathways were described or proposed in the literature reviewed.
Vertigo, dizziness	See effects of non-audible sound.
Vision problems	See effects of non-audible sound.
Nervous System: Auditory	
Communication interference	This could be a result of annoyance, and is often an indication of noise annoyance. No evidence testing the association has been found, however.
Ear pressure or pain	A pathway based on activation of the cochlea by sound in populations with certain medical conditions has been proposed; however, no evidence supporting its existence has been found.
Respiratory System	
Nosebleed	No pathways were described or proposed in the literature reviewed.

The conditions and symptoms listed here are those attributed to wind turbine noise from various sources (see Table 5.1), for which the Panel found no empirical research specific to wind turbine noise. In each case, the evidence is inadequate with respect to a causal link with wind turbine noise.

Furthermore, the Panel noted a paucity of research regarding the health effects of wind turbine noise on sensitive populations, including children and infants as well as populations affected by clinical conditions that may lead to an increased sensitivity to sound. This includes research on the potential impacts of noise exposure on cognitive development and learning in children. This is also true of research on the health effects of environmental noise in general.

7.2 QUALITY OF THE EVIDENCE REVIEWED

In view of the relative novelty of research on health effects of wind turbine noise, the Panel found it useful to review the general quality of the evidence available in comparison with research on the health impacts of other environmental stressors, and to provide an overview of limitations and general knowledge gaps.

Selection Bias

All population-based studies, and most of the experiments reviewed by this Panel, were based on self-reported data on health impacts. Self-reported surveys of environmental stressors are susceptible to selection bias (i.e., people who are affected by an environmental impact are more likely to respond to a survey than those who are not) (Rief *et al.*, 2011). In order to reduce selection bias in self-reported cross-sectional surveys, researchers may hide the true intent of surveys from respondent to the extent possible. The three largest cross-sectional studies reviewed (SWE-00, SWE-05, NL-07) stated that the questionnaires used were masked as general surveys on quality of life. Other studies noted that they used similar methodologies, but do not explicitly state whether questionnaires were sufficiently masked to avoid selection bias. The Panel therefore noted that the current evidence base may be affected by some degree of selection bias.

Confounding Factors

Factors other than noise may be responsible for a health outcome. If those same factors are also associated with exposure to wind turbine noise (for example, if those living closer to wind turbines happen to be older than average), it is possible that a confounder (in this example, age) is causing the increase in adverse health effects, and not the sound from wind turbines. Age, health history, pre-existing medical conditions, and attitudes towards wind turbines or visual impacts are factors that might be considered potential confounders and need to be controlled in the study analysis. While the cross-sectional studies reviewed for this assessment made reasonable efforts to control for those potential confounding factors, it is unlikely that they were able to control them completely.

Sample Size

In observational epidemiological studies, the number of people in the study (sample size) is important, for a number of reasons. The actual number required depends on the study design, but, generally speaking, studies must have adequate numbers of participants to ensure that different exposure levels are adequately represented (e.g., exposed and control groups) as well as, for example, all demographic categories (old and young, male and female, etc.) in order to control for potential confounding. Researchers must also ensure that the sample size is sufficient to rule out a result occurring by random chance. This is called statistical significance and depends on a number of factors, including the anticipated increase in risk for disease among the exposed persons. In the studies reviewed by the Panel, sample size was sufficiently large to capture annoyance and sleep disturbance, while sample sizes may have been too small to detect other health effects such as cardiovascular diseases, for which the anticipated increase in risk among the exposed would be quite small.

Exposure Monitoring

The Panel observed that most of the studies estimated exposure to indoor or outdoor wind turbine noise using computer-based models, rather than direct observations. A combination of measurements, modelled exposure, and outcomes is needed to settle the question of how to estimate exposure and its effects. In addition, the Panel noted that studies most often used a long-term equivalent A-weighted level (L_{Aeq}) to describe sound exposure. However, such approaches do not capture sound characteristics such as amplitude modulation. Identifying specific wind turbine sound characteristics may help to better understand the cause of certain health outcomes such as annoyance. This is discussed in further detail in Section 8.2.

Most epidemiological studies of wind turbine noise lacked sufficient power to detect meaningful health effects, or were designed in a way that could not convincingly rule out bias in responses or confounding factors. As a result, the evidence for a causal relationship between exposure to wind turbine noise and many health effects was inconsistent or unclear. In addition to the issues described above (selection bias, confounding factors, sample size, and exposure monitoring), the Panel also identified an absence of longitudinal health studies. However, the Panel recognizes, in the context of research on the health effects of wind turbine noise exposure, the difficulty of recruiting large samples of participants and following them over time.

7.3 FURTHER RESEARCH

Evidence shows that annoyance is likely to be caused by exposure to wind turbine noise. However, little is known in Canada about the prevalence of annoyance within the population exposed to wind turbine noise. In addition, the evidence reviewed suggested an association might exist between wind turbine noise and sleep disturbance or stress, either caused directly by noise or indirectly mediated by annoyance. Further research and surveillance would provide a better understanding of the prevalence in the general and exposed populations. In particular, research is needed to gain knowledge of (1) the incidence of the health outcome in the general population, (2) the proportion of the population exposed to wind turbine noise; and (3) the incremental risk of developing the disease that is associated with exposure to wind turbine noise.

Chronic annoyance and sleep disturbance are linked to stress responses in the context of long-term exposure to other sources of noise, such as air and road traffic. Furthermore, these are risk factors for other health effects, such as cardiovascular disease, which are also associated with long-term exposure to other sources of community noise. Further research on stress and sleep disturbance would provide more input in assessing a causal relationship between exposure to wind turbine noise and those two conditions. Useful research would involve studies with appropriate designs (addressing sample bias and confounding factors in particular) and sample sizes with adequate statistical power. Such research may help to better assess the causality between wind turbine noise and those conditions. At the time this report was being finalized (November 2014), preliminary results from a large-scale study from Health Canada became available (see Box 7.1).

Box 7.1
Health Canada’s Wind Turbine Noise and Health Study

In 2012, Health Canada started a large-scale cross-sectional epidemiological study involving approximately 2,000 dwellings. The aim of this study was to measure potential health outcomes in areas exposed to sound from wind turbines. This study was developed by Health Canada in collaboration with Statistics Canada to provide an evidence base and inform policies and practices in Canada regarding the development of wind energy projects. Among the outcomes measured by the Health Canada study were:

- Sleep disturbance, measured with a sleep watch that gauges sleep onset, sleep time, and efficiency. Self-reported sleep quality was also assessed with a questionnaire.
- Stress, measured by cortisol concentration in hair samples, blood pressure, and heart rate, as well as by a questionnaire (perceived stress).
- Self-reporting annoyance (indoor and outdoor), measured by self-reporting.
- Quality of life, measured using a questionnaire.

Health Canada’s preliminary findings were made publicly available in November 2014. The Panel reviewed those findings but, as they were preliminary, it could not integrate this research into the evidence considered in Chapter 6. However, the Panel observed that the findings from this study were mainly concordant with its own findings. The main results are presented below.

Of the dwellings selected, 1,238 households (78.9%) agreed to participate in the study. Both self-reported conditions and physiological measurements were described in the preliminary results. Regarding self-reported conditions, the study did not find associations between wind turbine noise exposure and self-reported sleep, self-reported illnesses (such as dizziness, tinnitus, and headaches), and chronic diseases (such as heart disease, high blood pressure, and diabetes). The study also did not find any association between noise exposure and self-reported perceived stress and quality of life. However, it found an association between increasing levels of wind turbine noise and annoyance towards wind turbine characteristics (noise, shadow flicker, blinking lights, vibrations, and visual impacts). Health Canada also captured physiological measures related to stress and sleep quality and found that the measures (e.g., hair cortisol levels, blood pressure, sleep watch) were consistent with self-reported results (no association between cortisol concentration, blood pressure, sleep efficiency, and exposure to wind turbine noise was found).

(Health Canada, 2014a, 2014b)

7.4 CHAPTER SUMMARY

After its review of the evidence, the Panel returned to the framework proposed in Chapter 5 that outlined possible relationships between wind turbine noise exposure and health effects. Based on the literature reviewed, including studies of other types of environmental noise, the Panel proposes a complex model of causal pathways (Figure 7.1), in which characteristics of wind turbine noise (low-frequency, tonality, and amplitude modulation) are modified by visual impact, personal attitudes, noise sensitivity, and existing medical conditions. These can lead to direct health effects via hearing, and to cognitive and emotional responses via processing in the brain.

To confirm possible pathways, knowledge gaps need to be filled. For each health outcome, knowledge gaps are outlined to help inform the research agenda. For many other health symptoms for which no studies specific to wind turbines were found, plausible pathways are suggested based on the literature.

Many of the studies reviewed had limitations or design weaknesses that affected the quality of the evidence. Population-based studies that relied on self-reported surveys were susceptible to selection bias, but many did not explain any steps taken to avoid this.

Relationships among noise exposure, chronic annoyance, sleep disturbance, and stress are a particularly fruitful area for further research to elucidate pathways. Future research into specific health outcomes is needed to understand the general incidence and prevalence of the health outcome, the population exposed to wind turbine noise, and the risks associated with exposure.

8

Promising Practices

- Engineering Technologies
- Promising Practices to Monitor Noise
- Increasing Acceptance
- Chapter Summary

8 Promising Practices

Key Findings

- Wind turbine designs that may lessen sound production are being explored; however, technological development is unlikely to resolve, in the short term, the current issues related to perceived adverse health effects of wind turbine noise.
- Sound pressure levels can vary widely within a structure — even within the same room — because of interference of sound waves reflected from walls. Improved measurement protocols have been proposed to more accurately account for this variation in indoor sound.
- Further studies focused on amplitude modulation are needed to better understand the potential impact of wind turbine noise on human health. Locals in some countries have recommended the use of measures that capture this characteristic.
- Impact assessments and community engagement give communities greater knowledge and control over wind energy projects.

The previous chapters demonstrate the complex nature of wind turbine sound production, propagation, and potential effects on humans. The Sponsor specifically requested that the Panel consider practices in engineering and other fields that could minimize adverse community response to wind turbine noise. In light of its findings, the Panel has identified several promising strategies, which are presented in this chapter:

- Reducing sound emission at the source through technological improvements;
- Better monitoring and understanding of the characteristics of sound from wind turbines through adequate measurement methods, both indoors and outdoors.
- Implementing adequate impact assessments and community engagement activities.

8.1 ENGINEERING TECHNOLOGIES

Modern utility-scale wind turbines produce sound from mechanical and aerodynamic sources (see Chapter 3). As discussed in that chapter, mechanical sound is not usually significant in modern turbines, as it has been greatly reduced through high-quality manufacturing and design elements such as soundproofing and insulation between mechanical components and the nacelle structure (Hau, 2006). These and other advances in design and manufacturing can generally reduce mechanical noise below the level of aerodynamic noise from the blades (Oerlemans, 2011).

Aerodynamic noise is produced by air flow interacting with different parts of the blade (see Section 3.1.2). No single technology was identified that will drastically reduce the sound output of modern utility-scale wind turbines, but the Panel did identify noise reduction technologies and practices that are actively being studied (Barone, 2011; Oerlemans, 2011):

- pitch control optimization;
- blade modifications; and
- technologies to manage curtailment to minimize both noise and loss of power.

8.1.1 Pitch Control Optimization

Modern utility-scale wind turbines use information from wind sensors on the nacelle to automatically make physical adjustments to parts of the turbine, such as the blade pitch and rotational speed, in order to generate the maximum power possible (Manwell *et al.*, 2010). Pitch control systems allow the blades to be rotated around their long axis (from the hub to the blade tip). This allows a degree of control over the angle of attack, or the angle at which air hits the leading edge of the turbine blade. Reducing the angle of attack can reduce noise emissions, but only by sacrificing some power production (Oerlemans, 2011). Theoretical and empirical research continues to identify optimal pitch control settings that strike a balance between power and sound output (Manwell *et al.*, 2010; Bakker *et al.*, 2012). Applying these settings in response to continually changing wind speed and direction, however, poses additional challenges.

8.1.2 Trailing Edge Modifications

Even with optimal blade pitch, the most common source of aerodynamic noise is interaction between air flow and the trailing edge of the turbine blades (see Section 3.1.2). Modifying the physical shape or properties of the blade’s trailing edge can therefore affect the level and characteristics of sounds produced. Aeroacoustic theory suggests that serrations or brushes along the trailing edge of the blade would decorrelate the sound and make it propagate less effectively, and would thus reduce aerodynamic sound emissions. In full-scale tests, trailing edge serrations were most effective at high wind speeds, reducing noise by up to 5 dB in 10 m/s winds (Barone, 2011; Oerlemans, 2011). Noise levels were reduced on average by about 3 dB, but at low wind speeds, additional high-frequency noise was produced, reducing the effectiveness of the blade serrations. Although trailing edge serrations have shown potential for reducing wind turbine noise, the mechanisms responsible are still not well understood (Barone, 2011).

