

**BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA**

**IN THE MATTER OF THE APPLICATION OF
CROWNED RIDGE WIND II, LLC FOR A FACILITIES PERMIT TO
CONSTRUCTION 300.6 MEGAWATT WIND FACILITY**

Docket No. EL19-027

**SUPPLEMENTAL TESTIMONY AND EXHIBITS
OF DR. ROBERT MCCUNNEY**

September 20, 2019

INTRODUCTION

Q. PLEASE STATE YOUR NAME AND BUSINESS ADDRESS.

A. My name is Dr. Robert McCunney. My business address is PO Box 29077, Charlestown MA 02129.

Q. BY WHOM ARE YOU EMPLOYED AND IN WHAT CAPACITY?

A. I am employed at Brigham and Women's Hospital in Boston, Massachusetts as a Staff physician in Pulmonary, Center for Chest Diseases. In my role I perform clinical evaluations and recommend treatment of occupational and environmental illnesses. I also serve in an educational capacity on the faculty of Harvard Medical School. My curriculum vitae is attached as Exhibit RM-S-1.

Q. WHAT ARE YOUR RESPONSIBILITIES?

A. I was hired by Crowned Ridge Wind, II LLC ("CRW II") to submit testimony in this proceeding on health and welfare issues raised in the proceeding.

Q. PLEASE DESCRIBE YOUR BACKGROUND AND QUALIFICATIONS.

A. In summary, I am a licensed practicing physician. I completed training as a specialist in internal medicine and am also board certified in occupational and environmental medicine. My background in noise and health includes post graduate residency training in occupational medicine at Harvard, as an author of peer-reviewed publications, such as three book chapters on occupational noise exposure, clinical experience in reviewing audiometric tests of workers exposed to noise, and experience related to occupational hearing conservation programs. With respect to wind turbines and health, I am the lead

1 author of a critical review of the scientific literature on wind turbines and health
2 sponsored by the Massachusetts Institute of Technology and published in the Journal of
3 Occupational and Environmental Medicine in 2014; a co-author of a document entitled
4 “Wind Turbines and Health”; (Colby et al, 2009); and lead author of a mathematical
5 analysis of a proposed case definition related to health and living proximity to wind
6 turbines. (Full citations are set forth in Exhibit RM-S-1). I have also been admitted as an
7 expert to testify in wind turbine hearings in numerous jurisdictions in the USA and
8 Canada.

9
10 **Q. HAS THIS SUPPLEMENTAL TESTIMONY BEEN PREPARED BY YOU OR**
11 **UNDER YOUR DIRECT SUPERVISION?**

12 A. Yes.

13
14 **Q. HAVE YOU PREVIOUSLY TESTIFIED BEFORE THE SOUTH DAKOTA**
15 **PUBLIC UTILITIES COMMISSION?**

16 A. Yes, in Docket No. EL19-003.

17
18 **Q. PLEASE DESCRIBE THE PURPOSE OF YOUR SUPPLEMENTAL**
19 **TESTIMONY.**

20 A. The purpose of my testimony is to address the comments made at the August 26, 2019
21 Public Input Meeting on whether there are any health or welfare issues associated with
22 the proposed CRW II wind project.

HEALTH AND WELFARE

Q. AT THE AUGUST 26, 2019 PUBLIC INPUT MEETING COMMENTS WERE MADE ON THE SOUND AND SHADOW FLICKER THAT WILL BE PRODUCED BY THE PROJECT. ARE YOU FAMILIAR WITH THE CRW II WIND PROJECT AND THE PREDICTED SOUND AND SHADOW FLICKER?

A. Yes, I understand that CRW II is proposing to build up to 300.6 megawatts of wind generation and up to 132 wind turbines. I have also reviewed the Direct and Supplemental Testimony of CRW II witness Jay Haley, and the associated sound and shadow flicker studies. Based on a review of Mr. Haley's testimony, I understand that CRW II wind project will not exceed 45 dBA at a non-participant's residence and 50 dBA at a participant's residence. I also understand that the CRW II wind project will not exceed 30 hours per year of shadow and flicker at any non-participant or participant residence.

Health and Welfare

Q. AT THE AUGUST 26, 2019 PUBLIC INPUT MEETING COMMENTS WERE MADE ABOUT THE SOUND LEVELS THAT WILL BE PRODUCED BY THE PROJECT. BASED ON YOUR UNDERSTANDING THAT NON-PARTICIPANTS WILL NOT EXPERIENCE SOUND ABOVE 45 DBA AT THEIR RESIDENCE, DO YOU HAVE ANY HEALTH AND WELFARE CONCERNS?

A. No. The results of the largest epidemiology study that evaluated health issues associated with living in proximity to wind turbines noted no adverse health effects, including sleep and stress, among others, at noise levels up to 46 dB. This study is attached as Exhibit

RM-S-2. This is a cross-sectional study that was carried out in 2013 and included 1238 randomly selected participants aged 18-79, living between 0.25 and 11.22 kilometers from a wind turbine. The authors noted that, on the basis of the self-reported questionnaire results, the sound from wind turbines was not associated with:

- self-reported sleep disturbance or disorders;
- self-reported illnesses and chronic health conditions; and
- self-reported perceived stress and quality of life.

The authors also noted no association between the sound produced by wind turbines and objectively measured results such as blood pressure, resting heart rate, sleep efficiency, the rate or awakenings, duration of awakenings, total sleep time, or how long it took to fall asleep. In fact, the study concluded:

Self-reported health effects (e.g., migraines, tinnitus, dizziness, etc.), sleep disturbance, sleep disorders, quality of life, and perceived stress were not related to wind turbine noise (WTN) levels. Visual and auditory perception of wind turbines as reported by respondents increased significantly with increasing WTN levels as did high annoyance toward several wind turbine features, including the following: noise, blinking lights, shadow flicker, visual impacts, and vibrations... Beyond annoyance, results do not support an association between exposure to WTN up to 46 dBA and the evaluated health-related endpoints.

Based on this study, I have no concern the sound produced by the CRW II turbines for non-participants will impact their health or welfare.

Q. BASED ON YOUR UNDERSTANDING OF THAT PARTICIPANTS WILL NOT EXPERIENCE SOUND ABOVE 50 DBA AT THEIR RESIDENCES, DO YOU HAVE ANY HEALTH AND WELFARE CONCERNS?

A. No. While participants may experience sound levels up to 50 dBA at their residences, there is no evidence that experiencing sound levels at 50 dBA result in health impacts.

1 **Q. WILL THEIR BE ANY HEALTH OR WELFARE IMPACTS BECAUSE OF**
2 **INFRASOUND OR LOW FREQUENCY SOUND?**

3 A. No. First, it is not necessary to differentiate low frequency sound or infrasound from
4 broad sound level measurements conducted in the A scale. Second, in a study I co-
5 authored, it was shown that there is no scientific evidence to support the hypothesis that
6 wind turbine infrasound and low-frequency sound have unique adverse health effects that
7 other sources of noise do not have. This study is attached as Exhibit RM-S-3. Third,
8 detectable levels of infrasound and low-frequency sound at residences are not at harmful
9 levels based on studies near wind farms in the United States, the United Kingdom, the
10 Netherlands, Denmark, and Australia. (Exhibit RM-S-4, Exhibit RM-S-5, Exhibit RM-S-
11 6) To my knowledge, no peer-reviewed studies demonstrate harmful effects to humans
12 as a result of exposure to infrasound or low-frequency sound at the sound levels
13 measured in the vicinity of wind turbines or in experimental studies involving sound
14 levels several orders of magnitude higher than those noted in the vicinity of wind
15 turbines.

16 **Q. AT THE AUGUST 26, 2019 PUBLIC INPUT MEETING THERE WERE**
17 **COMMENTS ON THE SHADOW FLICKER THAT WILL BE PRODUCED BY**
18 **PROJECT. BASED ON YOUR UNDERSTANDING THAT NO NON-**
19 **PARTICIPANT NOR PARTICIPANT WILL EXPERIENCE SHADOW AND**
20 **FLICKER ABOVE 30 HOURS A YEAR, DO YOU HAVE ANY HEALTH AND**
21 **WELFARE CONCERNS?**

22 A. No. Shadow flicker is the visual, strobe-like effect that can occur when the rotating
23 blades of wind turbines cast shadows. The primary health concern that has been raised by

1 some regarding shadow flicker is the risk of seizures in individuals with photosensitive
2 epilepsy. Studies addressing risk of this type of epilepsy have concluded, however, the
3 absence of risk of shadow flicker inducing this type of seizure. (Exhibit RM-S-7 and
4 Exhibit RM-S-8).

5 **Q. AT THE AUGUST 26, 2019 PUBLIC INPUT MEETING THERE WERE**
6 **COMMENTS ON ANNOYANCE THAT COULD BE PRODUCED BY THE**
7 **PROJECT. IS ANNOYANCE ASSOCIATED WITH A WIND PROJECT**
8 **CONSIDER A HEALTH OR WELFARE ISSUE?**

9 A. No. Self-reported annoyance is not coded as a specific diagnosis in the International
10 Classification of Diseases. (ICD, 10th edition). The ICD is used worldwide for
11 diagnostic, insurance, and research purposes. Accordingly, I do not view that annoyance
12 is as a health or welfare concern, and, therefore, should not be used to downwardly adjust
13 the following CRW II thresholds for its project: (1) no more than 30 hours per year of
14 shadow and flicker at the residences of all participants and non-participants; (2) no more
15 than 45 dBA of sound at a non-participants residence and (3) not more than 50 dBA of
16 sound at a participant's residence.