8.1.3 Curtailment

Curtailment generally refers to sacrificing some power generation to reduce sound output to below an acceptable threshold. As described above, this might include adjusting blade pitch to reduce the angle of attack, or reducing the rotation speed of the turbines, if possible (Oerlemans, 2011). In extreme cases, wind turbines may have to be shut off to prevent sound emission.

Curtailment is often a last resort if other adjustments cannot reduce noise emissions below applicable limits. It is more commonly used at night, or when the wind is blowing from certain directions or above certain speeds, in order to reduce exposure levels for residents at particular locations (EPA, 2011). Identifying conditions under which curtailment is necessary can help reduce the need to apply it. Therefore, better sensors and automated systems offer another approach to limiting the amount of power that must be sacrificed to reduce noise levels. If certain levels or types of turbulence are known to cause enhanced amplitude modulation, meteorological sensors (e.g., LIDAR or SODAR) could be used to detect such weather conditions before they reach a turbine, and operations could be adjusted accordingly, by changing blade pitch or reducing power output (RenewableUK, 2013).

8.1.4 Continual Technological Improvement in a Global Market

The technologies described above are examples of promising methods for reducing noise levels in some situations, but the Panel notes that no single solution is likely to address all noise concerns in the short term. Nevertheless, ongoing research in wind turbine design and manufacture means that there is continual technological development in this area. Over 20 years, many small improvements have combined to reduce the overall sound power level of wind turbines for the same rotor diameter. This allows the use of larger turbines with the same level of noise emissions.

The Panel also notes that wind turbine manufacturers sell their products on a global market. An individual country such as Canada would therefore have a limited ability to influence technology trends through turbine design standards, since wind turbine manufacturers sell their products around the world (see Chapter 2). Most standards for wind turbine design, manufacture, and sound measurement are set by international organizations, such as the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO).

Canadian regulations could affect which wind turbine technologies are used here. Noise limits and regulations are often set at national, provincial, and even local levels. Therefore, while regulations and noise limits may not be able to directly affect technology development, they may determine which technologies are used, and how they are applied.

8.2 PROMISING PRACTICES TO MONITOR NOISE

As discussed in Chapter 2, noise limits are an important and necessary tool to limit exposure to sound from wind turbines. Adequate measurement of sound from wind turbines is paramount to properly inform such regulations but also to better understand the effect of wind turbine sound for research purposes. The Panel identified four criteria that are important to consider in terms of noise guidelines and measurement: background noise, indoor measurement, night-time measurement, and measurement of amplitude modulation.

8.2.1 Background Noise

Background noise is an important element in sound perception. A specific sound is more noticeable if the competing sound signals are at lower pressure levels; that is, if background noise is absent or low. This effect is captured by the masked hearing threshold (see Chapter 4), the sound pressure level at which a sound can be heard in the presence of competing sound signals such as background noise. The effect of background noise has been observed in research on sound from wind turbines (see Chapter 6). Studies showed that, for the same exposure, reported annoyance was more prevalent in quieter rural areas than in noisier urban areas (Pedersen & Persson Waye, 2007).

Wind can contribute to background noise as well as noise produced by wind turbines. As discussed in Chapter 3, the wind speed at the elevation of the blades may be much higher than that at ground level, an effect called wind shear. As a result, the high wind speed at the blade elevation leads to increased noise, but the lower wind speed at the ground reduces the masking effect of natural wind sound for residents. For example, in Sweden, particular attention is paid to houses in wind-sheltered areas, where the wind speed is about half of that at the wind turbine site. In such sheltered areas, the sound from wind turbines is more prominent than in wind-exposed locations (Persson Waye, personal communication). When regulating noise, taking into account background noise creates a level of complication, as background noise changes depending on factors that vary over time (e.g., wind speed).

8.2.2 Indoor Measurement

Indoor measurement is particularly relevant for environmental sound exposure, including wind turbine noise, as this sound may affect people in their homes, particularly at night when they are sleeping. As well, the lower frequency sound associated with wind turbines loses less energy than higher frequencies when transmitted through walls and windows (see Chapter 3). Furthermore, interference among sound waves may create large variations in sound pressure level in the same room.

There are specific guidelines to measure low-frequency sound indoors (Jakobsen, 2001; Pedersen *et al.*, 2007b; HGC Engineering, 2010). However, because of the variations in sound pressure level noted above, it is challenging to measure sound indoors. The variations result from reflection of sound waves by walls, causing interference with the original wave. The pattern of high and low sound pressure levels produced is called a standing wave pattern: at low frequencies, it may create large variations in the same room. Despite this challenge, there are methods to accurately measure the sound pressure levels indoors. For example, Pedersen *et al.* (2007b) suggested an improved measurement protocol to more accurately assess indoor sound (see Box 8.1). However, such measurements are not always possible. Some countries, such as Denmark, do not use indoor measurements and rely instead on computer-based simulations to assess compliance with regulations (DME, 2011).

Box 8.1
Improved Indoor Sound Pressure Measurement

Because of interference among sound waves within a structure, the sound pressure level at low frequencies may vary as much as 20 to 30 dB. Adequate measurement of areas of the room with high sound pressure levels is critical for assessing the causes of annoyance. Pedersen *et al.* (2007b) studied typical indoor measurement methods and concluded that these methods are not optimal and suggested a new methodology. This methodology is based on the average of measurements of sound pressure levels taken in four corners of a room at a maximum distance of 0.1 metres from the room boundaries (Pedersen *et al.*, 2007b).

8.2.3 Night-Time Measurements

In contrast to traffic noise, which usually subsides at night, wind turbine noise may carry on overnight when background noise is lower. Noise is therefore often more noticeable at night and more likely to affect sleep. WHO has suggested that, in residential areas, sound pressure levels should not exceed 40 dB(A) at night (outside) (WHO, 2009). Ellenbogen *et al.* (2012) recommended night-time noise limits of 37 dB(A) in residential area (6 m/s wind) and 42 dB(A) (6 m/s wind) in sparsely populated areas. There are various standards for reporting day and night sound pressure levels, with a “penalty” added for exposure during night-time. For example, L_{dn} adds a 10 dB(A) adjustment to night-time exposure (see Chapter 3). The Panel recognizes the usefulness of measuring night-time exposure to sound from wind turbines, which is currently not widely undertaken in Canada.

8.2.4 Measurement Methods to Better Assess Possible Health Effects of Wind Turbine Noise

There are several ways to describe and measure sound exposure, and each emphasizes some and deemphasizes other sound characteristics (e.g., pressure level, frequency, amplitude modulation; see Chapter 3). As noted in the WHO's *Guidelines for Community Noise*, "there is a very complex multidimensional relationship between the various characteristics of the environmental noise and the effects it has on people" (WHO, 1999). Proper measurement and reporting standards are important, because they allow sound levels to be comparable across studies, and they can help identify and clarify the sound characteristics associated with reported adverse health outcomes.

As noted earlier in this report, sound from wind turbines has the following characteristics: (1) it is broadband and composed of a range of frequencies including low-frequency sound; (2) higher frequencies tend to be reduced more indoors and with increasing distance, leading to an emphasis on low-frequency components; (3) it can have periodic amplitude modulation; and (4) the sound power level varies with wind speed at hub height. The first and second characteristics are common among many sources of environmental sound, such as the sound from the wind.

In reviewing literature specific to wind turbines, the Panel noted that most measurements in research papers were presented as A-weighted, time-averaged measurements (L_{Aeq}; see Table 3.1). Although A-weighting best approximates human hearing and is a well-adopted measure, it may not adequately capture the low-frequency components of sound from wind turbines. In addition, periodic amplitude modulation ("swishing" or "thumping"), a characteristic specific to sound from wind turbines, is not captured by time-averaged indicators (e.g., L_{eq}) (RenewableUK, 2013). Periodic amplitude modulation and dominance of low-frequency components may contribute to health effects such as annoyance, as documented in Chapter 6. These characteristics are critical to better understanding the effects of sound from wind turbines on humans. A practice to better measure the amplitude modulation of sound from wind turbines is presented in Box 8.2.

Box 8.2
Improved Capturing of Amplitude Modulation

A recent report reviewed the various methods of sound measurement to best characterize the sound from wind turbines (Kaliski, 2014). The report was prepared for the Massachusetts Wind Turbine Noise Technical Advisory Group (WNTAG), which provides advice to the Massachusetts Department of Environmental Protection (MassDEP) concerning noise regulations and policies for wind turbines (CoM, 2014). As part of its activities, WNTAG has logged about 120 million wind turbine sound records captured in 150 different conditions (e.g., meteorological, operational), which constitute an important base for better understanding the characteristics of sound from wind turbines.

The report suggested that the best measure to capture amplitude modulated sound is the fast response sound level (L_{Af}),* which is already used by MassDEP to assess "short duration repetitive sound." Using 1 second L_{Afmax} "allows for comparison of background and operating sound levels during similar wind speeds, without ignoring amplitude modulation peaks" (Kaliski, 2014). Use of such short-period measurements to capture amplitude modulation has also been suggested in conclusions from primary research (RenewableUK, 2013). Such measurements have been shown to be a good predictor of the risk of annoyance (Seong *et al.*, 2013) (see Chapter 6).

---

* For more information on time-weighted sound metrics, see Figure 3.6.

8.3 INCREASING ACCEPTANCE

In Chapter 6, the Panel concluded that annoyance results from combinations of contributing factors, including personal attitude. Studies showed that residents with negative attitudes towards wind energy were more likely to be annoyed than those with positive attitudes. Negative attitudes towards wind energy can be triggered by a process that is perceived as unfair. For example, Krogh (2011) illustrated the relationship between wind energy development, health impacts, and the loss of social justice. The author argued that loss of social justice arises from several factors associated with wind energy development, including "the lack of fair process, loss of rights, and associated disempowerment." The author also proposed that the lack of consultation with communities, as well as the construction of many wind turbines over short periods of time in certain parts of Canada, increased the feeling of injustice and resulted in negative social impact. In this section, the Panel describes practices pertaining to impact assessments and community engagement.

8.3.1 Environmental and Health Impact Assessment

In order to meet noise regulations at a prospective site, depending on the jurisdiction, size, and capacity of a planned wind facility, wind energy developers may need to undertake an environmental impact assessment. In Canada, there are no requirements at the federal level except for locations within federal jurisdiction (Haugen, 2011). Rules vary among provinces and territories. For example, under the Alberta Utilities Commission's rules, applicants to set up a new energy facility need to submit a noise impact assessment and predict the impact of noise under normal conditions at the most affected dwelling(s) (AUC, 2013). The Ontario Ministry of the Environment also requires a Noise Assessment Report for all proposed wind energy projects and provides detailed guidelines to conduct noise impact assessments (MOE, 2008). The Quebec Ministère du Développement durable, Environnement et Lutte contre les changements climatiques also provides instructions on how to conduct a noise impact assessment (MDDELCC, 2006). Outside of Canada, other countries have similar requirements. For example, the Irish Department of the Environment has developed particularly comprehensive guidelines to assess the impact of wind turbine development (Box 8.3).

Box 8.3
Assessing the Impact of Wind Turbine Development: the Irish Example

In the Republic of Ireland, the Department of the Environment, Community and Local Government (DECLG), the regulatory body responsible for wind energy development, requires developers to conduct full impact assessments to evaluate the areas of safety (setback), environment (heritage of site, noise, shadow flicker, and visibility), ecology, as well as social and economic sustainability. These guidelines cover activities from pre-application consultations to decommissioning and reinstatement. In particular, the DECLG suggests that the developer engages in consultations with the local community at the early stage of the planning process, allowing the communities to have an input. Appropriate mitigation and compensatory measures must be established before construction to prepare for impacts or changes that were previously unanticipated.

(DEHLG, 2006)

8.3.2 Community Engagement

> The success of wind power depends on how well the wind industry learns to include the public in decisions, both for the opportunities this allows for broader dissemination of information about wind power and for the suggestions the public can contribute to the discussion of their concerns and how to accommodate them.
>
> (Pasqualetti, 2002)

Residents want the opportunity to be involved in the decision-making process for the location of wind turbines, since equity and fairness are crucial for community acceptance (Wolsink, 2007). Collaborative approaches can give local communities an opportunity to discuss and address their concerns (Toke *et al.*, 2008). Various best practices exist to guide wind turbine developers and policy-makers in community engagement (RABDTI, 2007; CanWEA, n.d.).

The objective of community engagement is to inform, educate, and involve the local residents with the wind energy project, specifically highlighting its benefits and taking into account concerns, with the goal of achieving social acceptance. Public participation techniques include processes such as referenda, public hearings, public surveys, and negotiated rule-making (Jami & Walsh, 2014).

In addition to implementing setbacks and noise limits, most international best practices strongly recommend that the wind energy developer engage in consultation and communication with the local authorities and residents at an early stage of project development. For example, the Australian government recognizes that community consultation is an important two-way process: informing the stakeholders and actively encouraging local people to offer feedback and ask questions (EPHC, 2010) (see Box 8.4). A new model for environmental noise annoyance is relevant in the context of community engagement: "soundscape" — a concept introduced to comprehensively measure the potential effect of noise on quality of life (Schulte-Fortkamp, 2014). Soundscape techniques take into account both the context and the perception of sound and consider that human response is not a single factor but is related to the human perception of the situation (Schomer *et al.*, 2010).

Box 8.4
Guidelines for Engaging Communities

The Australian Environment Protection and Heritage Council (EPHC) has developed a series of guidelines to assist developers in addressing stakeholder participation in wind energy development. The goals of these guidelines are to provide:

- Principles and considerations for wind energy developers for planning and delivering stakeholder participation activities.
- Recommendations for stakeholder input to the assessment and how to manage key study areas (including noise).

These guidelines cover the various stages of wind energy project development: site selection, project feasibility, planning application, construction, operation, and decommissioning. For each project stage, the EPHC recommends specific milestones be met, such as continuously seeking feedback and input from stakeholders at the project feasibility and planning stages to better understand their concerns and opinions. Regarding noise, the guidelines recommend measuring background noise at the project feasibility stage and the construction stage, as well as conducting noise monitoring at identified stakeholder properties. Although these guidelines have been developed in Australia, the general principles of risk management and communication can easily be applied to the Canadian context.

(EPHC, 2010)

With the combination of public inquiries and environmental impact assessments, many European countries have been able to make wind energy development less controversial, in large part because communities are engaged in and benefit directly from this process (CSE, 2009).

8.4 CHAPTER SUMMARY

Technological improvements in wind turbine design have resulted in larger and more powerful turbines over the past 20 years. While turbines now produce less noise for the same size than previous-generation turbines, this effect is offset by their growth in size and production capacity. There are some promising technologies being studied to lessen sound production, but no “silver-bullet” technology is expected to resolve all problems of sound from wind turbines. The regulatory measures (noise limits and setbacks) currently used in Canadian and international jurisdictions will therefore continue to be necessary. Many of these measures have taken into account the need to adjust to different wind speeds, to daytime and night-time differences, and to background noise.

These adjustments are important to any future regulatory measures, but they all rely on sound measurement. Measurement techniques and standards need to be established, as current use of A-weighted time-averaged measurement does not capture some of the aspects of sound from wind turbines, in particular amplitude modulation. Measuring indoor sound is important to capture sound affecting residents, but it is challenging due to the wide variation in sound pressure levels within a single room.

Fortunately, there are many international practices in these areas that can inform future directions in Canada, including choice of measure, and methods for measuring indoor sound pressure levels. However, because perception of wind turbines has to do with aspects other than sound, health and environmental impact assessment and community engagement are also critical. Several international studies have found that environmental assessment, from the proposal stage to after installation, helps lead to successful, well-accepted wind energy projects. Engaging communities results in greater acceptance and involvement. These measures might also mitigate health effects through feedback, information, and positive attitudes.

9

Conclusions

- Final Thoughts

9 Conclusions

This chapter synthesizes the findings and evidence of the previous chapters to summarize the Panel's response to the Charge. The main question and sub-questions asked by the Sponsor are answered individually.

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

The Panel found ***sufficient evidence*** to establish a causal relationship between exposure to wind turbine noise and annoyance, and ***limited evidence*** to establish a causal relationship between exposure to wind turbine noise and sleep disturbance. The Panel found evidence suggesting a ***lack of causality*** between exposure to wind turbine noise and hearing loss. The available evidence was ***inadequate*** to draw any conclusion regarding causation for all other health effects considered (see Chapter 6 for details, summarized in Tables 7.1 and 7.2). Although evidence concerning the association between wind turbine noise and stress is inconsistent and not of high enough quality to permit firm conclusions, stress has been linked to many other environmental sources of noise, often with links to annoyance and sleep disturbance. Nevertheless, causal relationships between these three effects are often unclear: each may lead to another, with more than one causal pathway likely accounting for observed cases of each health effect in a population. Other health effects commonly attributed to wind turbine noise, including headache and communication interference, have been attributed to many factors. However, no empirical research exists to establish a causal relationship between these effects and wind turbine noise.

Some additional causal mechanisms have been proposed that could link wind turbine noise to symptoms such as vertigo, dizziness, nausea, or vision problems. Such symptoms would be consistent with stimulation of the vestibular system, which can be activated by sound at levels that are above normal human hearing thresholds for infrasound and low-frequency sound. Sensitive individuals with certain clinical conditions might have lower activation thresholds, below normal hearing thresholds, but whether such activation thresholds are within typical sound levels from wind turbines remains unclear, as does the prevalence of these conditions in populations exposed to wind turbine noise. However, the Panel concluded that wind turbine signals are unlikely to reach activation threshold in individuals.

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?

The Panel identified specific knowledge gaps for each health condition studied, where specific types of evidence would help clarify the strength of associations, avoid bias, or eliminate possible confounding factors with respect to exposure to wind turbine noise. For example, it is unclear whether annoyance is caused by wind turbine noise alone, or whether factors such as visual impacts and personal attitudes modify the noise-annoyance relation. The possible pathway that could lead to sleep disturbance or stress is also unclear. It is similarly unclear whether the possible pathway that could lead to sleep disturbance or stress is the direct result of exposure to wind turbine noise or is the result of annoyance as a mediating factor. The Panel also noted that knowledge gaps concerning potentially sensitive populations such as children and infants, as well as individuals with certain clinical conditions, complicate any attempts to assess the level of health risk associated with exposure to sound from wind turbines. In addition, the Panel noticed the lack of data on adverse health effects at the population level, which could be gathered through rigorous research designs to minimize bias and confounding factors, and could link outcomes to exposure measurement.

Reviewing the evidence, the Panel observed that most of the cross-sectional studies used standard modelling approaches to predict sound levels. Combinations of measurements, modelled exposure, and outcomes are needed to settle the question of how to estimate exposure and its effects. In addition, modelling and some measurement approaches do not capture many sound characteristics relevant to wind turbines, such as amplitude modulation. Being able to link those specific wind turbine sound characteristics to effects may help researchers to better understand the cause of certain health outcomes such as annoyance.

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?

In reviewing the literature, the Panel identified many research and knowledge gaps concerning pathways and causality. However, the Panel notes that it was not within its mandate to assess whether specific research should be prioritized over other public health research, or to provide recommendations on any specific type of research. The Panel can comment on lines of research that would be useful in addressing existing knowledge gaps.

For many adverse health effects, questions and uncertainties remain. Of the wide range of reported health effects attributed to wind turbine noise exposure, many are possible secondary outcomes of long-term sleep disturbance or stress, but may have other causes. In particular, cardiovascular diseases, a set of conditions responsible for almost one third of the deaths in Canada, are known to be affected by long-term annoyance, sleep disruption, and stress. It would therefore be beneficial to improve understanding about the potential risks arising from long-term exposure to wind turbine noise, and to further study the causal relationship between exposure to wind turbine noise and sleep disturbance and stress.

Although sound from wind turbines appears to be at levels similar to other common sounds in the environment, some characteristics are more common in sound from wind turbines than in sound from other sources, such as periodic amplitude modulation (causing a "swishing" or "thumping" sound), and variations linked to wind speed at the height of the blades (which can be 60 to 100 metres or more above the ground). Continued research could help identify measurements of sound exposure that are most relevant to possible health effects, as well as improve our understanding of the mechanisms responsible for annoyance or other plausible health effects of exposure to sound from wind turbines or other sources. In particular, the Panel noted that periodic amplitude modulation may be a critical component of sound from wind turbines that triggers annoyance.

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?

The Panel found insufficient data available for Canada to answer this question. However, in terms of the nature of health effects, there is no reason to believe that potential health effects for our population would be significantly different than those for other nations. The conclusions concerning health effects drawn from studies worldwide would therefore be applicable to Canada. In terms of the prevalence of these effects, none of the population-based studies cited in this report were conducted in Canada, so their conclusions offer no insight into how prevalence of adverse health effects might compare with other countries. At the time of the writing of this report, Health Canada released preliminary results from the first-ever study to combine subjective and objective health measures with measured and modelled sound levels from wind turbines. Previous population studies of health effects of wind turbine noise have relied almost entirely on health conditions self-reported by survey participants. The preliminary results of the Health Canada study suggest differences in the prevalence of self-reported annoyance between the two provinces examined. Therefore, regional differences in the prevalence of effects are certainly possible, either due to differences in the perception of wind turbines, or in other as-yet-unknown factors that affect individual sensitivity. The full peer-reviewed results of the Health Canada study were not available before the Panel's report went to publication.

Other countries, such as Australia, have set up reporting systems for the consistent collection of noise and health complaints, which has allowed systematic analyses of complaints related to wind turbines. Such complaints are, at best, a weak surrogate for self-reported health effects. The only comparable analysis of complaints in Canada was carried out in Alberta, and found overall low levels, in contrast with pockets of high levels of complaints in Australia. However, this finding may be attributable to the fact that Canada's wind energy industry is relatively new compared to the industries in other countries.

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 identified three areas of current technological development that show the most promise in reducing the sound output of modern utility-scale wind turbines: pitch control optimization, blade modifications (serrations or brushes), and technologies to manage curtailment under conditions known to produce excessive noise. Each of these developments attempts to reduce sound output while minimizing loss of power output, thus striking a balance between environmental impacts and economic benefits. Regardless of whether these particular technologies may ultimately be viable, research and development has produced a steady stream of improvements that have continually led to reductions in sound power level for wind turbines of a given size. Such continual technological improvement is expected to lead to further reductions in sound output.

However, no "silver-bullet" technology is expected to resolve all problems of sound from wind turbines, especially in the short term. Therefore, other measures will continue to be relevant.

Wind turbines are sold on a global market, and regulations in a single country such as Canada are unlikely to provide sufficient incentive to further reduce their sound power. However, there is a global initiative across the wind energy industry to continually reduce the sound power of wind turbines in order to increase social acceptability across all markets. As well, regulatory measures taken in a particular jurisdiction (country, province) determine which available technologies and practices can be used to achieve local goals.

Thus, regulation is an important tool to control exposure to wind turbine noise and, consequently, its potential health impact on the public. The Panel reviewed best practices for improved measurement of background noise, indoor sound, night-time sound, and amplitude modulation. The Panel suggests that a combination of those practices would provide a better understanding of noise exposure and inform noise guidelines or regulation by the various orders of governments (federal, provincial, and municipal).

Finally, the Panel reviewed best practices for impact assessment and community engagement. In the past, failure to engage with the community has increased negative attitudes among the public toward wind projects and the wind industry. By contrast, health and environmental impact assessment and community engagement, from the inception of projects throughout the project lifecycle including after installation, can provide an opportunity to adapt to community feedback and concern.

9.1 FINAL THOUGHTS

Wind turbines have become a contentious source of energy, in Canada and internationally. Although some hail them as a source of renewable, clean energy, others have expressed concerns about undesirable environmental and human health impacts. Assessing the possible human health impacts of exposure to wind turbine noise poses several scientific and technical challenges.

This report has found sufficient evidence that exposure to wind turbine noise (possibly in combination with other factors) can contribute to annoyance, and that such exposure does not lead to hearing loss. However, for many other adverse health effects investigated, there was inadequate evidence to reach conclusions concerning the absence or presence of a causal link.

The Panel stresses that, given the nature of the sound produced by wind turbines and the limited quality of available evidence (small sample sizes, small number of studies available, lack of comprehensive exposure measurement), the health impacts of wind turbine noise cannot be comprehensively assessed at this time. Furthermore, in noting the challenges of undertaking research on health impacts caused by multiple factors (large cohort studies, longitudinal studies, double-blind experiments), the Panel emphasizes that providing high-quality evidence would require a major research effort.

Glossary

Glossary

Absolute hearing threshold is the lowest sound pressure level at which a person can hear different frequencies in a very quiet environment with focused concentration.

Air conduction of sound is the conveyance of sound through the external auditory canal and middle ear to the inner ear (Dorland, 2011).

Amplitude modulation refers to changes in sound pressure over time. It has two characteristics: the difference between the highest and lowest sound pressure levels (modulation depth), and the frequency range in which variations in sound pressure occur (modulation frequency, not to be confused with the frequency of the sound itself) (van den Berg & Bowdler, 2011). Amplitude modulation can also be periodic, with changes in sound pressure occurring at regular intervals. In the case of sound from wind turbines, the amplitude is modulated at the same rate as the rotation of the blades (the "blade pass frequency").

Association describes a relationship between two variables that makes them statistically dependent. An association does not necessarily mean that one variable is causing the other, as the association may be due to another, unknown variable; it may also be unclear which variable is affecting the other.

Bone conduction of sound is the conveyance of sound to the inner ear through the bones of the skull (Dorland, 2011).

Broadband see *Frequency*.

Case definition is "a set of standard criteria for deciding whether a person has a particular disease or health-related condition" (Columbia University, n.d.).

Cut-in wind speed is the minimum wind speed for a wind turbine to generate power.