17 This conclusion is supported in the Health Canada study, Exhibit RM-S-2. In that
18 study, annoyance was related to several reported measures of health and well-being,
19 although these associations were statistically weak ($R^2 < 0.09\%$), independent of wind
20 turbine sound levels, and not retained as a significant predictive variable in multiple
21 regression models. A correlation coefficient (R^2) of 0.09 is extremely weak and indicates
22 that the wind turbine sound category alone was a weak predictor of whether an individual
23 was highly annoyed by wind turbine sound or not. The Health Canada study confirmed

1 earlier research in which noise from wind turbines was noted to play a minor-if any- role
2 in people reporting annoyance, in contrast to more significant factors, such as attitudes
3 towards wind turbines, the impact of visual factors on the landscape, and whether a
4 person derives economic benefit from the turbines. Notably, the group that received an
5 economic benefit is completely absent from reported annoyance, despite residing in areas
6 with the highest wind turbine sound levels. Therefore, sound pressure levels appear to
7 play a limited-role in the experience of annoyance associated with wind turbines.

8 **Q. AT THE AUGUST 26, 2019 PUBLIC INPUT MEETING THERE WERE**
9 **COMMENTS ON WIND TURBINES CAUSING VERTIGO AND NAUSEA. IS**
10 **THERE A CORRELATION BETWEEN WIND TURBINES AND VERTIGO AND**
11 **NAUSEA?**

12 A. No. As far as I am aware, there is no credible scientific evidence to support the
13 conclusion that living near wind turbines at appropriate setbacks causes vertigo and
14 nausea. (See the results of the Health Canada study discussed earlier in this report.)

15 **Q. AT THE AUGUST 26, 2019 PUBLIC INPUT MEETING, THERE WERE**
16 **COMMENTS ON WIND TURBINES CAUSING DIRECT TISSUE AND ORGAN**
17 **DAMAGE, INCLUDING THE THICKENING OF THE HEART WALL. IS**
18 **THERE A CORRELATION BETWEEN WIND TURBINES AND DIRECT**
19 **TISSUE AND ORGAN DAMAGE?**

20 A. No. There is no credible scientific evidence to support the notion that living near wind
21 turbines will cause thickening of the cardiac wall.

1 **Q. AT THE AUGUST 26, 2019 PUBLIC INPUT MEETING, THERE WERE**
2 **COMMENTS THAT WIND TURBINES CAUSE PEOPLE WITH HEALTH**
3 **ISSUES, SUCH AS CANCER, TO HAVE THOSE HEALTH ISSUES MADE**
4 **WORSE. IS THERE A CORRELATION BETWEEN WIND TURBINES AND**
5 **MAKING ALREADY EXISTING HEALTH ISSUS WORSE?**

6 **A.** No, there is no credible evidence in the scientific literature that supports the notion that
7 people living near wind turbines at distances used by CRW II will aggravate any existing
8 medical diagnosis.

9 **Q. AT THE AUGUST 26, 2019 PUBLIC INPUT MEETING, THERE WERE**
10 **COMMENTS ON WIND TURBINES VIEWSHED CAUSING PEOPLE TO**
11 **BECOME DEPRESSED, OR FOR THEIR DEPRESSION TO BE COME MORE**
12 **ACUTE. IS THERE A CORRELATION BETWEEN WIND TURBINES AND**
13 **DEPRESSION?**

14 **A.** No, there is no credible evidence in the scientific literature that supports the notion that
15 people living near wind turbines at distances used by CRW II will become depressed or
16 experience acute depressive episodes.

17 **Q. AT THE AUGUST 26, 2019 PUBLIC INPUT MEETING, THERE WERE**
18 **COMMENTS ON WIND TURBINES CAUSING DIRECT TISSUE AND ORGAN**
19 **DAMAGE. IS THERE A CORRELATION BETWEEN WIND TURBINES AND**
20 **DIRECT TISSUE AND ORGAN DAMAGE?**

21 **A.** No.

22

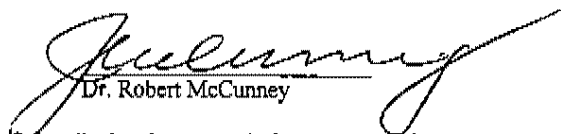
1 **Q. DOES THIS CONCLUDE YOUR SUPPLEMENTAL TESTIMONY?**

2 **A. Yes, it does.**

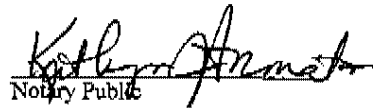
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Commonwealth of Massachusetts)
) ss
 County of Suffolk)

I, Robert McCunney, being duly sworn on oath, depose and state that I am the witness identified in the foregoing prepared testimony and I am familiar with its contents, and that the facts set forth are true to the best of my knowledge, information and belief.


 Dr. Robert McCunney
 Subscribed and sworn to before me this ___th day of ___,
 2019.

SEAL


 Notary Public

My Commission Expires 8-14-26



KATHRYN ARMATA
 Notary Public
 Commonwealth of Massachusetts
 My Commission Expires Aug. 14, 2026

Harvard Medical School Curriculum Vitae

Date Prepared: September 17, 2019

Name: Robert J. McCunney, M.D., M.P.H., M.S.

Office Address: Brigham and Women's Hospital; Pulmonary Division, 75 Francis Street, Boston, MA 02115

Work Phone: 617-732-6770; 617-251-5152

Work Email: mccunney@mit.edu; rmccunney@bwh.harvard.edu

Place of Birth: Philadelphia, PA

Education

1971	BS	Chemical Engineering	Drexel University, Philadelphia, PA
1972	MS	Environmental Health	University of Minnesota, Minneapolis, MN
1976	MD	Medicine	Thomas Jefferson University Medical School, Philadelphia, PA
1981	MPH	Occupational Medicine	Harvard School of Public Health, Boston, MA

Postdoctoral Training

7/76 – 6/77	Intern	Internal Medicine	Northwestern University Medical Center, Chicago, IL
7/77 – 6/78	Resident	Internal Medicine	Northwestern University Medical Center
1/79- 6/79	Resident	Internal Medicine	Faulkner Hospital, Boston
1/80 – 6/81	Fellow	Occupational Medicine	Peter Bent Brigham Hospital, Boston, MA

Faculty Academic Appointments

1981 – 1983	Instructor	Medicine	Brown University School of Medicine, Providence, RI
1983 – 1993	Adjunct Assistant Professor	Public Health	Boston University School of Medicine, Boston, MA
1989 – 1995	Clinical Assistant Professor	Preventive Medicine	Medical College of Wisconsin, Milwaukee, WI
1996 – present	Lecturer	Medicine	Harvard Medical School, Boston, MA

Appointments at Hospitals/Affiliated Institutions

1983 – 1994	Director	Medicine Occupational Health	Boston University School of Medicine
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1996 – 2010	Physician	Medicine Pulmonary Unit	Massachusetts General Hospital
2012-present	Physician	Medicine Pulmonary Division	Brigham and Women's Hospital, Boston
2001 – present	Research Scientist	Biological Engineering	Massachusetts Institute of Technology
2014-2016	Consulting Staff	Dana Farber Cancer Institute	Dana Farber Cancer Institute

Major Administrative Leadership Positions

Local

1981 – 1983	Medical Director, Occupational Health	Sturdy Memorial Hospital, Attleboro, MA
1983 – 1989	Medical Director, Occupational Health	Goddard Memorial Hospital, Stoughton, MA
1989 – 1994	Medical Director, Occupational Health Residency Program	Boston University Medical Center, Boston, MA
1994 – 2000	Director, Environmental Medicine	Massachusetts Institute of Technology

Regional

1982 – 1986	Board Member	New College of Occupational and Environmental Medicine, Boston, MA
1983 – 1985	President	New College of Occupational and Environmental Medicine

Committee Service

Local

2005-present	Member of Residency Advisory Committee for the occupational and environmental medicine training program	Harvard School of Public Health
1994 – 2000	Radiation Protection Committee	Massachusetts Institute of Technology
1994 – 2000	Pharmacy and Therapeutics Committee	Massachusetts Institute of Technology

Professional Societies: Past President of the American College of Occupational and Environmental Medicine. (1999-2000)

1981 -	American College of Occupational and Environmental Medicine	Member
1983 – 1989		Member, House of Delegates
1984 – 1986		President, New England Chapter
1986 – 1994		Member, Publications Committee
1985 – 1988		Chair, Publications Committee
1988 – 1993		Member, Residency Director Section
1989		Chair, Scientific Sessions of Annual Meeting

	1989 – 1993	Member, Government Affairs
	1994	Member, Ethical Practice Committee
	1993 – 1995	Co-Chair, Occupational Medicine Self-Assessment Program
	1996 – 1999	President Elect, 1 st VP, 2 nd VP
	1999 – 2000	President
1981 -	New England College of Occupational and Environmental Medicine	Member
1986 -	Medichem	Member
	1989 – 1993	Secretary
	1995	Chair, Annual Congress
	1999	Honorary Life Membership
1981 – 1991	American Public Health Association	Member
1983 -	American College of Preventive Medicine	Member
	1983 -	Fellow
1983 – 2000	American Medical Association	Member
2008 -	American Thoracic Society	Member
2010 -	American College of Chest Physicians	Member

Grant Review Activities

1996 - 1997	Medical Research Committee	US Department of Energy Member
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Editorial Activities (Ad hoc peer reviewer for the journals noted below)

Journal of Occupational and Environmental Medicine
Environmental Research
Journal of the Acoustical Society of America
Epidemiology
Chest
American Journal of Industrial Medicine
International Archives of Occupational and Environmental Medicine
Inhalation Toxicology

Other Editorial Roles

1995	Co-Editor	International Archives of Occupational and Environmental Medicine (special issue: 1996; 6: 349-530)
1996	Co-Editor	Inhalation Toxicology (special issue: 1996; 8 (suppl): 29-39)
2000	Guest Editor	Journal of Occupational and Environmental Medicine (special issue: 2001; 43: 1-55)
2006	Guest Editor	Journal of Occupational and Environmental Medicine (special issue: 2006; 48: 1217-1338)

Honors and Prizes

1971	Phi Beta Epsilon	National Honor Society
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1972	Tau Beta Pi	National Engineering Honor Society
1995	Presidential Award	American College of Occupational and Environmental Medicine (ACOEM)
1996	Drexel 100	Drexel University
2000	National Leadership	Central States Occupational Medical Association
2001	Harriet Hardy Leadership Award	New England College of Occupational and Environmental Medicine
2004	Health Achievement Award	ACOEM
2006	Presidential Award	ACOEM

Report of Funded and Unfunded Projects

Funding Information

Past

2000 – 2009 Cabot Corporation foundation for unrestricted work in occupational and environmental medicine
PI
The goal of this gift was to publish and teach in occupational medicine.

Current

International Carbon Black Association
Mortality study of USA carbon black workers
Particle exposure and risk of heart disease: an international meta analysis of German, British and American cohorts
American Wind Energy Association
Health effects of wind turbine operations: a critical review of literature
US Power Gen
Cluster evaluation of apparent cancer elevation among employees: a preliminary assessment
Parkinson's Disease and Environmental Risk Factors

Current Unfunded Projects

2007 - Occupational causes of kidney cancer
PI
The purpose of this project is to evaluate occupational causes of kidney cancer secondary to recognition of a "cluster" of kidney cancer at a manufacturing plant
2007 - Health implications of occupational and environmental mold exposure.
The purpose of this project is to develop a Continuing Medical Education (CME) course for physicians with other MGH colleagues.

Report of Local Teaching and Training

Teaching of Students in Courses

2000 -	Occupational Noise Exposure Graduate students	Harvard School of Public Health 1 hr/yr
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2007 -	Public Health and Epidemiology Graduate students	Massachusetts Institute of Technology 4 hr/wk x 6 wks
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Clinical Supervisory and Training Responsibilities

1994 – 1999	Preceptor, Occupational Medicine, Boston University Medical Center	6-8 hr/wk x 6 wks
1994 – 1999	Preceptor, Occupational Medicine, Harvard School of Public Health	6-8 hr/wk x 6 wks
2000 - 2010	Preceptor, Allergy and Immunology, Massachusetts General Hospital	

Formally Supervised Trainees

1991 – 1993	Cheryl Barbanel, M.D., M.P.H., M.B.A., Prof Occupational Medicine, University of Connecticut; Chair, Residency section, ACOEM I served as residency director. Trainee published a paper on chest film opacities in workers and noise exposure.
1992 – 1994	Joseph Chern, M.D., M.P.H., Director of Occupational Neurology at University of Taipei, Taiwan I served as residency director. Trainee published a book chapter on health effects of solvents.
1990 – 1992	Alain Couturier, M.D., M.P.H., Editor: "Occupational Infectious Disease" <i>deceased</i> I served as residency director. Trainee published a paper on medical surveillance.
1988 – 1990	Ross Myerson, M.D., M.P.H., Chair ACOEM Annual Meeting Consultant, 2004 I served as residency director. Trainee published a book chapter on Health effects of cleaning agents and sterilants
1988 – 1990	John Doyle, M.D., M.P.H., Director, Occupational Health, Taunton Hospital I served as residency director. Trainee published a paper on occupational illness in the arts.
1989 – 1991	Robert Godefroi, M.D., M.P.H., Director, Occupational Health Center, Manchester, NH I served as residency director. Trainee published a paper on drug screening practices in industry
1991 – 1993	Khalid Kabrum, M.D., M.P.H., Medical Director, Aluminum Company of Bahrain I served as residency director. Trainee published a book chapter on Health effects of cleaning agents and sterilants

Formal Teaching of Peers (e.g., CME and other continuing education courses)

1987	Managing Occupational Risks in the High Technology Industries Annual Meeting of American Occupational Medical Association	½ day postgraduate seminar Philadelphia, PA
1987	Introduction to Occupational Medicine Annual Meeting of American Occupational Medical Association	½ day postgraduate seminar Philadelphia, PA
1987	Indoor Air Quality and Health Annual Meeting of American Occupational Medical Association	½ day postgraduate seminar Philadelphia, PA
1988	Establishing Health Services for Small Businesses Annual Meeting of American Occupational Medical Association	4 hr postgraduate seminar New Orleans, LA

1988	Occupational Medicine: An Introduction American College of Occupational Medicine	1 presentation San Antonio, TX
1990	Introduction to Occupational Medicine American College of Occupational Medicine	4 hr seminar Pittsburgh, PA
1991	Introduction to Occupational Medicine American College of Occupational Medicine	1 presentation San Francisco, CA
1991	Ethical Issues in Occupational Medicine American College of Occupational Medicine	seminar San Francisco, CA
1991	Publishing in Occupational Medicine American College of Occupational Medicine	1 presentation San Francisco, CA
1994	Introduction to Occupational Medicine American College of Occupational Medicine	Seminar Dallas, TX

Local Invited Presentations

*Sponsored Lectures are marked **

1984	Setting Policy for Reproductive Hazards/Invited Talk Harvard School of Public Health, Boston, MA	
1985	Medical Surveillance: Screening for Occupational Illness/ Invited Talk Harvard School of Public Health and the New England Occupational Medical Association, Boston, MA	
1986	Cholesterol and Heart Disease: A Role for Fitness Programs?/Invited Talk Harvard School of Public Health, Boston, MA	
1987	Indoor Pollution. A Look at an Active Problem/Invited Talk Harvard School of Public Health, Boston, MA	
1989	The American Government and Occupational Medicine: New Developments/Invited Talk New England College of Occupational Medicine, Harvard School of Public Health, Boston, MA	
1994	Setting Policy for Reproductive Hazards/Invited Talk New England Occupational Medical Association and the Harvard School of Public Health, Boston, MA	
1998	Occupational Health at a Major Research Institution/Grand Rounds Harvard School of Public Health, Boston, MA	
2001	Noise and Hearing Loss/Grand Rounds Harvard School of Public Health, Boston, MA	
2007	Screening for Lung Cancer/Grand Rounds Harvard School of Public Health, Boston, MA	
2007	Screening for Lung Cancer/Grand Rounds Pulmonary Unit, Massachusetts General Hospital	
2014	Wind Turbines and Health effects; New England College of Occ/Env Med regional meeting	
2014	Pulmonary Grand Rounds at BWH: Lung cancer screening	
2017	Update on Occupational Medicine: Invited presentation for BWH Pulmonary Medicine Update; Boston, MA	
2018	Epidemiology studies of titanium dioxide workers; presented at annual meeting of TDMA; Boston, MA	
2019	Pulmonary Grand Rounds at BWH: Pitfalls in interpreting PFTs in the Occupational Setting	

Report of Regional, National and International Invited Teaching and Presentations

Invited Presentations and Courses

*Sponsored Lectures are marked **

Regional

- 1981 A Clinical Approach to the Patient with Exposure to Asbestos/Invited Talk
Medicine/Surgery Sturdy Memorial Hospital, Attleboro, MA
- 1982 The Health Hazards in the Jewelry Industry/Invited Talk
25th Annual Safety Institute of Rhode Island, University of Rhode Island, Providence, RI
- 1982 The Health Hazard Evaluation/Invited Talk
Occupational Medicine, Brown University School of Medicine, Providence, RI
- 1982 Medical Concerns of the Jewelry Industry/Invited Talk
Medicine/Surgery Sturdy Memorial Hospital, Attleboro, MA
- 1982 Stress and Its Ramifications/Invited Talk
Medicine/Surgery Sturdy Memorial Hospital, Attleboro, MA
- 1982 The Role of an Occupational Health Service./Invited Talk
Board of Trustees, Goddard Memorial Hospital, Brockton, MA
- 1983 A Clinical Approach to the Patient Exposed to Asbestos/Invited Talk
Roger Williams Hospital, Brown University School of Medicine affiliate, Providence, RI
- 1983 Should Your Company Have an Employee Assistance Program?/Invited Talk
Attleboro Chamber of Commerce Personnel Directors monthly meeting, Attleboro, MA
- 1983 Asbestosis: A Survey of the Health Effects/Medical Grand Rounds
Department of Medicine, Pawtucket Memorial Hospital, Pawtucket, RI
- 1983 Occupational Medicine in the People's Republic of China/Invited Talk
South Shore Community Hospital, Weymouth, MA
- 1983 Cost Containment Through Occupational Health/Invited Talk
South Shore Community Hospital, Weymouth, MA
- 1984 Asbestos, Current Controversies/Invited Talk
Massachusetts American Lung Association, Boston, MA
- 1984 Does Exercise Reduce the Risk of Heart Disease?/Invited Talk
Goddard Memorial Hospital and Massasoit College, Brockton, MA
- 1984 Occupational Medicine Today/Invited Talk
Boston University School of Public Health, Boston, MA
- 1984 Role of Occupational Medicine Today/Medical Grand Rounds
Braintree Hospital, Braintree, MA
- 1985 Stress, How To Recognize and Control its Effects/Invited Talk
S.E. Mass Chapter of American Society of Inventory Control Specialist, Stoughton, MA
- 1985 Indoor Air Pollution/Invited Talk
Down East American Industrial Hygiene Association, Portland, ME
- 1986 Indoor Air Pollution: An Update/Invited Talk
University of Massachusetts Medical Center, Worcester, MA
- 1986 Clinical Applications of Epidemiology/ 2 3hr Invited Talks
Occupational Nursing Program, Boston, MA
- 1986 Drug Screening in Industry: An Overview/Invited Talk
New England Occupational Medical Association, Boston, MA
- 1986 Staying Healthy in Retirement/Invited Talk