Cut-out wind speed is a maximum wind speed for a wind turbine to generate power.

dB(A), dB(C), dB(G) all refer to sound pressure level measurements that have been adjusted according to a weighting filter, indicated by the letter in parentheses following "dB" (decibel). For example, "dB(A)" or "dBA" indicates A-weighted sound pressure levels. This weighting de-emphasizes sounds at low and very high frequencies in a way that approximates the sensitivity of the human ear to sound at low pressure levels (Leventhall, 2011). C-weighting de-emphasizes low frequency sound less than A-weighting, whereas G-weighting emphasizes infrasound more than other frequencies. See Section 3.1.1 for a more detailed discussion of sound measurement and weighting filters.

Epidemiology is the science that studies the patterns of diseases and factors associated with outcomes in a population.

Exposure is the condition of being subjected to something (e.g., sound) that could have a detrimental effect. In this report, the type of exposure is always mentioned (e.g., exposure to wind turbine sound).

Frequency of sound is the number of pressure waves per second, measured in Hertz (Hz). Frequency is perceived as tone or pitch, with higher frequencies having a higher tone: Middle C is 261.6 Hz. The human ear is most sensitive in the 2 kHz to 5 kHz range, which is roughly the range of the highest octave on a piano. Sound at a single frequency is called a pure tone, whereas sound composed of a wide range of frequencies is described as *broadband*.

Health is "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO, 1946).

Infrasound is sound at frequencies below 20 Hz; when physiological effects are discussed, a lower bound of 1 Hz is often used (ANSI/ASA S1.1, 2013). Infrasound is audible at high sound pressure levels, typically above 70 to 100 dB, with higher thresholds at lower frequencies (Watanabe & Møller, 1990).

Latency period is the time period between exposure and development of disease.

Loudness refers to a person's subjective sound perception or magnitude of resulting sensation when a sound impinges on the ear. By contrast, *sound pressure* is an objective measure of the energy in a sound wave. *Sound* and *noise* are often measured by sound pressure level, but this is not always a reliable indicator of loudness — how these sounds are perceived by people — since loudness is affected not only by sound pressure but also by personal physiological and psychological factors.

Low-frequency sound, as used in this report, refers to sound at frequencies in the range of 20 to 200 Hz (Persson Waye, 2005, 2011; Pedersen *et al.*, 2007b). The boundaries between infrasound, low-frequency sound, and other frequencies are somewhat arbitrary, however, and vary in the literature depending on the context and application.

Masked hearing threshold is the sound pressure level at which a sound can be heard in the presence of competing sound signals.

Nameplate capacity: see *Rated power.*

Noise: Two different definitions of noise are used in this report — one technical definition and one that describes the perception of sound by an individual. In the field of acoustics, noise is a competing acoustic signal that masks a sound of interest. Noise also defines an unpleasant or unwanted sound that causes disturbance. The perception of noise depends on the individual and the context (i.e., the same sound may be considered noise by one individual and not by another).

Noise limit is a maximum sound power level (at the source) or sound pressure level (at a receiver) recommended or regulated to prevent noise-related problems in an environment.

Rated power or **nameplate capacity** is the maximum power output of a wind turbine generator.

Rated wind speed is the lowest speed at which a wind turbine will generate the maximum power (the rated power).

Receiver: A location at which sound is measured or detected. A receiver can also refer to a recording instrument measuring sound, or a person exposed to sound at a given location. A receiver is often exposed to sound from multiple sources in the environment, although one source (e.g., one or more wind turbines) is often of particular interest.

Selection bias is a statistical bias that may arise from the method used to select the subjects of a study; if not corrected for during analysis, selection bias may lead to incorrect conclusions. Examples of selection bias include self-selection of subjects or non-random selection of subjects for a study. In these cases, the subjects may have different characteristics from those not selected (age and income are common ones), which may affect outcomes of the study. Another example is attrition bias, in which subjects who do not complete the study may have poorer outcomes that are not included in the analysis.

Setback, in land use, is the distance that a building or structure is set back from any place that is deemed to need protection; in the case of wind turbines, it is distance to the closest building or residence. Setbacks are commonly used to limit noise exposure and other hazards from wind turbines.

Sound is a pressure wave (oscillation) that travels through a medium such as air (ANSI/ASA S1.1, 2013). Sound can also refer to an auditory sensation evoked by the pressure wave.

Sound power level (L_W) is a measure of sound produced at a source, in contrast to the *sound pressure level*, which is measured at a receiver location. Both are measured in decibels (dB), which represent power relative to a reference value, on a logarithmic scale. The reference level (0 dB) for sound power is 1×10^{-12} W. Sound power is a characteristic of the source, used to predict the propagation of sound in an environment (Crocker, 2007; Leventhall, 2011).

Sound pressure level (sound level; acoustic pressure; SPL; L_p) is an objective measure of the amplitude of sound: the magnitude of fluctuations in pressure around atmospheric pressure. The value at a given location depends on the characteristics of the source, and the transmission of sound between the source and the receiver, where the sound pressure level is measured. Sound pressure levels are measured in decibels (dB), which represent pressure fluctuations in Pascals (Pa), relative to a reference value, on a logarithmic scale. The reference level (0 dB) for sound pressure is 20 µPa (2×10^{-5} Pa), which is close to the human hearing threshold at a frequency of 1 kHz.

Stress is defined as conditions of a physical, biological, or psychological nature that strain the adaptive capacity of a person up to or beyond his or her limits (Welford, 1974; Gemmert & Van Galen, 1997).

Superior canal dehiscence is a health condition resulting from a loss of bone that covers the superior canal of the vestibular system. It may allow communication between the superior canal and the cranial cavity, which can cause loss of air-conducted hearing in low and middle frequencies (≤ 2,000 Hz); in some cases it can also increase the threshold of bone-conducted hearing, which may increase sound sensitivity.

Wind energy facilities (e.g., wind energy projects, wind farms) consist of multiple wind turbines in a defined geographic area, owned and operated to generate electricity at utility scales, and connected to the main electrical grid.

Wind turbines, as used in this report, refer to modern utility-scale devices that generate electricity from the kinetic energy of the wind. These typically consist of three blades, each roughly 40 metres long or more, attached to a rotor and horizontal nacelle, mounted on a tower roughly 80 metres tall or more, with the blades spinning in front (upwind) of the tower. The focus of this report is onshore turbines connected to an electricity grid; offshore wind turbines, or smaller devices used to provide electricity to a single building, are outside the scope of this report.

References

References

Alimohammadi, I., Sandrock, S., & Gohari, M. R. (2013). The effects of low frequency noise on mental performance and annoyance. *Environmental Monitoring and Assessment, 185*, 7043-7051. doi: 10.1007/s10661-013-3084-8.

Alves-Pereira, M. & Branco, N. A. A. C. (2007). Vibroacoustic disease: Biological effects of infrasound and low-frequency noise explained by mechanotransduction cellular signalling. *Progress in Biophysics and Molecular Biology, 93*, 256-279. doi: 10.1016/j.pbiomolbio.2006.07.011.

Ambrose, S. E., Rand, R. W., & Krogh, C. M. E. (2012). Wind turbine acoustic investigation: Infrasound and low-frequency noise—A case study. *Bulletin of Science, Technology & Society*, 32, 128-141. doi: 10.1177/0270467612455734.

ANSI/ASA S1.1 (The American National Standards Institute/The Acoustical Society of America). (2013). *Acoustical Terminology*. Melville (NY): The American National Standards Institute, Inc. Accredited Standards Committee S1, Acoustics.

ASHA (American Speech-Language-Hearing Association). (1981). Degree of Hearing Loss. Retrieved November 2014, from http://www.asha.org/public/hearing/Degree-of-Hearing-Loss/.

AUC (Alberta Utilities Commission). (2013). *Rule 12: Noise Control*. Calgary (AB): AUC.

Babisch, W. (2002). The noise/stress concept, risk assessment and research needs. *Noise & Health, 4*(16), 1-11.

Babisch, W., Ising, H., & Gallacher, J. E. J. (2003). Health status as a potential effect modifier of the relation between noise annoyance and incidence of ischaemic heart disease. *Occupational and Environmental Medicine, 60*(10), 739-745. doi: 10.1136/oem.60.10.739.

Babisch, W. (2008). Road traffic noise and cardiovascular risk. *Noise & Health, 10*(38), 27-33.

Babisch, W. (2011). Cardiovascular effects of noise. *Noise & Health, 13*(52), 201.

Babisch, W., Pershagen, G., Selander, J., Houthuijs, D., Breugelmans, O., Cadum, E., ... Hansell, A. L. (2013). Noise annoyance—A modifier of the association between noise level and cardiovascular health? *Science of the Total Environment, 452-453*(C), 50-57. doi: 10.1016/j.scitotenv.2013.02.034.

Baguley, D. M. (2003). Hyperacusis. *Journal of the Royal Society of Medicine, 96*(12), 582-585.

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., & Bouma, J. (2012). Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. *Science of the Total Environment, 425*, 42-51. doi: 10.1016/j.scitotenv.2012.03.005.

Baqtasch, M., Van Dam, J., Søndergaard, B., & Rogers, A. (2006). Wind turbine noise—An overview. *Canadian Acoustics, 34*(2), 7-15.

Barone, M. (2011). *Survey of Techniques for Reduction of Wind Turbine Blade Trailing Edge Noise.* Albuquerque (NM): Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Barregard, L., Bonde, E., & Öhrström, E. (2009). Risk of hypertension from exposure to road traffic noise in a population-based sample. *Occupational and Environmental Medicine, 66*(6), 410-415. doi: 10.1136/oem.2008.042804.

Basner, M., Müller, U., & Elmenhorst, E. M. (2011). Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. *Sleep, 34*(1), 11-23.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014). Auditory and non-auditory effects of noise on health. *The Lancet, 383*(9925), 1325-1332. doi: 10.1016/S0140-6736(13)61613-X.

Bauer, L. (nd). Welcome to wind-turbine-models.com. Retrieved June 2014, from http://en.wind-turbine-models.com/.

Berger, E. H., Kieper, R. W., & Gauger, D. (2003). Hearing protection: Surpassing the limits to attenuation imposed by the bone-conduction pathways. *The Journal of the Acoustical Society of America, 114*(4), 1955-1967.

Berglund, B., Hassmén, P., & Job, R. S. (1996). Sources and effects of low-frequency noise. *The Journal of the Acoustical Society of America, 99*, 2985-3002.

Bockstael, A., Dekoninck, L., Can, A., Oldoni, D., De Coensel, B., & Botteldooren, D. (2012). Reduction of wind turbine noise annoyance: An operational approach. *Acta Acustica united with Acustica, 98*, 392-401. doi: 10.3813/AAA.918524.

Bockstael, A., Van Renterghem, T., De Weirt, V., & Botteldooren, D. (2013). *Exploring Underlying Mechanisms for Human Response to Wind Turbine Noise.* Paper presented at INTER-NOISE 2013, the 42nd International Congress and Exposition on Noise Control Engineering, Innsbruck, Austria.

Bolin, K., Bluhm, G., Eriksson, G., & Nilsson, M. E. (2011). Infrasound and low frequency noise from wind turbines: Exposure and health effects. *Environmental Research Letters*, 6(3), 1-6. doi: 10.1088/1748-9326/6/3/035103.

Bolin, K., Kedhammar, A., & Nilsson, M. E. (2012). The Influence of Background Sounds on Loudness and Annoyance of Wind Turbine Noise. *Acta Acustica united with Acustica*, 98(5), 741-748. doi: 10.3813/aaa.918555.

Bowdler, D. (2008). Amplitude modulation of wind turbine noise. A review of the evidence. *Institute of Acoustics Bulletin, 33*(4).

Bradford Hill, A. (1965). The environment and disease: Association or causation? *Proceedings of the Royal Society of Medicine, 58*, 295-300.

Bradley, J. S. (1994). Annoyance caused by constant-amplitude and amplitude-modulated sounds containing rumble. *Noise Control Engineering Journal, 42*(6), 203-208.

Brisson, G., Gervais, M.-C., Martin, R., Blackburn, D., Chagnon, M., Martel, K., ... Tardiff, I. (2013). *Éoliennes et Santé Publique: Synthèse des Connaissances – Mise à Jour.* Quebec (QC): Institut national de Santé Publique du Québec, Direction de la santé environnementale et de la toxicologie.

Broadbent, D. E. (1971). *Decision and Stress.* London, United Kingdom: Academic Press Inc.

Bryant, P. & Bradley, L. (1985). *Children's Reading Problems: Psychology and Education.* Oxford, United Kingdom: Wiley-Blackwell.

Bullmore, A. (2011). Chapter 3. Sound Propagation from Wind Turbines. In D. Bowdler & G. Leventhall (Eds.), *Wind Turbine Noise.* Essex, United Kingdom: Multi-Science Publishing Company, Ltd.

Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. (2011). Wind Turbine Installations and Wind Farms. In T. Burton, N. Jenkins, D. Sharpe & E. Bossanyi (Eds.), *Wind Energy Handbook* (2 ed.). West Sussex, United Kingdom: John Wiley & Sons, Ltd.

CanWEA (Canadian Wind Energy Association). (2008). *Wind Vision 2025: Summary.* Ottawa (ON): CanWEA.