Billerica, MA
 1986 Indoor Air Pollution: An Update/Invited Talk
 University of Massachusetts Medical Center, Worcester, MA.
 1986 Clinical Applications of Epidemiology/2 3 hr Invited Talks
 Occupational Nursing Program, Simmons College, Boston, MA
 1986 Drug Screening in Industry: An Overview/Invited Talk
 New England Occupational Medical Association, Boston, MA
 1986 AIDS: What are the Occupational Risks?/Invited Talk
 Goddard Memorial Hospital, Stoughton, MA
 1986 Silicosis: A Disease of the Past or Current Concern/Invited Talk
 Goddard Memorial Hospital, Stoughton, MA
 1987 Controlling the Health Risks of Asbestos/Invited Talk
 Asbestos Information Center of Tufts University Medical Center, Boston, MA
 1987 Health Care Hazardous Waste Sites/Invited Talk
 Environmental Protection Agency, Boston, MA
 1987 Recognition and Treatment of Occupational Skin disease/Invited Talk
 Associated Industries of Massachusetts, Boston, MA
 1987 Drug Screening. Scientific and Ethical Issues/Invited Talk
 New England Chapter of the American Industrial Hygiene Association, Boston, MA
 1988 Occupational Medicine: An Introduction/Invited Talk
 American College of Occupational Medicine,
 1989 When to Suspect the Building as a Cause of Your Patient's Symptoms/Grand Rounds
 University Hospital, Boston, MA
 1989 Preventing Back Injuries at Work/Invited Talk
 Massachusetts Safety Council, Boston, MA
 1990 Occupational Health in Cost Containment/Invited Talk
 Health Care Financial Management Association, Boston, MA
 1990 Emergency Triage Systems for Work Related Injuries/Invited Talk
 American College of Rehabilitation Medicine, Boston, MA
 1990 Occupational Health and Cost Containment/Invited Talk
 Health Care Financial Management Association, Boston, MA
 1990 Recognizing Hand Disorders Due to Vibrating Tools/Invited Talk
 New England College of Occupational Medicine, Boston, MA
 1991 Occupational Health Challenges in Primary Care/Grand Rounds
 Carney Hospital, Boston, MA
 1991 Occupational Cancer in the 1990s/Invited Talk
 National Workers Compensation and Occupational Medicine Seminar, Hyannis, MA
 1993 Indoor Air pollution: A Recurring Problem in Occupational Medicine Practice; the Case
 Report: Recognition of Occupational Disease/Invited Talk
 Workers Compensation and Occupational Medicine, Hyannis, MA
 1998 Genetics in the Courtroom/Invited Talk
 Einstein Institute for Science, Health and the Courts, Orleans, MA
 2000 Work Implications of Sedating Antihistamines/Invited to Testify
 Boston City Council, Boston, MA
 2001 Risk Assessment: Current Issues/Invited Talk
 MIT, Cambridge, MA
 2006 Future of Occupational and Environmental Medicine/Invited Talk
 Cape Cod Conference SEAK, Hyannis, MA
 2010 Health Implications of Wind Turbines/Invited Talk
 Rutland Medical Center, Rutland, VT

National

- 1981 The Need for a National Commission in Boxing/Scientific Panel
American Medical Association, Chicago, IL
- 1982 Health Hazards in the Garment Industry/Invited Talk
International Ladies Garment Workers Union. New York, New York.
- 1983 A Hospital Develops an Occupational Health Service/Invited Talk
American Occupational Medical Association, Washington, DC
- 1983 The Role of Fitness in Preventing Heart Disease/Invited Talk
Amateur Athletic Union Annual Meeting, Washington, DC
- 1983 Diverse Manifestations of Trichloroethylene/Invited Invited Talk
American Academy of Occupational Medicine Annual Meeting, New Orleans, LA
- 1985 The Effect of Fitness on High Density Lipoproteins and Heart Disease/Panel Moderator
American Occupational Medical Association, Kansas City, MO.
- 1985 Indoor Air Quality: A Review With Recommended Protocol to Evaluate
Complaints/Invited Invited Talk
New York State Medical Society, New York, New York
- 1986 Staying Healthy in Retirement/Invited Talk
Cabot Corp, Champagne, IL, Indianapolis, MO, Atlanta, GA, Ville Platte, LA, Amarillo
and Midland, TX
- 1986 Environmental Medicine: Setting Policy at Hazardous Waste Sites/Invited Talk
New York State Medical Society, New York, New York
- 1987 Managing Workers Compensation Costs Through Fitness Programs/Invited Talk
Food Marketing Institute, New Orleans, LA
- 1988 Pulmonary Alveolar Proteinosis and Cement Dust: A Case Report/Invited Talk
The 7th International conference on Pneumoconiosis, Pittsburgh, PA
- 1988 Occupational Medicine: An Introduction/Invited Talk
American College of Occupational Medicine, San Antonio, TX
- 1989 Establishing Health Services for Small Businesses/Seminar Leader
New York Academy of Sciences, Boston, MA
- 1989 Hand-Arm Vibration Syndrome: Means of Control/Invited Talk
National Safety Council annual meeting, Chicago, IL
- 1989 Providing High Quality Occupational Medical Services/Invited Invited Talk
Annual Symposium on Delivery of Occupational Health Services, Washington, DC
- 1990 Current Developments in Occupational Medicine/Invited Invited Talk
Centers for Disease Control, Atlanta, GA
- 1990 Ethical Issues in Occupational Medicine/Invited Talk
American College of Occupational Medicine, Houston, TX
- 1992 A Hospital Based Occupational Medicine Residency Program/Moderator and Presenter
American College of Occupational and Environmental Medicine, Washington, DC
- 1992 The Academic Industry Interface in Occupational Medicine/Invited Talk
American College of Occupational and Environmental Medicine State of the Art
Conference, New York City, New York
- 1993 Advanced Occupational Medicine/Invited Talk
American College of Preventive Medicine, Chicago, IL
- 1994 The Use of Biomarkers in Clinical Practice/Invited Talk
US Department of Energy, Santa Fe, NM
- 1995 Health effects of ionizing radiation exposure/Invited Talk
US Department of Energy, Tampa, FL
- 1995 Preserving Confidentiality in Occupational Medical Practice; The Physician's Role in
Emergency Response; The Occupational Medical Self Assessment Program/3 Invited

Talks

- American College of Occupational and Environmental Medicine Annual Meeting, Las Vegas, NV
- 1996 New Directions in Occupational Medical Practice/Invited Talk
American College of Occupational and Environmental Medicine, San Antonio, TX
- 1996 The International Agency for Research on Cancer (IARC) decision on Evaluating the Carcinogenicity of Carbon Black/Invited Talk
Annual Joint Labor/Management Health and Safety Conference on United Rubber and Steel Workers, Cleveland, Ohio.
- 1997 The New EPA Standard on Ambient Particulates and Ozone: Implications for the Occupational Physician
American College of Occupational and Environmental Medicine (ACOEM), Nashville, TN
- 1998 Health and Productivity: A Role for Occupational Health? /Invited Talk
4th Annual Employers Summit, Chicago, IL
- 1998 The Legacy of the Cold War; Challenges to the Occupational Health Professional/Invited Talk
Annual Department of Energy meeting in Occupational Medicine, Washington, DC
- 1998 The Flu, A new Medication and Occupational Health; A Look At The Links/Seminar Leader
Naples, Florida (Glaxo Wellcome)
- 1998 The Future of Occupational and Environmental Medicine/Invited Talk
Annual meeting of the Maryland, Virginia, and Pennsylvania components of the American College of Occupational and Environmental Medicine (ACOEM), Williamsburg, VA.
- 2000 Health and Productivity/Invited Talk
Annual meeting of American Journal of Health Promotion on Health and Productivity, Colorado Springs, CO
- 2000 Occupational Health and Productivity/Invited Talk
Central States Occupational Medical Association annual meeting, Chicago, IL
- 2000 On behalf of ACOEM, gave oral testimony to OSHA on the proposed ergonomics standard/Invited to Testify (April and May)
Washington, DC
- 2000 Latex Allergy/Invited Talk
Annual meeting of the Michigan College of Occupational Medicine, Ann Arbor, MI
- 2000 Clinical application of recent research in occupational medicine/Invited Talk
State of the art meeting, American College of Occupational and Environmental Medicine, Nashville, TN
- 2001 Health and Productivity: A Role for Occupational Health/Invited Talk
Annual meeting of the Health Enhancement Research Organization, (HERO), Washington, DC
- 2001 The Human Genome Project: Implications on Occupational Medical Practice/Invited Talk
Annual meeting at the American College of Occupational and Environmental Medicine, San Francisco, CA
- 2001 Health and Productivity Research/Invited Talk
Annual meeting of the Institute of Productivity Management, Orlando, FL
- 2003 Future of Occupational Medicine/Invited Talk
MIT and the American College of Occupational and Environmental Medicine, San Juan, Puerto Rico
- 2006 Should we screen for occupational lung cancer with low dose CT?/Invited Talk
Annual meeting of the American College of Occupational and Environmental Medicine,

- Atlanta Georgia
- 2009 Are there health effects of wind turbine operations?/Invited Talk
Annual meeting of American Wind Energy Association
Orlando, FL
- 2010 thru Harvard School of Public Health; Graduate students in Public Health; “Health effects of
2015 occupational and environmental noise exposure
- 2012 thru Evaluating Occupational Lung Disease Part 1; Harvard Medical School Pulmonary
2015 Fellows Conference
- 2013 Evaluating Occupational Lung Disease Part 2; Harvard Medical School Pulmonary
Fellows Conference
- 2014 “Evaluating health effects from exposure to hazardous materials.” and “How to critically
interpret the scientific literature.” State Supreme Court Justices’ Conference,
sponsored by a grant from the US Department of Justice. Chapel Hill, NC
- 2014 Grand Rounds: Pulmonary Division. “Radiation risks in lung cancer screening
programs.” Brigham and Women’s Hospital, Boston
- 2015 Grand Rounds: Harvard School of Public Health. Hypersensitivity Pneumonitis, Boston
Grand Rounds: Pulmonary Division; Brigham and Women’s (BWH) Hospital, Boston.
- 2016 Hypersensitivity Pneumonitis
Occupational Lung Disease: Lecture to Pulmonary Fellows of BWH
- 2017 Amorphous Silica; A review of a cross sectional study at German plants; Grand Rounds:
Pulmonary Division; Brigham and Women’s (BWH) Hospital, Boston.
Lung Tumors in Lab Rats: Implications for humans. Grand Rounds: Pulmonary
Division; Brigham and Women’s (BWH) Hospital, Boston. ;
- 2018 Epidemiology studies of Titanium Dioxide workers. Annual meeting of titanium
dioxide manufacturers. Boston, MA
- 2019 Grand Rounds Pulmonary: Pitfalls in interpreting PFTs in the Occupational setting.
- 2019 Uranium Lung: An approach to diagnosing illness. Indian Health Service of Navajo Nation
- 2019 Health implications of wild fires. Southern Oregon University

International Presentations

- 1982 Sino-American study tour in occupational medicine to hospitals and factories/Invited
Participant
People’s Republic of China (Peking, Shanghai, Hangzhou and Canton)
- 1985 Diverse Manifestations of Trichloroethylene/Invited Talk
Kyoto University Hospital, Kyoto, Japan
- 1985 Fitness and Heart Disease/Seminar Leader
Mahidol University Hospital, Bangkok, Thailand
- 1985 Indoor Air Pollution: A Summary of an Investigation in an Office Setting/Invited Talk
Society of Occupational Setting, Society of Occupational Medicine, Hong Kong, United
Kingdom
- 1986 Diverse Manifestations of Trichloroethylene/Invited Speaker
Annual meeting of Medichem, Ludwigshafen, West Germany
- 1987 Annual Health/Safety Meeting of Cabot Corporation/Seminar Leader
Toronto, Canada

1987	Annual Health/Safety Meeting of Cabot Corporation/Educational Leader Kenya, East Africa
1988	A Cross-cultural Epidemiology Study/Invited Talk 16th Annual Meeting of Medichem, Helsinki, Finland
1989	Occupational Health in the Chemical Industry/Invited Co-Chair International Commission on Occupational Health triennial meeting, Montreal, Canada
1994	Medical Response to Environmental Emergencies/Invited Talk Annual meeting of Medichem, Melbourne, Australia
1995	Health Effects of Carbon Black/Invited Talk Presented in German to the German Automobile Association, Frankfurt, Germany
1997	Biomarkers and the Human Genome: A look at the Clinical Issues/Invited Talk US Department of Energy International Meeting, Charleston, SC.
1997	Particles and Lung Disease: A Look at the Clinical Issues/Invited Talk Health and Safety Executive of the United Kingdom, University of Leicester, Leicester, England
1999	Occupational Health and Productivity/Invited Talk Annual Latin American Conference on Occupational Medicine, Dorado, Puerto Rico
1999	Occupational Health and Productivity/Invited Talk Annual meeting of Medichem, Vienna, Austria
2000	Chemical Sensitivity and Idiopathic Environmental Intolerance/Invited Talk Ottawa, Canada
2001	The Role of the Human Genome in Occupational Medical Practice/Invited Talk Pulmonary Division, University of Bochum, Bochum, Germany
2002	Review of Epidemiology Studies and the Exposure Limit for Carbon Black./Invited Talk Health and Safety Executive Meeting (UK), London, England
2008	Occupational Health Research in the Carbon Black Industry/Invited Talk Carbon Black World Conference, Guilin, China
2015	Health Effects of Carbon Black; Institute of Occupational Medicine; Edinburgh, Scotland
2015	Health Effects of living near wind turbines: An update; annual meeting of the Canadian Wind Energy Association (Toronto, Canada)
2016	Lung tumors in Lab Rats: Implications for Human Risk Assessment; Titanium Dioxide International Meeting; Paris France
2016	Setting Occupational Exposure Limits; German MAK Commission; Berlin, Germany
2017	Role of epidemiology in evaluating Health Risks; presentation to Risk Assessment Committee of European Chemical Agency; Helsinki, Finland

Report of Clinical Activities and Innovations

Current Licensure and Certification

1983	American Board of Preventive Medicine – Occupational and Environmental Medicine
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Practice Activities

1996 – 2010	Ambulatory Practice	MGH	1-2 days per week
2010-current	Ambulatory Practice	Brigham and Women's Hospital, Boston	1-2 days per week

Clinical Innovations

Implemented three hospital-based occupational health programs at:

- Sturdy Memorial Hospital, Attleboro, MA
- Goddard Memorial Hospital, Stoughton, MA
- University Hospital of Boston University Medical Center, Boston, MA

Report of Scholarship

Publications

Peer reviewed publications in print or other media

Research Investigations

1. **McCunney RJ.** "Acute and Chronic Brain Injuries in Boxers; Causes and Prevention". Physician and Sports Medicine, 1984;12:52-64.
2. **McCunney RJ.** "A Hospital-Based Occupational Health Service". Journal of Occupational Medicine, 1984;26:375-80.
3. **McCunney RJ.** "Are Stress Management Programs Cost Effective?" Journal of Occupational Medicine, 1984;26:410.
4. **McCunney RJ.** "Confidentiality of Medical Records." Journal of Occupational Medicine. 1984;26:790-91.
5. **McCunney RJ.** "Are Exercise EKG's Needed Prior to a Fitness Program?" Occupational Health and Safety. 1984, 23-24.
6. **McCunney RJ.** "Corporate Medical Programs". (letter) Harvard Business Review, Nov/Dec, 1984; 16-18
7. **McCunney RJ.** "Video display Terminals: What are the Health Risks?" Boston Business Journal, December 24, 1984; 7-9
8. **McCunney RJ.** Acid Rain. (book review) Journal of the American Medical Association, 1985;253: 2291-92.
9. **McCunney RJ.** "The Role of Fitness in Preventing Health Disease". Cardiovascular Reviews and Reports 1985;6:776-78.
10. **McCunney RJ.** "Health Effects of Work at Wastewater Treatment Plants: A review of the literature with guidelines for medical surveillance". American Journal of Industrial Medicine 1986;9:271-79.
11. **McCunney RJ.** Indoor Air Quality. (book review) Journal of the American Medical Association 1986;255:1261-62.
12. **McCunney RJ.** "The Patient with Asbestos Exposure". Journal of Family Practice 1986;22:73-78.
13. **McCunney RJ.** "Distilling Questions on Drug Testing". Boston Business Journal, November 17, 1986.; 2-3
14. **McCunney RJ.** "Physical Activity and HDL Levels". Physician and Sports Medicine 1987;15:67-74.
15. **McCunney RJ.** "The Role of Building Construction and Ventilation in Indoor Air Pollution: A Review of a Recurring Problem". New York State Journal of Medicine 1987;87:203-09.