CanWEA (Canadian Wind Energy Association). (2011). *Federal / Provincial Initiatives on Wind Energy.* Ottawa (ON): CanWEA.

CanWEA (Canadian Wind Energy Association). (2014). Why Wind Works. Retrieved January 2015, from http://windfacts.ca/why-wind-works.

CanWEA (Canadian Wind Energy Association). (n.d.). *Best Practices for Community Engagement and Public Consultation.* Ottawa (ON): CanWEA.

Chapman, S., St George, A., Waller, K., & Cakic, V. (2013). The pattern of complaints about Australian wind farms does not match the establishment and distribution of turbines: Support for the psychogenic, 'communicated disease' hypothesis. *PLOS ONE, 8*(10), e76584. doi: 10.1371/journal.pone.0076584.t002.

Ciliska, D., Thomas, H., & Buffett, C. (2008). *An Introduction to Evidence-Informed Public Health and A Compendium of Critical Appraisal Tools for Public Health Practice.* Hamilton (ON): National Collaborating Centre for Methods and Tools.

Clark, C. & Stansfeld, S. A. (2007). The effect of transportation noise on health and cognitive development: A review of recent evidence. *International Journal of Comparative Psychology, 20*(2).

Clark, C. & Sörqvist, P. (2012). A 3 year update on the influence of noise on performance and behavior. *Noise & Health, 14*(61), 292-296.

Colby, W. D., Dobie, R., Leventhall, G., Lipscomb, D. M., McCunney, R. J., Seilo, M. T., & Søndergaard, B. (2009). *Wind Turbine Sound and Health Effects: An Expert Panel Review (AWEA and CWEA).* Ottawa (ON): Canadian Wind Energy Association.

Colebatch, J. G. & Halmagyi, G. M. (1992). Vestibular evoked potentials in human neck muscles before and after unilateral vestibular deafferentation. *Neurology, 42*(8), 1635-1636.

Colebatch, J. G., Halmagyi, G. M., & Skuse, N. F. (1994). Myogenic potentials generated by a click-evoked vestibulocollic reflex. *Journal of Neurology, Neurosurgery, and Psychiatry 57*(2), 190-197.

Columbia University. (n.d.). Glossary of epidemiological terms. Retrieved January 2015, from http://www.cs.columbia.edu/digigov/LEXING/CDCEPI/gloss.html.

CoM (Commonwealth of Massachusetts). (2014). MassDEP Wind Turbine Noise Technical Advisory Group. Retrieved October 2014, from http://www.mass.gov/eea/agencies/massdep/news/advisory-committees/wntag.html.

Crichton, F., Dodd, G., Schmid, G., Gamble, G., Cundy, T., & Petrie, K. J. (2014a). The power of positive and negative expectations to influence reported symptoms and mood during exposure to wind farm sound. *Health Psychology, 33*(12), 1588-1592. doi: 10.1037/hea0000037.

Crichton, F., Dodd, G., Schmid, G., Gamble, G., & Petrie, K. J. (2014b). Can expectations produce symptoms from infrasound associated with wind turbines? *Health Psychology, 33*(4), 360-364. doi: 10.1037/a0031760.

Crocker, M. J. (2007). *Handbook of Noise and Vibration Control.* Hoboken (NJ): John Wiley & Sons.

Croy, I., Smith, M. G., & Waye, K. P. (2013). Effects of train noise and vibration on human heart rate during sleep: An experimental study. *BMJ Open, 3, 1-8.*

CSE (Centre for Sustainable Energy). (2009). *Delivering Community Benefits from Wind Energy Development: A Toolkit.* London, United Kingdom: CSE.

Curthoys, I. S., Kim, J., McPhedran, S. K., & Camp, A. J. (2006). Bone conducted vibration selectively activates irregular primary otolithic vestibular neurons in the guinea pig. *Experimental Brain Research, 175*(2), 256-267.

Danielsson, A. & Landstrom, U. (1985). Blood pressure changes in man during infrasonic exposure. An experimental study. *Acta Medica Scandinavica, 217*(5), 531-535.

DEHLG (Department of Environment, Heritage and Local Government). (2006). *Wind Energy Development.* Dublin, Ireland: DEHLG.

Diamond, A. (2002). Normal Development of Prefrontal Cortex from Birth to Young Adulthood: Cognitive Functions, Anatomy, and Biochemistry. In D. T. Stuss & R. T. Knight (Eds.), *Principles of Frontal Lobe Function.* New York (NY): Oxford University Press.

DME (Danish Ministry of the Environment). (2011). *Statutory Order on Noise from Wind Turbines.* Copenhagen, Denmark: DME.

Dorland, W. A. N. (2011). *Dorland's Illustrated Medical Dictionary* (32 ed.). Philadelphia (PA): Elsevier Health Sciences.

Eberhardt, J. L., Stråle, L. O., & Berlin, M. H. (1987). The influence of continuous and intermittent traffic noise on sleep. *Journal of Sound and Vibration, 116*(3), 445-464.

Eggermont, J. J. (2005). Tinnitus: Neurobiological substrates. *Drug Discovery Today, 10*(19), 1283-1290.

Ellenbogen, J. M., Grace, S., Heiger-Bernays, W. J., Manwell, J. F., Mills, D. A., Sullivan, K. A., & Weisskopf, M. G. (2012). *Wind Turbine Health Impact Study: Report of Independent Expert Panel.* Prepared for Massachusetts Department of Environmental Protection, Massachusetts Department of Public Health.

EPA (United States Environmental Protection Agency). (2003). *A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information.* Washington (DC): U.S. Environmental Protection Agency.

EPA (Ireland Environmental Protection Agency). (2011). *Guidance Note on Noise Assessment of Wind Turbine Operations at EPA Licensed Sites (NG3).* Wexford, Ireland: Environmental Protection Agency Ireland.

EPHC (Environment Protection and Heritage Council). (2010). *National Wind Farm Development Guidelines Draft.* Adelaide, Australia: EPHC.

Erdogan, N., Songu, M., Akay, E., Mete, B. D., Uluc, E., Ona, l. K., & Oyar, O. (2011). Posterior semicircular canal dehiscence in asymptomatic ears. *Acta Oto-Laryngologica 131*(1), 4-8. doi: 10.3109/00016489.2010.502184.

Eriksson, C., Hilding, A., Pyko, A., Bluhm, G., Pershagen, G., & Östenson, C.-G. (2014). Long-term aircraft noise exposure and body mass index, waist circumference, and type 2 diabetes: A prospective study. *Environmental Health Perspectives, 122*(7), 693.

Evans, G. W., Hygge, S., & Bullinger, M. (1995). Chronic noise and psychological stress. *Psychological Science, 6*(6), 333-338. doi: 10.1111/j.1467-9280.1995.tb00522.x.

Evans, G. W. & Maxwell, L. (1997). Chronic noise exposure and reading deficits: The mediating effects of language acquisition. *Environment and Behavior, 29*(5), 638-656.

Evans, G. W., Bullinger, M., & Hygge, S. (1998). Chronic noise exposure and physiological response: A prospective study of children living under environmental stress. *Psychological Science, 9*(1), 75-77.

Evans, T. & Cooper, J. (2012). Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms. *Acoustics Australia, 40*(1), 28-36.

EWEA (European Wind Energy Association). (2005). *Prioritising Wind Energy Research: Strategic Research Agenda of the Wind Energy Sector.* Brussels, Belgium: EWEA.

Fastl, H. & Menzel, D. (2013). *Psychoacoustic Aspects of Noise from Wind Turbines.* Paper presented at INTER-NOISE 2013, the 42nd International Congress and Exposition on Noise Control Engineering, Innsbruck, Austria.

Ferguson-Martin, C. J. & Hill, S. D. (2011). Accounting for variation in wind deployment between Canadian provinces. *Energy Policy, 39*(3), 1647-1658.

Findeis, H. & Peters, E. (2004). Disturbing effects of low frequency sound immissions and vibrations in residential buildings. *Noise & Health, 6*(23), 29-35.

Fortin, P., Rideout, K., Copes, R., & Bos, C. (2013). *Wind Turbines and Health.* Vancouver (BC): National Collaborating Centre for Environmental Health.

Frey, B. J. & Hadden, P. J. (2012). *Wind Turbines and Proximity to Homes: The Impact of Wind Turbine Noise on Health.*

Fruhstorfer, B., Fruhstorfer, H., Grass, P., Milerski, H. G., Sturm, G., Wesemann, W., & Wiesel, D. (1985). Daytime noise stress and subsequent night sleep: Interference with sleep patterns, endocrine and neurocrine functions. *International Journal of Neuroscience, 26*(3-4), 301-310.

GE (General Electric Company). (2004). *1.5sle/1.5sl/1.5s/1.5se Wind Turbines.* Amsterdam, The Netherlands: General Electric.

GoC (Government of Canada). (2004). Radiation Emitting Devices Act (R.S.C., 1985, c. R-1). Retrieved November 2014, from http://laws-lois.justice.gc.ca/eng/acts/R-1/page-1.html.

GreyNet International. (2014). Grey Literature Network Service. Retrieved September 2014, from http://www.greynet.org/home/aboutgreynet.html.

Griefahn, B. (2002). Sleep disturbances related to environmental noise. *Noise & Health, 4*(15), 57-60.

GWEC (Global Wind Energy Council). (2014). *Global Wind Report: Annual Market Update 2013.* Brussels, Belgium: GWEC.

Hagiwara, M., Shaikh, J. A., Fang, Y., Fatterpekar, G., & Roehm, P. C. (2012). Prevalence of radiographic semicircular canal dehiscence in very young children: An evaluation using high-resolution computed tomography of the temporal bones. *Pediatric Radiology 42*(12), 1456-1464. doi: 10.1007/s00247-012-2489-9.

Haines, M. M., Stansfeld, S. A., Job, R. S., Berglund, B., & Head, J. (2001). Chronic aircraft noise exposure, stress responses, mental health and cognitive performance in school children. *Psychological Medicine, 31*(2), 265-277.

Hansen, M. O. & Stinson, M. R. (1998). Air conducted and body conducted sound produced by own voice. *Canadian Acoustics, 26*(2), 11-19.

Hardoy, M. C., Carta, M. G., Marci, A. R., Carbone, F., Cadeddu, M., Kovess, V., ... Carpiniello, B. (2005). Exposure to aircraft noise and risk of psychiatric disorders: The Elmas survey—aircraft noise and psychiatric disorders. *Social Psychiatry and Psychiatric Epidemiology, 40*(1), 24-26.

Harrison, R. V. (2014). On the biological plausibility of wind turbine syndrome. *International Journal of Environmental Health Research, 8,* 1-6. doi: 10.1080/09603123.2014.963034.

Hau, E. (2006). *Wind Turbines Fundamentals, Technologies, Application, Economics* (2^{nd} ed.). New York (NY): Springer.

Haugen, K. M. B. (2011). *International Review of Policies and Recommendations for Wind Turbine Setbacks from Residences: Setbacks, Noise, Shadow Flicker, and Other Concerns.* Saint Paul (MN): Minnesota Department of Commerce: Energy Facility Permitting.

HCN (Health Council of the Netherlands). (1994). *Committee Noise and Health: Noise and Health.* The Hague, Netherlands: HCN.

Health Canada. (2003a). *Chronic Disease Surveillance in Canada: A Background Paper.* Ottawa (ON): Population and Public Health Branch, Health Canada.

Health Canada. (2003b). *Learning from SARS.* Ottawa (ON): Health Canada.

Health Canada. (2011). *Canada Health Act—Annual Report 2010-2011.* Ottawa (ON): Health Canada.

Health Canada. (2012). Health Canada Announces Wind Turbine Noise and Health Study. Retrieved July 2014, from http://www.hc-sc.gc.ca/ahc-asc/media/nr-cp/_2012/2012-109-eng.php.

Health Canada. (2013a). Health Canada Wind Turbine Noise and Health Study Design Consultation. Retrieved August 2014, from http://www.hc-sc.gc.ca/ewh-semt/consult/_2013/wind_turbine-eoliennes/index-eng.php.

Health Canada. (2013b). Health Canada Wind Turbine Noise and Health Study Design Consultation. Retrieved August 2014, from http://www.hc-sc.gc.ca/ewh-semt/consult/_2013/wind_turbine-eoliennes/index-eng.php.

Health Canada. (2014a). Wind Turbine Noise and Health Study: Summary of Results. Retrieved November 2014, from http://www.hc-sc.gc.ca/ewh-semt/noise-bruit/turbine-eoliennes/summary-resume-eng.php.

Health Canada. (2014b). Health Impacts and Exposure to Sound From Wind Turbines: Updated Research Design and Sound Exposure Assessment. Retrieved November 2014, from http://www.hc-sc.gc.ca/ewh-semt/consult/_2013/wind_turbine-eoliennes/research_recherche-eng.php.

Henry, J. A., Dennis, K. C., & Schechter, M. A. (2005). General review of tinnitus: Prevalence, mechanisms, effects, and management. *Journal of Speech, Language & Hearing Research, 48*(5), 1204-1235.

Hensel, J., Scholz, G., Hurttig, U., Mrowinski, D., & Janssen, T. (2007). Impact of infrasound on the human cochlea. *Hearing Research, 233*(1), 67-76.

Hepburn, H. G. (2006). Acoustic and geophysical measurement of infrasound from wind farm turbines. *Canadian Acoustics, 34*(2), 51.

Hessler, D. (2011). Chapter 7. Measuring and Analyzing Wind Turbine Noise. In D. Bowdler & G. Leventhall (Eds.), *Wind Turbine Noise.* Essex, United Kingdom: Multi-Science Publishing Company, Ltd.

HGC Engineering. (2010). *Low Frequency Noise and Infrasound Associated with Wind Turbine Generator Systems: A Literature Review.* Toronto (ON): Ontario Ministry of the Environment.

Hockey, G. R. J. (1984). Varieties of Attentional State: The Effects of Environment. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of Attention.* New York (NY): Academic Press.

Hodgetts, M. & O'Connor, K. (2013). *Wind Turbines and Health: Summary of a Scoping Review.* Kingston (ON): Research and Evaluation Division of Kingston, Frontenac and Lennox & Addington Public Health.

Howick, J., Glasziou, P., & Aronson, J. K. (2009). The evolution of evidence hierarchies: What can Bradford Hill's 'guidelines for causation' contribute? *Journal of the Royal Society of Medicine, 102*(5), 186-194. doi: 10.1258/jrsm.2009.090020.

Hubbard, H. H. (1982). Noise induced house vibrations and human perception. *Noise Control Engineering Journal, 19*(2), 49-55.

Hughes, R. & Jones, D. M. (2001). The intrusiveness of sound: Laboratory findings and their implications for noise abatement. *Noise & Health, 4*(13), 51-70.

IARC (International Agency for Research on Cancer, World Health Organization). (2006). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans: Preamble.* Lyon, France: IARC.

Ising, H., Babisch, W., & Kruppa, B. (1999). Noise-induced endocrine effects and cardiovascular risk. *Noise & Health, 1*(4), 37-48.

Jakobsen, J. (2001). Danish guidelines on environmental low frequency noise, infrasound and vibration. *Journal of Low Frequency Noise, Vibration and Active Control, 20*(3), 141-148.

Jakobsen, J. (2005). Infrasound emission from wind turbines. *Journal of Low Frequency Noise, Vibration and Active Control, 24*(3), 145-155.

Jami, A. A. N. & Walsh, P. R. (2014). The role of public participation in identifying stakeholder synergies in wind power project development: The case study of Ontario, Canada. *Renewable Energy, 68,* 194-202. doi: 10.1016/j.renene.2014.02.004.

Janssen, S. A., Vos, H., Eisses, A. R., & Pedersen, E. (2011). A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. *The Journal of the Acoustical Society of America, 130,* 3746-3753. doi: 10.1121/1.3653984.

Jeffery, R. D., Krogh, C., & Horner, B. (2013). Adverse health effects of industrial wind turbines. *Canadian Family Physician, 59,* 473-475.

Kaliski, K. (2014). *Wind Turbine Research Study Interim Modeling Report for WNTAG.* White River Junction (VT): RSG, Inc.

Kalveram, K. T., Dassow, J., & Vogt, J. (1999). How information about the source influences noise annoyance. *The Journal of the Acoustical Society of America, 105,* 942. doi: 10.1121/1.425715.

Kantarelis, C. & Walker, J. (1988). The identification and subjective effect of amplitude modulation in diesel engine exhaust noise. *Journal of Sound and Vibration, 120*(2), 297-3032. doi: 10.1016/0022-460X(88)90438-5.

Kåsin, J. I., Kjellevand, T. O., Kjekshus, J., Nesheim, G. B., & Wagstaff, A. (2012). CT examination of the pericardium and lungs in helicopter pilots exposed to vibration and noise. *Aviation, Space, and Environmental Medicine, 83*(9), 858-864.

Kjiellberg, A. & Wide, P. (1988). *Effects of Simulated Ventilation Noise on Performance of Grammatical Reasoning Task.* Paper presented at Noise as a Public Health Problem, Stockholm, Sweden.

Klatte, M., Bergstroem, K., & Lachmann, T. (2013). Does noise affect learning? A short review on noise effects on cognitive performance in children. *Frontiers in Psychology, 4,* 578. doi: 10.3389/fpsyg.2013.00578.

Krogh, C. M. E. (2011). Industrial wind turbine development and loss of social justice? *Bulletin of Science, Technology & Society, 31*(4), 321-333. doi: 10.1177/0270467611412550.

Krogh, C. M. E., Gillis, L., Kouwen, N., & Aramini, J. (2011). WindVOiCe, a self-reporting survey: Adverse health effects, industrial wind turbines, and the need for vigilance monitoring. *Bulletin of Science, Technology & Society, 31*(4), 334-345. doi: 10.1177/0270467611412551.

Kurakata, K. & Mizunami, T. (2008). The statistical distribution of normal hearing thresholds for low-frequency tones. *Low Frequency Noise, Vibration and Active Control, 27*(2), 97-104.

Kuwano, S., Yano, T., Kageyama, T., Sueoka, S., & Tachibana, H. (2013). *Social Survey on Community Response to Wind Turbine Noise.* Paper presented at INTER-NOISE 2013, the 42nd International Congress and Exposition on Noise Control Engineering, Innsbruck, Austria.

Lane, J. (2013). *Association Between Industrial Wind Turbine Noise and Sleep Quality in a Comparison Sample of Rural Ontarians.* Waterloo (ON): University of Waterloo.

Lazarus, R. S. & Folkman, S. (1984). *Stress, Appraisal and Coping.* New York (NY): Springer Publishing Company.

Lee, S., Kim, K., Choi, W., & Lee, S. (2011). Annoyance caused by amplitude modulation of wind turbine noise. *Noise Control Engineering Journal, 59*(1), 38-46. doi: 10.3397/1.3531797.

Leventhall, G. (2009). Low Frequency Noise. What we know, what we do not know, and what we would like to know. *Low Frequency Noise, Vibration and Active Control, 28*(2), 79-104. doi: 10.1260/0263-0923.28.2.79.

Leventhall, G. (2011). Chapter 1. Basic Acoustics. In D. Bowdler & G. Leventhall (Eds.), *Wind Turbine Noise.* Essex, United Kingdom: Multi-Science Publishing Company, Ltd.

Madsen, K. D. & Pedersen, T. H. (2010). *EFP-06 Project: Low Frequency Noise from Large Wind Turbines (www.madebydelta.com search for EFP-06).* Hørsholm, Denmark: Delta, performed for the Danish Energy Authority.

Maffei, L., Iachini, T., Masullo, M., Aletta, F., Sorrentino, F., Senese, V. P., & Ruotolo, F. (2013). The effects of vision-related aspects on noise perception of wind turbines in quiet areas. *International Journal of Environmental Research and Public Health, 10*(5), 1681-1697. doi: 10.3390/ijerph10051681.

Magari, S. R., Smith, C. E., Schiff, M., & Rohr, A. C. (2014). Evaluation of community response to wind turbine-related noise in Western New York State. *Noise & Health, 16*(71), 228.

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind Energy Explained: Theory, Design And Application* (2nd ed.). Chichester, United Kingdom: John Wiley & Sons Ltd.

Maschke, C. & Hecht, K. (2004). Stress hormones and sleep disturbances - electrophysiological and hormonal aspects. *Noise & Health, 6*(22), 49-54.

Masotti, P. & Hodgetts, M. (2011). *Wind Turbines and Health: A Modified Scoping Review.* Kingston (ON): Kingston, Frontenac, Lennox & Addington (KFL&A) Public Health.

Mathias, B., Uwe, M., Eva-Maria, E., Götz, K., & Barbara, G. (2008). Aircraft noise effects on sleep: A systematic comparison of EEG awakenings and automatically detected cardiac activations. *Physiological Measurement, 29*(9), 1089.

McBride, D., Shepherd, D., Welch, D., & Dirks, K. N. (2013). *A Longitudinal Study of the Impact of Wind Turbine Proximity on Health Related Quality of Life.* Paper presented at INTER-NOISE 2013, the 42nd International Congress and Exposition on Noise Control Engineering, Innsbruck, Austria.

MDDELCC (Ministère du Développement durable, Environnement et Lutte contre les changements climatiques). (2006). *Traitement des plaintes sur le bruit et exigences aux entreprises qui le génèrent.* Québec (QC): MDDELCC.

Merlin, T., Newton, S., Ellery, B., Milverton, J., & Farah, C. (2013). *Systematic Review of the Human Health Effects of Wind Farms.* Adelaide, Australia: National Health and Medical Research Council (NHMRC).

Miedema, H. M. & Oudshoorn, C. G. (2001). Annoyance from transportation noise: Relationships with exposure metrics DNL and DENL and their confidence intervals. *Environmental Health Perspectives, 109*(4), 409-419.

Minor, L. B. (2000). Superior canal dehiscence syndrome. *American Journal of Otology, 21*(1), 9-19.

Minor, L. B., Solomon, D., Zinreich, J. S., & Zee, D. S. (1998). Sound- and/or pressure-induced vertigo due to bone dehiscence of the superior semicircular canal. *Archives of Otolaryngology - Head and Neck Surgery 124*(3), 249-258.

MOE (Ministry of Environment). (2008). *Noise Guidelines for Wind Farms.* Toronto (ON): MOE.

Møller, H. & Pedersen, C. S. (2011). Low-frequency noise from large wind turbines. *The Journal of the Acoustical Society of America, 129*, 3727-3744. doi: 10.1121/1.3543957.

Møller, H., Pedersen, C. S., & Pedersen, S. (2011). *Lavfrekvent støj fra store vindmøller-opdateret 2011*: Acoustics, Department of Electronic Systems, Aalborg University.

Mroczek, B., Kurpas, D., & Karakiewicz, B. (2012). Influence of distances between places of residence and wind farms on the quality of life in nearby areas. *Annals of Agricultural and Environmental Medicine, 19*(4), 692-696.

Mulvaney, K. K., Woodson, P., & Prokopy, L. S. (2013). Different shades of green: A case study of support for wind farms in the rural midwest. *Environmental Management, 51*, 1012-1024. doi: 10.1007/s00267-013-0026-8.

Münzel, T., Gori, T., Babisch, W., & Basner, M. (2014). Cardiovascular effects of environmental noise exposure. *European Heart Journal.* doi: 10.1093/eurheartj/ehu030.

Muzet, A. (2007). Environmental noise, sleep and health. *Sleep Medicine Reviews, 11*(2), 135-142. doi: 10.1016/j.smrv.2006.09.001.

Nagai, N., Matsumoto, M., Yamasumi, Y., Shiraishi, T., Nishimura, K., Matsumoto, K., ... Takeda, S. (1989). Process and emergence on the effects of infrasonic and low frequency noise on inhabitants. *Journal of Low Frequency Noise and Vibration, 8*, 87-99.

Ndrepepa, A. & Twardella, D. (2011). Relationship between noise annoyance from road traffic noise and cardiovascular diseases: A meta-analysis. *Noise & Health, 13*(52), 251.

NEB (National Energy Board). (2013). *Canada's Energy Future 2013: Energy Supply and Demand Projections to 2035.* Calgary (AB): NEB.

Nelson, D. I., Nelson, R. Y., Concha-Barrientos, M., & Fingerhut, M. (2005). The global burden of occupational noise-induced hearing loss. *American Journal of Industrial Medicine, 48*(6), 446-458.

NHMRC (National Health and Medical Research Council). (2010). *Wind Turbines and Health: A Rapid Review of the Evidence.* Canberra, Australia: National Health and Medical Research Council.

NHMRC (National Health and Medical Research Council). (2014). *NHMRC Draft Information Paper: Evidence on Wind Farms and Human Health.* Canberra, Australia: NHMRC.

Nissenbaum, M. A., Aramini, J. J., & Hanning, C. D. (2012). Effects of industrial wind turbine noise on sleep and health. *Noise & Health, 14*, 237-243.

NSF (National Sleep Foundation). (2013). *Bedroom Poll: Summary of Findings.* Washington (DC): NSF.

Oerlemans, S. & Méndez López, M. (2005). *Acoustic Array Measurements on a Full Scale Wind Turbine.* Madrid, Spain: National Aerospace Laboratory NLR.

Oerlemans, S., Sijtsma, P., & Méndez López, B. (2007). Location and quantification of noise sources on a wind turbine. *Journal of Sound and Vibration, 299*(4–5), 869-883.

Oerlemans, S. (2009). *Detection of Aeroacoustic Sound Sources on Aircraft and Wind Turbines.* Thesis. Zwolle, The Netherlands: University of Twente, Enschede.

Oerlemans, S. & Schepers, J. (2009). Prediction of wind turbine noise and validation against experiment. *International Journal of Aeroacoustics, 8*(6), 555-584.

Oerlemans, S. (2011). Chapter 2. Primary Noise Sources. In D. Bowdler & G. Leventhall (Eds.), *Wind Turbine Noise.* Essex, United Kingdom: Multi-Science Publishing Company, Ltd.