16. **McCunney RJ.** "Effective Drug Screening Programs Should Be Applied Judiciously". Occupational Health and Safety: News Digest, Feature Story, May 1987, 9-10.
17. **McCunney RJ.** "The Role of Fitness in Controlling Workers Compensation Costs". Proceedings of the Annual Food Marketing Institute, 1987, Washington DC.
18. **McCunney RJ.** Cluster Mystery: Epidemic and The Children of Woburn, Mass. (book review). JAMA 1987; 258: 969-71.
19. **McCunney RJ,** Doyle JR, Russo PK. "Occupational Illness in the Arts" American Family Physician. 1987;36:145-53.
20. Godefroi R, **McCunney RJ.** "Drug Screening Practices in Small Businesses: A Survey". Journal of Occupational Medicine 1988;30:300-02.
21. **McCunney RJ.** "Diverse Manifestations of Trichloroethylene", British Journal of Industrial Medicine, 1988; 45:122-26.
22. **McCunney RJ,** Cashins R. "Environmental Tobacco Smoke: A Problem Revisited". Journal of Occupational Medicine 1988;30:540-42.
23. **McCunney RJ.** "Occupational Health: What the Future Holds". Industry, December 1988.
24. **McCunney RJ,** Walter E. "Occupational Medicine Services" in Handbook of Occupational Medicine (**McCunney RJ,** ed.), Little Brown, Boston 1988;3-20.
25. Godefroi R, **McCunney, RJ,** "The Role of Regulatory Agencies" in Handbook of Occupational Medicine (**McCunney RJ,** ed.), Little Brown, Boston 1988; 36-46.
26. Jacknow D, **McCunney RJ,** Jofe M. "Musculoskeletal Disorders" in Handbook of Occupational Medicine (**McCunney RJ,** ed.), Little Brown, Boston 1988;106-29.
27. **McCunney RJ.** "Cardiovascular Disorders" in Handbook of Occupational Medicine (**McCunney 00RJ,** ed.), Little Brown, Boston 1988; 143-58.
28. **McCunney RJ.** "Medical Surveillance" in Handbook of Occupational Medicine (**McCunney RJ,** ed.), Little Brown, Boston 1988; 297-308.
29. McCauley M, **McCunney RJ,** Scofield M. "Health Promotion" in Handbook of Occupational Medicine (**McCunney RJ,** ed.), Little Brown, Boston 1988; 335-49.
30. Melius J, Wallingford RM, **McCunney RJ.** "The Health Hazard Evaluation: Investigating Occupational Health Problems in Handbook of Occupational Medicine (**McCunney RJ,** ed.), Little Brown, Boston 1988;362-73.
31. Frumkin H, **McCunney RJ.** "Health Effects of Common Substances" in Handbook of Occupational Medicine (**McCunney RJ,** ed.), Little Brown, Boston 1988; 423-39.
32. **McCunney RJ,** Godefroi R. "Pulmonary Alveolar Proteinosis: A Case Report." Journal of Occupational Medicine 1989;31:233-237.
33. **McCunney RJ.** "Drug Screening: Technical Complications of a Complex Social Issue." American Journal of Industrial Medicine; 1989;15:589-600.
34. **McCunney RJ** "Providing High Quality Occupational Medical Services." J Amb Health Care Marketing 1990; 4: 9-18.
35. **McCunney RJ.** Greaves, W, "Addressing the Shortage of Occupational Physicians," Journal of Occupational Medicine 1990:1247-48.
36. Ducatman A, **McCunney RJ.** "What is Environmental Medicine?" Journal of Occupational

Medicine 1990;32:1130-32.

37. **McCunney RJ**, Cikins W. "The Effect of Federal Health Policy on Occupational Medicine. Polish Journal of Occupational Medicine, 1990;3:241-56.
38. **McCunney RJ**, Brandt-Rauf P. "Ethical Issues in the Private Practice of Occupational Medicine. Journal of Occupational Medicine 1991;33:80-82.
39. **McCunney RJ**. "Occupational Noise Exposure," in Rom WM. (Ed) Environmental and Occupational Medicine, Little Brown, Boston, 1992, 2nd edition.
40. **McCunney, RJ**, "Recognizing Hand Disorders caused by Vibrating Tools." Journal of Musculoskeletal Medicine, 1992;9(3): 91-110.
41. **McCunney RJ**, Jetzer T. "Hand Vibration Isolation: A Study of Various Materials" Journal Applied Occupational Hygiene 1992;7:8-12.
42. **McCunney RJ**, Harzbecker J. "The Role of Occupational Medicine in General Medical Practice: A Look at the Journals." Journal of Occupational Medicine, 1992; 34: 279-286.
43. **McCunney RJ**, Boswell R, Harzbecker J. "Environmental Health in the Journals." Environmental Research 1992;59:114-24.
44. **McCunney RJ**, Couturier A. "Where do Occupational Medicine Residency Programs Belong in the Institution?" Journal of Occupational Medicine 1993; 35: 889-890.
45. **McCunney RJ**, Barbanell C. "Auditing Workers Compensation Claims." Occupational Health and Safety 1993;63:75-84.
46. **McCunney RJ**. "The Academic Occupational Physician as Consultant: A Ten Year Perspective." Journal of Occupational and Environmental Medicine 1994;36:438-42.
47. Barbanell C, **McCunney RJ**. "Environmental Surveillance of Respiratory Disorders: The Hazardous Waste Site as an Example" Environmental Respiratory Disease," Cordasco E., Demeter SL, Zene C. (eds.) Yearbook Medical publishers, Chicago 1995; pp 479-504.
48. **McCunney RJ**. "Challenges and Opportunities in Occupational Medicine". Journal of the American Osteopathic Medical Assoc. 1994;95(2):107-14.
49. **McCunney RJ**, Schmitz, S. Cardiovascular disorders, in A Practical Approach to Occupational and Environmental Medicine, (**McCunney RJ**, ed.) Little Brown, Boston, 1994;3-19.
50. **McCunney RJ**. Boswell R. Musculoskeletal Disorders, in A Practical Approach to Occupational and Environmental Medicine, (**McCunney RJ**, ed.) Little Brown, Boston, 1994;166-86.
51. **McCunney RJ**. Schmitz S. Cardiovascular Disorders, in A Practical Approach to Occupational and Environmental Medicine, (**McCunney RJ**, ed.) Little Brown, Boston, 1994;199-213.
52. Harber P, **McCunney RJ**, Monosson I. Medical Surveillance, in A Practical Approach to Occupational and Environmental Medicine, (**McCunney RJ**, ed.) Little Brown, Boston, 1994;358-75.
53. McLellan R, **McCunney RJ**. Indoor Air Pollution, in A Practical Approach to Occupational and Environmental Medicine, (**McCunney RJ**, ed.) Little Brown, Boston, 1994;633-50.
54. McCauley M, **McCunney RJ**. Health Promotion in A Practical Approach to Occupational and Environmental Medicine, (**McCunney RJ**, ed.) Little Brown, Boston, 1994;465-78.
55. **McCunney RJ**, Barbanell C, Frumkin H. Health Effects of Common Substances in A Practical Approach to Occupational and Environmental Medicine, (**McCunney RJ**, ed.) Little Brown,

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58. **McCunney RJ**. "Clinical Applications of Biomarkers in Occupational Medicine" in *Biomarkers and Occupational Health: Progress and Perspectives*. (Mendelsohn, ML, Peeters, JP, Normandy MJ, eds.) Joseph Henry Press, Washington, DC, 1995;148-60.
59. **McCunney RJ**. "From the Lab Bench to the Work Place: Implications of Toxicology Studies on Occupational Medical Practice." *Inhalation Toxicology* 1996;8(suppl):29-39.
60. **McCunney RJ**. "Preserving Confidentiality in Occupational Medical Practice". *Am Fam Phys* 1996;53(5):1751-56.
61. **McCunney RJ**. "Emergency Response to Environmental Toxic Incidents: The Role of the Occupational Physician." *Occupational Medicine* 1996;46(6):397-401.
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Organization, Geneva, 1998;16.35-16.38.

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Exposure to wind turbine noise: Perceptual responses and reported health effects

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Health Canada, in collaboration with Statistics Canada, and other external experts, conducted the Community Noise and Health Study to better understand the impacts of wind turbine noise (WTN) on health and well-being. A cross-sectional epidemiological study was carried out between May and September 2013 in southwestern Ontario and Prince Edward Island on 1238 randomly selected participants (606 males, 632 females) aged 18–79 years, living between 0.25 and 11.22 km from operational wind turbines. Calculated outdoor WTN levels at the dwelling reached 46 dBA. Response rate was 78.9% and did not significantly differ across sample strata. Self-reported health effects (e.g., migraines, tinnitus, dizziness, etc.), sleep disturbance, sleep disorders, quality of life, and perceived stress were not related to WTN levels. Visual and auditory perception of wind turbines as reported by respondents increased significantly with increasing WTN levels as did high annoyance toward several wind turbine features, including the following: noise, blinking lights, shadow flicker, visual impacts, and vibrations. Concern for physical safety and closing bedroom windows to reduce WTN during sleep also increased with increasing WTN levels. Other sample characteristics are discussed in relation to WTN levels. Beyond annoyance, results do not support an association between exposure to WTN up to 46 dBA and the evaluated health-related endpoints.

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I. INTRODUCTION

Jurisdiction for the regulation of noise is shared across many levels of government in Canada. As the federal department of health, Health Canada's mandate with respect to

wind power includes providing science-based advice, upon request, to federal departments, provinces, territories and other stakeholders regarding the potential impacts of wind turbine noise (WTN) on community health and well-being. Provinces and territories, through the legislation they have enacted, make decisions in relation to areas including installation, placement, sound levels, and mitigation measures for wind turbines. In July 2012, Health Canada announced its

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intention to undertake a large scale epidemiological study in collaboration with Statistics Canada entitled Community Noise and Health Study (CNHS). Statistics Canada is the federal government department responsible for producing statistics relevant to Canadians.

In comparison to the scientific literature that exists for other sources of environmental noise, there are few original peer-reviewed field studies that have investigated the community response to modern wind turbines. The studies that have been conducted to date differ substantially in terms of their design and evaluated endpoints (Krogh *et al.*, 2011; Mroczek *et al.*, 2012; Mroczek *et al.*, 2015; Nissenbaum *et al.*, 2012; Pawlaczyk-Łuszczynska *et al.*, 2014; Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2009; Shepherd *et al.*, 2011; Tachibana *et al.*, 2012; Tachibana *et al.*, 2014; Kuwano *et al.*, 2014). Common features among these studies include reliance upon self-reported endpoints, modeled WTN exposure and/or proximity to wind turbines as the explanatory variable for the observed community response.

There are numerous health symptoms attributed to WTN exposure including, but not limited to, cardiovascular effects, vertigo, tinnitus, anxiety, depression, migraines, sleep disturbance, and annoyance. Health effects and exposure to WTN have been subjected to several reviews and the general consensus to emerge to date is that the most robust evidence is for an association between exposure to WTN and community annoyance with inconsistent support observed for subjective sleep disturbance (Bakker *et al.*, 2012; Council of Canadian Academies, 2015; Knopper *et al.*, 2014; MassDEP MDPH, 2012; McCunney *et al.*, 2014; Merlin *et al.*, 2014; Pedersen, 2011).

The current analysis provides an account of the sample demographics, response rates, and observed prevalence rates for the various self-reported measures as a function of the outdoor WTN levels calculated in the CNHS.

II. METHOD

A. Sample design

Factors considered in the determination of the study sample size, including statistical power, have been described by Michaud *et al.* (2013), Michaud *et al.* (2016b), and Feder *et al.* (2015). The target population consisted of adults, aged 18 to 79 years, living in communities within approximately 10 km of a wind turbine in southwestern Ontario (ON) and Prince Edward Island (PEI). Selected areas in both provinces were characterized by flat lands with rural/semi-rural type environments. Prior to field work, a list of addresses (i.e., potential dwellings) was developed by Statistics Canada. The list consists mostly of dwellings, but it can include industrial facilities, churches, demolished/vacant dwellings, etc. (i.e., non-dwellings), that would be classified as out-of-scope for the purposes of the CNHS. The ON and PEI sampling areas included 315 and 84 wind turbines, respectively. Wind turbine electrical power output ranged between 660 kW to 3 MW (average 2.0 ± 0.4 MW). All turbines were modern design with 3 pitch controlled rotor blades (~ 80 m diameter) upwind of the tower, and predominantly 80 m hub heights. This study was approved by the Health Canada and Public Health Agency of Canada

Research Ethics Board (Protocols #2012–0065 and #2012–0072).

B. Wind turbine sound pressure levels at dwellings

A detailed description of the approach applied to sound pressure level modeling [including background nighttime sound pressure (BNTS) levels] is presented separately (Keith *et al.*, 2016b). Briefly, sound pressure levels were estimated at each dwelling using both ISO (1993) and ISO (1996) as incorporated in the commercial software CadnaA version 4.4 (Datakustik, 2014). The calculations were based on manufacturers' octave band sound power spectra at 10 m height, 8 m/s wind speed for favorable propagation conditions (Keith *et al.*, 2016a). As described in detail by Keith *et al.* (2016b), BNTS levels were calculated following provincial noise regulations for Alberta, Canada (Alberta Utilities Commission, 2013). With this approach BNTS levels can range between 35 dBA to 51 dBA. The possibility that BNTS levels due to highway road traffic noise exposure may exceed the level estimated by Alberta regulations was considered. Where the upper limits of this approach were exceeded (i.e., 51 dB), nighttime levels were derived using the US Traffic Noise Model (United States Department of Transportation, 1998) module in the CadnaA software.

Low frequency noise was estimated in the CNHS by calculating outdoor C-weighted sound pressure levels at all dwellings. There was no additional gain by analysing the data using C-weighted levels because the statistical correlation between C-weighted and A-weighted levels was very high (i.e., $r = 0.81$ – 0.97) (Keith *et al.*, 2016a).

C. Data collection

1. Questionnaire content and collection

The final questionnaire, available on the Statistics Canada website (Statistics Canada, 2014) and in the supplementary materials,¹ consisted of basic socio-demographics, modules on community noise and annoyance, health effects, lifestyle behaviors and prevalent chronic illnesses. In addition to these modules, validated psychometric scales were incorporated, without modification, to assess perceived stress (Cohen *et al.*, 1983), quality of life (WHOQOL Group, 1998; Skevington *et al.*, 2004) and sleep disturbance (Buysse *et al.*, 1989).

Questionnaire data were collected through in-person home interviews by 16 Statistics Canada trained interviewers between May and September 2013. The study was introduced as the “Community Noise and Health Study” as a means of masking the true intent of the study, which was to investigate the association between health and WTN exposure. All identified dwellings within ~ 600 m from a wind turbine were selected. Between 600 m and 11.22 km, dwellings were randomly selected. Once a roster of adults (between the ages of 18 and 79 years) living in the dwelling was compiled, one individual from each household was randomly invited to participate. No substitutions were permitted under any circumstances. Participants were not compensated for their participation.

2. Long-term high annoyance

To evaluate the prevalence of annoyance, participants were initially asked to spontaneously identify sources of noise they hear originating from outdoors while they are either inside or outside their home. The interviewer grouped the responses as road traffic, aircraft, railway/trains, wind turbine, and “other.” Follow-up questions were designed to confirm the initial response where the participant may not have spontaneously identified wind turbines, rail, road and aircraft as one of the audible sources. For each audible noise source participants were asked to respond to the following question from ISO/TS (2003a): “Thinking about the last year or so, when you are at home, how much does noise from [SOURCE] bother, disturb or annoy you?” Response categories included the following: “not at all,” “slightly,” “moderately,” “very,” or “extremely.” Participants who reported they did not hear a particular source of noise, were classified into a “do not hear” group and retained in analysis (to ensure that the correct sample size was accounted for in the modeling). The analysis of annoyance was performed after collapsing the response categories into two groups (i.e., “highly annoyed” and “not highly annoyed”). As per ISO/TS (2003a), participants reporting to be either “very” or “extremely” annoyed were treated as “highly annoyed” in the analysis. The “not highly annoyed” group was composed of participants from the remaining response categories in addition to those who did not hear wind turbines. Similarly, an analysis of the percentage highly subjectively sleep disturbed, highly noise sensitive, and highly concerned about physical safety from having wind turbines in the area was carried out applying the same classification approach used for annoyance.

The use of filter questions and an assessment of annoyance using only an adjectival scale are approaches not recommended by ISO/TS (2003a). The procedures followed in the current study were chosen to minimize the possibility of participant confusion (i.e., by asking how annoyed they are toward the noise from a source that may not be audible). Although there is value in confirming the response on the adjectival scale with a numerical scale, this approach would have added length to the questionnaire, or led to the removal of other questions. Collectively, the deviations from ISO/TS (2003a) conformed to the recommendations by Statistics Canada and to the approach adopted in a large-scale study conducted by Pedersen *et al.* (2009).

D. Statistical methodology

The analysis for categorical outcomes closely follows the description outlined in Michaud *et al.* (2013), which provides a summary of the pre-data collection study design and objectives, as well as the proposed data analysis. Final wind turbine distance and WTN categories were defined as follows: distance categories in km { ≤ 0.550 ; (0.550–1]; (1–2]; (2–5]; and > 5 }, WTN exposure categories in dBA { < 25 ; [25–30]; [30–35]; [35–40]; and [40–46]}. The top category included 46 dB as only six cases were observed at ≥ 45 dBA. All models were adjusted for provincial differences. Province was initially assessed as an effect modifier. When the interaction between WTN and province was significant,

separate models were reported for each province. This included reporting separate chi-square tests of independence or logistic regression models for each province. When the interaction was not statistically significant, province was treated as a confounder in the model. This included using the Cochran-Mantel-Haenszel (CMH) chi-square tests for contingency tables (which adjusts for confounders), as well as adjusting the logistic regression models for the confounder of province.

The questionnaire assessed participant’s long-term (~ 1 year) annoyance to WTN in general (i.e., location not specified), and specifically with respect to location (outdoors, indoors), time of day (morning, afternoon, evening, nighttime) and season (spring, summer, fall, winter). In addition, participants’ long-term annoyance in general, to road, aircraft and rail noise was assessed. These evaluations of annoyance are considered to be clustered because they are derived from the same individuals (i.e., they are repeated measures). Therefore, in order to compare the prevalence of annoyance as a function of location, time of day, season, or noise source, generalized estimating equations for repeated measures were used to account for the clustered responses (Liang and Zeger, 1986; Stokes *et al.*, 2000).

Statistical analysis was performed using SAS version 9.2 (SAS Institute Inc., 2014). A 5% statistical significance level is implemented throughout unless otherwise stated. In addition, Bonferroni corrections are made to account for all pairwise comparisons to ensure that the overall type I (false positive) error rate is less than 0.05. In cases where cell frequencies were small (i.e., < 5) in the contingency tables or logistic regression models, exact tests were used as described in Agresti (2002) and Stokes *et al.* (2000).

III. RESULTS

A. Wind turbine sound pressure levels at dwellings

Modeled sound pressure levels, and the field measurements used to support the models are presented in detail by Keith *et al.* (2016a,b). Calculated outdoor sound pressure levels at the dwellings reached levels as high as 46 dB. Unless otherwise stated, all decibel references are A-weighted. Calculations are likely to yield typical worst case long-term (1 years) average WTN levels (Keith *et al.*, 2016b).

B. Response rate

Of the 2004 addresses (i.e., potential dwellings) on the sample roster, 434 dwellings were coded as out-of-scope by Statistics Canada during data collection (Table I). This was consistent with previous surveys conducted in rural areas in Canada (Statistics Canada, 2008). In the current study, 26.7% and 20.4% of addresses were deemed out-of-scope in PEI and ON, respectively. No significant difference in the distribution of out-of-scope locations by distance to the nearest wind turbine was observed in PEI ($\chi^2 = 3.19$, $p = 0.5263$). In ON, a higher proportion of out-of-scope addresses was observed in the closest distance group (≤ 0.55 km) compared to other distance groups ($p < 0.05$, in all cases). After adjusting for province, there was a

TABLE I. Locations coded out-of-scope.