Öhrström, E. (1989). Sleep distrubance, psycho-social and medial symptoms: A pilot survey among persons exposed to high-levels of road traffice noise. *Journal of Sound and Vibration 133*(1), 117-128.

Öhrström, E. & Rylander, R. (1982). Sleep disturbance effects of traffic noise—A laboratory study on after effects. *Journal of Sound and Vibration, 84*(1), 87-103.

Ollson, C. A., Knopper, L. D., McCallum, L. C., & Whitfield-Aslund, M. L. (2013). Letter to Editor: Are the findings of “Effects of industrial wind turbine noise on sleep and health” supported? *Noise & Health, 15,* 148-151.

Olson, H. F. (1972). The measurement of loudness. *Audio Magazine,* 18-22.

Ontario Regulation. (2012). Environmental Protection Act. *Ontario Regulation 359/09.*

Palmer, K., Griffin, M., Syddall, H., Davis, A., Pannett, B., & Coggon, D. (2002). Occupational exposure to noise and the attributable burden of hearing difficulties in Great Britain. *Occupational and environmental medicine, 59*(9), 634-639.

Pasqualetti, M. J. (2002). Living with Wind Power in a Hostile Landscape. In M. J. Pasqualetti, P. Gipe & R. W. Righter (Eds.), *Wind Power in View: Energy Landscapes in a Crowded World.* San Diego (CA): Academic Press.

Passchier-Vermeer, W. & Passchier, W. F. (2006). Environmental Noise, Annoyance and Sleep Disturbance. In P. Nicolopoulou-Stamati, L. Hens & V. Howard (Eds.), *Environmental Health Impacts of Transport and Mobility.* Dordrecht, The Netherlands: Springer Science & Business Media.

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska, M., & Waszkowska, M. (2013). Assessment of annoyance due to wind turbine noise. *Proceedings of Meetings on Acoustics, 19*(1), 1-9.

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska-Daniszewska, M., & Waszkowska, M. (2014). Evaluation of annoyance from the wind turbine noise–A pilot study. *International journal of occupational medicine and environmental health, 27*(3), 364-388.

Pedersen, E. & Persson Waye, K. (2004). Perception and annoyance due to wind turbine noise: A dose-response relationship. *The Journal of the Acoustical Society of America, 116*, 3460-3470. doi: 10.1121/1.1815091.

Pedersen, E., Hallberg, L.-M., & Persson Waye, K. (2007a). Living in the vicinity of wind turbines — A grounded theory study. *Qualitative Research in Psychology, 4*, 49-63. doi: 10.1080/14780880701473409.

Pedersen, E. & Persson Waye, K. (2007). Wind turbine noise, annoyance and self-reported health and well-being in different living environments. *Occupational and Environmental Medicine, 64*, 480-486. doi: 10.1136/oem.2006.031039.

Pedersen, E. & Larsman, P. (2008). The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines. *Journal of Environmental Psychology, 28*, 379-389.

Pedersen, E. & Persson Waye, K. (2008). Wind turbines—low level noise sources interfering with restoration? *Environmental Research Letters, 3*, 015002. doi: 10.1088/1748-9326/3/1/015002.

Pedersen, E., van den Berg, F., Bakker, R., & Bouma, J. (2009). Response to noise from modern wind farms in The Netherlands. *The Journal of the Acoustical Society of America, 126*, 634-643. doi: 10.1121/1.3160293.

Pedersen, E., van den Berg, F., Bakker, R., & Bouma, J. (2010). Can road traffic mask sound from wind turbines? Response to wind turbine sound at different levels of road traffic sound. *Energy Policy, 38*(5), 2520-2527. doi: 10.1016/j.enpol.2010.01.001.

Pedersen, E. (2011). Health aspects associated with wind turbine noise — Results from three field studies. *Noise Control Engineering Journal, 59*, 47-53.

Pedersen, S., Møller, H., & Persson Waye, K. (2007b). Indoor Measurements of Noise at Low Frequencies - Problems and Solutions. *Journal of Low Frequency Noise, Vibration and Active Control, 26*(4), 249-270. doi: 10.1260/026309207783571389.

Perron, S., Tétreault, L.-F., King, N., Plante, C., & Smargiassi, A. (2012). Review of the effect of aircraft noise on sleep disturbance in adults. *Noise & Health, 14*(57), 58-67.

Persson Waye, K. & Björkman, M. (1988). Annoyance due to low frequency noise and the use of the dB (A) scale. *Journal of Sound and Vibration, 127*(3), 491-497.

Persson Waye, K. & Rylander, R. (2001). The prevalence of annoyance and effects after long-term exposure to low-frequency noise. *Journal of Sound and Vibration, 240*(3), 483-497. doi: 10.1006/jsvi.2000.3251.

Persson Waye, K. & Öhrström, E. (2002). Psycho-acoustic characters of relevance for annoyance of wind turbine noise. *Journal of Sound and Vibration, 250*(1), 65-73.

Persson Waye, K., Clow, A., Edwards, S., Hucklebridge, F., & Rylander, R. (2003). Effects of nighttime low frequency noise on the cortisol response to awakening and subjective sleep quality. *Life Sciences, 72*(8), 863-875.

Persson Waye, K. (2005). Adverse effects of moderate levels of low frequency noise in the occupational environment. *ASHRAE Transactions, 111*(1), 672-683.

Persson Waye, K. (2009). *Perception and Environmental Impact of Wind Turbine Noise.* Paper presented at INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Ottawa (ON).

Persson Waye, K. (2011). Effects of Low Frequency Noise and Vibrations: Environmental and Occupational Perspectives. In J. Nriagu (Ed.), Encyclopedia of Environmental Health (Vol. 2). Ann Arbor (MI): Burlington.

Pfammatter, A., Darrouzet, V., Gärtner, M., Somers, T., Van Dinther, J., Trabalzini, F., ... Linder, T. A. (2010). Superior semicircular canal dehiscence syndrome multicenter study: Is there an association between size and symptoms? *Ontology & Neurotology 31*(3), 447-454. doi: 10.1097/MAO.0b013e3181d27740.

PHAC (Public Health Agency of Canada). (2008). History. Retrieved September, 2014, from http://www.phac-aspc.gc.ca/about_apropos/history-eng.php.

PHAC (Public Health Agency of Canada). (2009). 2009 Tracking Heart Disease and Stroke in Canada. Retrieved November 2014, from http://www.phac-aspc.gc.ca/publicat/2009/cvd-avc/report-rapport-eng.php.

Pierpont, N. (2006). *Wind Turbine Syndrome: Noise, Shadow Flicker, and Health.*

Pierpont, N. (2009). *Wind Turbine Syndrome: A Report on a Natural Experiment.* Santa Fe (NM): K-Selected Books.

RABDTI (Renewables Advisory Board and DTI). (2007). *The Protocol for Public Engagement with Proposed Wind Energy Developments in England.* London, United Kingdom: Centre for Sustainable Energy with BDOR and Peter Capener.

RenewableUK. (2013). *Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect.* London, United Kingdom: RenewableUK.

Rief, W., Barsky, A. J., Glombiewski, J. A., Nestoriuc, Y., Glaesmer, H., & Braehler, E. (2011). Assessing general side effects in clinical trials: Reference data from the general population. *Pharmacoepidemiology and Drug Safety, 20*(4), 405-415. doi: 10.1002/pds.2067.

Robert, G. & Hockey, J. (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology, 45*(1), 73-93.

Roberts, J. D. & Roberts, M. A. (2013). Wind turbines: Is there a human health risk? *Journal of Environmental Health, 75,* 8-13, 16-17.

Robertson, D. D. I. & Ireland, D.J. (1995). Vestibular evoked myogenic potentials. *Journal of Otolaryngology 24*(1), 3-8.

Rod, J. (2012). *Health & Safety Impacts from Large-Scale Wind Turbines.* Kentville (NS): Municipality of the County of Kings.

Ruotolo, F., Senese, V. P., Ruggiero, G., Maffei, L., Masullo, M., & Iachini, T. (2012). Individual reactions to a multisensory immersive virtual environment: The impact of a wind farm on individuals. *Cognitive Processing, 13 Suppl 1*, S319-323. doi: 10.1007/s10339-012-0492-6.

Russo, J. E., Crowson, M. G., DeAngelo, E. J., Belden, C. J., & Saunders, J. E. (2014). Posterior semicircular canal dehiscence: CT prevalence and clinical symptoms. *Ontology & Neurotology, 35*(2), 310-314.

Rylander, R. (2004). Physiological aspects of noise-induced stress and annoyance. *Journal of Sound and Vibration, 277*(3), 471-478.

Salt, A. N. & Hullar, T. E. (2010). Responses of the ear to low frequency sounds, infrasound and wind turbines. *Hearing Research, 268*, 12-21. doi: 10.1016/j.heares.2010.06.007.Responses.

Salt, A. N. & Kaltenbach, J. A. (2011). Infrasound from wind turbines could affect humans. *Bulletin of Science, Technology & Society, 31*, 296-302. doi: 10.1177/0270467611412555.

Salt, A. N., Lichtenhan, J. T., Gill, R. M., & Hartsock, J. J. (2013). Large endolymphatic potentials from low-frequency and infrasonic tones in the guinea pig. *The Journal of the Acoustical Society of America, 133*(3), 1561-1571.

Schomer, P., Brown, A., De Coensel, B., Genuit, K., Gjestland, T., Jeon, J. Y., ... Watts, G. (2010). *On Efforts to Standardize a Graphical Description of the Soundscape Concept.* Paper presented at Proceedings of the International Congress on Noise Control Engineering (internoise), Lisbon, Portugal.

Schulte-Fortkamp, B. (2014). Balancing the research approach on wind turbine effects through improving psychological factors that affect community response. *The Journal of the Acoustical Society of America, 136*(4), 2204-2204.

Schust, M. (2004). Effects of low frequency noise up to 100 Hz. *Noise & Health, 6*(23), 73-85.

Seong, Y., Lee, S., Gwak, D. Y., Cho, Y., Hong, J., & Lee, S. (2013). *An Experimental Study on Rating Scale for Annoyance due to Wind Turbine Noise.* Paper presented at INTER-NOISE 2013, the 42nd International Congress and Exposition on Noise Control Engineering, Innsbruck, Austria.

Shepherd, D., McBride, D., Welch, D., Dirks, K. N., & Hill, E. M. (2011). Evaluating the impact of wind turbine noise on health-related quality of life. *Noise & Health, 13*, 333-339.

Sierra Club Canada. (2011). *The Real Truth About Wind Energy: A Literature Review on Wind Turbines in Ontario.* Ottawa (ON): Sierra Club Canada.

Søndergaard, B. & Madsen, K. D. (2008). *Low Frequency Noise from Large Wind Turbines: Results from Sound Power Measurements.* Venlighedsvej, Denmark: DELTA (Danish Electronics, Light & Acoustics).

Søndergaard, B. (2011). Chapter 4. Wind Turbine Noise at the Receiver. In D. Bowdler & G. Leventhall (Eds.), *Wind Turbine Noise.* Essex, United Kingdom: Multi-Science Publishing Company, Ltd.

Sørensen, M., Andersen, Z. J., Nordsborg, R. B., Becker, T., Tjonneland, A., Overvad, K., & Raaschou-Nielsen, O. (2012). Long-term exposure to road traffic noise and incident diabetes: A cohort study. *Environmental Health Perspectives, 121*(2), 217-222.

Spreng, M. (2000). Central nervous system activation by noise. *Noise & Health, 2*(7), 49.

Stansfeld, S., Haines, M., Burr, M., Berry, B., & Lercher, P. (2000). A review of environmental noise and mental health. *Noise & Health, 2*(8), 1.

Stansfeld, S. A. (2003). Noise pollution: Non-auditory effects on health. *British Medical Bulletin, 68*(1), 243-257. doi: 10.1093/bmb/ldg033.

Stansfeld, S. A., Berglund, B., Clark, C., Lopez-Barrio, I., Fischer, P., Öhrström, E., ... Van Kamp, I. (2005). Aircraft and road traffic noise and children's cognition and health: A cross-national study. *The Lancet, 365*(9475), 1942-1949.

Stansfeld, S. A., Haines, M. M., Berry, B., & Burr, M. (2009). Reduction of road traffic noise and mental health: An intervention study. *Noise & Health, 11*(44), 169.

Suls, J. (2013). Anger and the heart: Perspectives on cardiac risk, mechanisms and interventions. *Progress in Cardiovascular Diseases,* 55(6), 538-547.

Sygna, K., Aasvang, G. M., Aamodt, G., Oftedal, B., & Krog, N. H. (2014). Road traffic noise, sleep and mental health. *Environmental Research, 131,* 17-24.

Tachibana, H., Yano, H., Fukushima, A., & Sueoka, S. (2014). Nationwide field measurements of wind turbine noise in Japan. *Noise Control Engineering Journal, 62*(2), 90-101.

Takahashi, Y. (2011). A study on the contribution of body vibrations to the vibratory sensation induced by high-level, complex lowfrequency noise. *Noise & Health,* 13(50), 2-8.

Tamura, H., Ohgami, N., Yajima, I., Iida, M., Ohgami, K., Fujii, N., ... Kato, M. (2012). Chronic exposure to low frequency noise at moderate levels causes impaired balance in mice. *PloS One, 7*(6), e39807.

Tassi, P., Saremi, M., Schimchowitsch, S., Eschenlauer, A., Rohmer, O., & Muzet, A. (2010). Cardiovascular responses to railway noise during sleep in young and middle-aged adults. *European Journal of Applied Physiology, 108*(4), 671-680. doi: 10.1007/s00421-009-1270-8.

Thibault, B., Angen, E., & Weis, T. (2013). *Survey of Complaints Received by Relevant Authorities Regarding Operating Wind Energy in Alberta.* Calgary (AB): The Pembina Institute.

Todd, N. P. M., Rosengren, S. M., & Colebatch, J. G. (2008). Tuning and sensitivity of the human vestibular system to low-frequency vibration. *Neuroscience Letters, 444,* 36-41. doi: 10.1016/j.neulet.2008.08.011.

Toke, D., Breukers, S., & Wolsink, M. (2008). Wind power deployment outcomes: How can we account for the differences? *Renewable and Sustainable Energy Reviews, 12*(4), 1129-1147.

Tullio, P. (1929). *Das Ohr und die Entstehung der Sprache und Schrift.* Berlin, Germany: Urban & Schwarzenberg.

van den Berg, F., Pedersen, E., Bouma, J., & Bakker, R. (2008). *WINDFARMperception: Visual and Acoustic Impact of Wind Turbine Farms on Residents.* Groningen, The Netherlands: University of Groningen, University of Gotenburg, Science Shop for Medicine and Public Health Applied Health Research.

van den Berg, F. (2011). Chapter 6. Effects of Sound on People. In D. Bowdler & G. Leventhall (Eds.), *Wind Turbine Noise.* Essex, United Kingdom: Multi-Science Publishing Company, Ltd.

van den Berg, F. & Bowdler, D. (2011). Chapter 5. Amplitude Modulation. In D. Bowdler & G. Leventhall (Eds.), *Wind Turbine Noise.* Essex, United Kingdom: Multi-Science Publishing Company, Ltd.

Van Gemmert, A. W. & Van Galen, G. P. (1997). Stress, neuromotor noise, and human performance: A theoretical perspective. *Journal of Experimental Psychology: Human Perception and Performance, 23*(5), 1299-1313.

van Kamp, I., Job, R. F. S., Hatfield, J., Haines, M., Stellato, R. K., & Stansfeld, S. A. (2004). The role of noise sensitivity in the noise-response relation: A comparison of three international airport studies. *The Journal of the Acoustical Society of America, 116*(6), 3471-3479.

Van Kamp, I. & Davies, H. (2008). *Noise as a Public Health Problem.* Paper presented at Proceedings of 9th Congress of the International Commission on the Biological Effects of Noise (ICBEN), Foxwoods (CT).

van Kempen, E. & Babisch, W. (2012). The quantitative relationship between road traffic noise and hypertension: A meta-analysis. *Journal of Hypertension, 30*(6), 1075-1086.

van Kempen, E. E., Kruize, H., Boshuizen, H. C., Ameling, C. B., Staatsen, B. A., & de Hollander, A. E. (2002). The association between noise exposure and blood pressure and ischemic heart disease: A meta-analysis. *Environmental Health Perspectives, 110*(3), 307-317.

Van Renterghem, T., Bockstael, A., De Weirt, V., & Botteldooren, D. (2013). Annoyance, detection and recognition of wind turbine noise. *The Science of the Total Environment, 456-457*, 333-345. doi: 10.1016/j.scitotenv.2013.03.095.

von Hünerbein, S., King, A., Piper, B., & Cand, M. (2013). Work Package B2: Development of an AM Dose-Response Relationship. In RenewableUK (Ed.), *Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effects.* London, United Kingdom: University of Salford, Acoustics Research Centre.

Wagner, S., Bareiß, R., & Guidati, G. (1996). *Wind Turbine Noise.* Berlin, Germany: Springer.

Watanabe, T. & Møller, H. (1990). Low frequency hearing thresholds in free field. *Journal of Low Frequency Noise and Vibration, 9*, 106-115.

Welford, A. T. (1974). Stress and Performance. In A. T. Welford (Ed.), *Man Under Stress.* New York (NY): Halsted Press.

Welgampola, M. S., Oluwaseun, A. M., Minor, L. B. Carey, J.P. (2008). Vestibular-evoked myogenic potential thresholds normalize on plugging superior canal dehiscence. *Neurology, 70*(6), 464-472.

WHO (World Health Organization). (1946). *Constitution of the World Health Organization.*

WHO (World Health Organization). (1999). *Guidelines for Community Noise.*

WHO (World Health Organization). (2009). *Night Noise Guidelines for Europe.* Copenhagen, Denmark: WHO.

WHO (World Health Organization). (2011). *Burden of Disease from Environmental Noise.*

WHO (World Health Organization). (2013). *Cardiovascular diseases (CVDs): Fact Sheet No. 317.* Geneva, Switzerland: WHO.

WHO (World Health Organization). (2014). *Diabetes: Fact sheet N°312.* Geneva, Switzerland: WHO.

Willich, S. N., Wegscheider, K., Stallmann, M., & Keil, T. (2006). Noise burden and the risk of myocardial infarction. *European Heart Journal, 27*(3), 276-282.

Wolsink, M. (2007). Wind power implementation: The nature of public attitudes: Equity and fairness instead of 'backyard motives'. *Renewable and Sustainable Energy Reviews, 11*, 1188-1207. doi: 10.1016/j.rser.2005.10.005.

Yano, T., Lee, S., & Gjestland, T. (2012). Community response to noise. *Noise & Health, 14*(61), 303. doi: 10.4103/1463-1741.104898.

Yano, T., Kuwano, S., Kageyama, T., Sueoka, S., & Tachibana, H. (2013). *Dose-response Relationships for Wind Turbine Noise in Japan.* Paper presented at INTER-NOISE 2013, the 42nd International Congress and Exposition on Noise Control Engineering, Innsbruck, Austria.

Yokoyama, S., Sakamoto, S., & Tachibana, H. (2013). Study on the Amplitude Modulation of Wind Turbine Noise: Part 2 Auditory Experiments. Paper presented at INTER-NOISE 2013, the 42nd International Congress and Exposition on Noise Control Engineering, Innsbruck, Austria.

Zajamsek, B., Moreau, D. J., & Doolan, C. J. (2014). Characterising noise and annoyance in homes near a wind farm. *Acoustics Australia, 42*(1), 15.

Zhang, A. S., Govender, S., & Colebatch, J. G. (2012). Tuning of the ocular vestibular evoked myogenic potential to bone-conducted sound stimulation. *Journal of Applied Psychology, 112*(8), 1279-1290. doi: 10.1152/japplphysiol.01024.2011.

Assessments of the Council of Canadian Academies

The assessment reports listed below are accessible through the Council's website (www.scienceadvice.ca):

- Understanding the Evidence: Wind Turbine Noise (2015)
- Accessing Health and Health-Related Data in Canada (2015)
- Leading in the Digital World: Opportunities for Canada's Memory Institutions (2015)
- Policing Canada in the 21st Century: New Policing for New Challenges (2014)
- Energy Prices and Business Decision-Making in Canada: Preparing for the Energy Future (2014)
- Improving Medicines for Children in Canada (2014)
- Science Culture: Where Canada Stands (2014)
- Enabling Sustainability in an Interconnected World (2014)
- Environmental Impacts of Shale Gas Extraction in Canada (2014)
- Aboriginal Food Security in Northern Canada: An Assessment of the State of Knowledge (2014)
- Ocean Science in Canada: Meeting the Challenge, Seizing the Opportunity (2013)
- The Health Effects of Conducted Energy Weapons (2013)
- The State of Industrial R&D in Canada (2013)
- Innovation Impacts: Measurement and Assessment (2013)
- Water and Agriculture in Canada: Towards Sustainable Management of Water Resources (2013)
- Strengthening Canada's Research Capacity: The Gender Dimension (2012)
- The State of Science and Technology in Canada (2012)
- Informing Research Choices: Indicators and Judgment (2012)
- Integrating Emerging Technologies into Chemical Safety Assessment (2012)
- Healthy Animals, Healthy Canada (2011)
- Canadian Taxonomy: Exploring Biodiversity, Creating Opportunity (2010)
- Honesty, Accountability, and Trust: Fostering Research Integrity in Canada (2010)
- Better Research for Better Business (2009)
- The Sustainable Management of Groundwater in Canada (2009)
- Innovation and Business Strategy: Why Canada Falls Short (2009)
- Vision for the Canadian Arctic Research Initiative: Assessing the Opportunities (2008)

- Energy from Gas Hydrates: Assessing the Opportunities and Challenges for Canada (2008)
- Small Is Different: A Science Perspective on the Regulatory Challenges of the Nanoscale (2008)
- Influenza and the Role of Personal Protective Respiratory Equipment: An Assessment of the Evidence (2007)
- The State of Science and Technology in Canada (2006)

The assessments listed below are in the process of expert panel deliberation:

- STEM Skills for the Future
- The Potential for New and Emerging Technologies to Reduce the Environmental Impacts of Oil Sands Development
- RISK: Is the Message Getting Through?
- Energy Use and Climate Change: A Synthesis of the Latest Evidence

Board of Governors of the Council of Canadian Academies*

Margaret Bloodworth, C.M., Chair, Former Federal Deputy Minister and National Security Advisor (Ottawa, ON)

Graham Bell, FRSC, President, Royal Society of Canada; Research Director, James McGill Professor, Chair, Department of Biology, McGill University (Montréal, QC)

John Cairns, FCAHS, President, Canadian Academy of Health Sciences; Professor of Medicine, University of British Columbia (Vancouver, BC)

Henry Friesen, C.C., FRSC, FCAHS, Vice Chair, Distinguished Professor Emeritus and Senior Fellow, Centre for the Advancement of Medicine, Faculty of Medicine, University of Manitoba (Winnipeg, MB)

Carol P. Herbert, FCAHS, Professor of Family Medicine, Western University (London, ON)

Claude Jean,** Executive Vice President and General Manager, Foundry Operation, Semiconductor, Teledyne DALSA (Bromont, QC)

Peter MacKinnon, O.C., Former President and Vice-Chancellor, University of Saskatchewan (Saskatoon, SK)

Jeremy McNeil, FRSC, Helen Battle Professor of Chemical Ecology, Western University (London, ON)

Axel Meisen, C.M., FCAE, Former Chair of Foresight at Alberta Innovates — Technology Futures (AITF) (Edmonton, AB)

Lydia Miljan, Associate Professor of Political Science and Chair of the Arts and Science Program, University of Windsor (Windsor, ON)

Ted Morton, Executive Fellow at the School of Public Policy, Professor of Political Science, University of Calgary (Calgary, AB)

P. Kim Sturgess, FCAE, CEO and Founder, Alberta WaterSMART (Calgary, AB)

---

* Affiliations as of March 2015

** Resigned in FY 2014–2015

Scientific Advisory Committee of the Council of Canadian Academies*

Susan A. McDaniel, FRSC, Chair, Director, Prentice Institute; Canada Research Chair in Global Population and Life Course; Prentice Research Chair (Tier 1) in Global Population and Economy; Professor of Sociology, University of Lethbridge (Lethbridge, AB)

Lorne Babiuk, O.C., FRSC, FCAHS, Vice President (Research), University of Alberta (Edmonton, AB)

Murray S. Campbell, Senior Manager, AI and Optimization, IBM T.J. Watson Research Center (Yorktown Heights, NY)

Clarissa Desjardins, CEO, Clementia Pharmaceuticals Inc. (Montréal, QC)

Jean Gray, C.M., FCAHS, Professor of Medicine (Emeritus), Dalhousie University (Halifax, NS)

John Hepburn, FRSC, Vice-President, Research and International, University of British Columbia (Vancouver, BC)

Gregory S. Kealey, FRSC, Professor, Department of History, University of New Brunswick (Fredericton, NB)

Daniel Krewski, Professor of Epidemiology and Community Medicine and Scientific Director of the McLaughlin Centre for Population Health Risk Assessment, University of Ottawa (Ottawa, ON)

Avrim Lazar, Former President and CEO, Forest Products Association of Canada (Ottawa, ON)

Norbert Morgenstern, C.M., FRSC, FCAE, University Professor (Emeritus), Civil Engineering, University of Alberta (Edmonton, AB)

Sarah P. Otto, FRSC, Professor and Director of the Biodiversity Research Centre, University of British Columbia (Vancouver, BC)

---

* Affiliations as of March 2015

Council of Canadian Academies
Conseil des académies canadiennes

Council of Canadian Academies
180 Elgin Street, Suite 1401
Ottawa, ON K2P 2K3
Tel: 613-567-5000
www.scienceadvice.ca