	Distance to nearest wind turbine (km)					Overall	CMH <i>p</i> -value ^a
	≤0.55	(0.55–1]	(1–2]	(2–5]	>5		
Range of WTN (dB)	37.4–46.1	31.8–43.6	26.3–40.4	14.6–30.9	0–18.2		
Total potential dwellings	143	887	781	95	98	2004	
ON	76	718	669	60	80	1603	
PEI	67	169	112	35	18	401	
Total number of potential dwellings out-of-scope n(%) ^b	48 (33.6)	158 (17.8)	189 (24.2)	19 (20.0)	20 (20.4)	434 (21.7)	0.9755
ON	29 (38.2)	109 (15.2)	166 (24.8)	9 (15.0)	14 (17.5)	327 (20.4)	<0.0001 ^c
PEI	19 (28.4)	49 (29.0)	23 (20.5)	10 (28.6)	6 (33.3)	107 (26.7)	0.5263 ^c
Code A	28 (19.6)	23 (2.6)	18 (2.3)	5 (5.3)	8 (8.2)	82 (4.1)	0.0068
Code B	12 (8.4)	54 (6.1)	55 (7.0)	5 (5.3)	6 (6.1)	132 (6.6)	0.8299
Code C	2 (1.4)	36 (4.1)	61 (7.8)	7 (7.4)	1 (1.0)	107 (5.3)	
Code D	4 (2.8)	35 (3.9)	50 (6.4)	2 (2.1)	5 (5.1)	96 (4.8)	
Code E	0 (0.0)	7 (0.8)	4 (0.5)	0 (0.0)	0 (0.0)	11 (0.6)	
Code F	2 (1.4)	3 (0.3)	1 (0.1)	0 (0.0)	0 (0.0)	6 (0.3)	

^aThe Cochran Mantel-Haenszel chi-square test is used to adjust for province, *p*-values <0.05 are considered to be statistically significant.

^bTotal number of potential dwellings out of scope (given as a percentage of total potential dwellings) is broken down by province, as well it is equal to the sum of Code A–F. The percentages of dwellings that are coded as out-of-scope are based on the total number of potential dwellings in the area. Code A—address was a business/duplicate/other (17%), address listed in error (83%). Code B—an inhabitable dwelling unoccupied at the time of the survey, newly constructed dwelling not yet inhabited, a vacant trailer in a commercial trailer park. Code C—summer cottage, ski chalet, or hunting camps. Code D—all participants in the dwelling were >79 years of age. Code E—under construction, institution, or unavailable to participate. Code F—demolished for unknown reasons.

^cChi-square test of independence.

significant association between distance groups and the proportion of locations assigned a *Code A* ($p = 0.0068$) (Table I). A post-collection screening of interviewer notes by Statistics Canada has confirmed that of the total number of *Code A* locations, the vast majority (i.e., 83%) were locations listed in error. In rural areas, there is more uncertainty in developing the address list frame and this can contribute to a higher prevalence of addresses listed in error within 0.55 km of a wind turbine where the population density is lower compared to areas at greater setbacks.²

The remaining 1570 addresses were considered to be valid dwellings, from which 1238 residents agreed to participate in the study (606 males, 632 females). This resulted in a final response rate of 78.9%, which was not statistically different between ON and PEI or by proximity to wind turbines (Table II).

C. Sample characteristics

Table III outlines demographic information for study populations in each 5 dB WTN category. The prevalence of

employment was the only variable that appeared to consistently increase within increasing WTN levels. Household income and education were unrelated to WTN levels. There was no obvious pattern to the changes observed in the other variables that were found to be statistically related to WTN level categories (i.e., age, type of dwelling, property ownership and facade type).

D. Perception of community noise and related variables as a function of WTN level

The prevalence of reporting to be very or extremely (i.e., highly) noise sensitive was statistically similar across all WTN categories ($p = 0.8175$). As expected and as shown in Fig. 1, visibility and audibility of wind turbines increased with increasing WTN levels.

The overall audibility of other noise sources is shown in Table IV. Not shown in Table IV is how often the noise source was spontaneously reported as opposed to being identified following a prompt by the interviewer (see Sec. II).

TABLE II. Sample response rate.

	Distance to nearest wind turbine (km)					Overall	<i>p</i> -value
	≤0.55	(0.55–1]	(1–2]	(2–5]	>5		
Final number of potential participants ^a	95	729	592	76	78	1570	
ON	47	609	503	51	66	1276	
PEI	48	120	89	25	12	294	
Participants n (%)	71 (74.7)	583 (80.0)	463 (78.2)	58 (76.3)	63 (80.8)	1238 (78.9)	0.9971 ^b
ON	34 (72.3)	488 (80.1)	396 (78.7)	42 (82.4)	51 (77.3)	1011 (79.2)	0.7009 ^c
PEI	37 (77.1)	95 (79.2)	67 (75.3)	16 (64.0)	12 (100.0)	227 (77.2)	0.1666 ^c

^aPotential participants from locations established to be valid dwellings (equal to the difference between “Total potential dwellings” and “total number of potential dwellings out-of-scope”; see Table I) used in the derivation of participation rates.

^bThe CMH chi-square test is used to adjust for province, *p*-values <0.05 are considered to be statistically significant.

^cChi-square test of independence.

TABLE III. Sample characteristics.

Variable	WTN (dB)					Overall	CMH <i>p</i> -value ^a
	<25	[25–30)	[30–35)	[35–40)	[40–46]		
n	84 ^b	95 ^b	304 ^b	521 ^b	234 ^b	1238 ^b	
Range of closest turbine (km)	2.32–11.22	1.29–4.47	0.73–2.69	0.44–1.56	0.25–1.05		
Range of BNTS (dB)	35–51	35–51	35–56	35–57	35–61		
BNTS (dB) mean (SD)	43.88(3.43)	44.68 (2.91)	45.21 (3.60)	43.29 (4.11)	41.43 (4.21)		
ON	44.98 (2.88)	44.86 (2.78)	45.54 (3.31)	44.06 (3.86)	42.70 (4.25)		<0.0001 ^c
PEI	41.13 (3.18)	43.00 (3.67)	43.81 (4.38)	38.44 (1.59)	38.05 (1.00)		<0.0001 ^c
Sex <i>n</i> (%)	37 (44.0)	48 (50.5)	150 (49.3)	251 (48.2)	120 (51.3)	606 (49.0)	0.4554
Age mean (SE)	49.75 (1.78)	56.38 (1.37)	52.25 (0.93)	51.26 (0.68)	50.28 (1.03)	51.61 (0.44)	0.0243 ^d
Marital status <i>n</i> (%)							0.2844
Married/Common-law	54 (64.3)	69 (73.4)	199 (65.7)	367 (70.6)	159 (67.9)	848 (68.7)	
Widowed/Separated/Divorced	16 (19.0)	18 (19.1)	61 (20.1)	85 (16.3)	35 (15.0)	215 (17.4)	
Single, never been married	14 (16.7)	7 (7.4)	43 (14.2)	68 (13.1)	40 (17.1)	172 (13.9)	
Employed <i>n</i> (%)	43 (51.8)	47 (49.5)	161 (53.0)	323 (62.0)	148 (63.2)	722 (58.4)	0.0012
Level of education <i>n</i> (%)							0.7221
≤High school	45 (53.6)	52 (54.7)	167 (55.1)	280 (53.7)	134 (57.3)	678 (54.8)	
Trade/Certificate/College	34 (40.5)	37 (38.9)	110 (36.3)	203 (39.0)	85 (36.3)	469 (37.9)	
University	5 (6.0)	6 (6.3)	26 (8.6)	38 (7.3)	15 (6.4)	90 (7.3)	
Income (×\$1000) <i>n</i> (%)							0.8031
<60	39 (51.3)	40 (54.8)	138 (52.5)	214 (49.1)	100 (49.3)	531 (50.5)	
60–100	18 (23.7)	17 (23.3)	72 (27.4)	134 (30.7)	59 (29.1)	300 (28.5)	
≥100	19 (25.0)	16 (21.9)	53 (20.2)	88 (20.2)	44 (21.7)	220 (20.9)	
Detached dwelling <i>n</i> (%) ^e	59 (70.2)	84 (88.4)	267 (87.8)	506 (97.1)	216 (92.3)	1132 (91.4)	
ON ^e	46 (76.7)	77 (89.5)	228 (93.1)	437 (97.1)	154 (90.6)	942 (93.2)	<0.0001 ^f
PEI ^e	13 (54.2)	7 (77.8)	39 (66.1)	69 (97.2)	62 (96.9)	190 (83.7)	<0.0001 ^f
Property ownership <i>n</i> (%)	60 (71.4)	85 (89.5)	250 (82.2)	466 (89.4)	215 (91.9)	1076 (86.9)	
ON	45 (75.0)	78 (90.7)	215 (87.8)	399 (88.7)	157 (92.4)	894 (88.4)	0.0085 ^f
PEI	15 (62.5)	7 (77.8)	35 (59.3)	67 (94.4)	58 (90.6)	182 (80.2)	<0.0001 ^f
Facade type <i>n</i> (%)							0.0137
Fully bricked	20 (23.8)	30 (31.6)	85 (28.0)	138 (26.5)	67 (28.6)	340 (27.5)	
Partially bricked	24 (28.6)	29 (30.5)	62 (20.4)	88 (16.9)	15 (6.4)	218 (17.6)	
No brick/other	40 (47.6)	36 (37.9)	157 (51.6)	295 (56.6)	152 (65.0)	680 (54.9)	

^aThe Cochran Mantel-Haenszel chi-square test is used to adjust for province unless otherwise indicated, *p*-values <0.05 are considered to be statistically significant.

^bTotals may differ due to missing data.

^cAnalysis of variance (ANOVA) model.

^dNon-parametric two-way ANOVA model adjusted for province.

^eNon-detached dwellings included semi/duplex/apartment.

^fChi-square test of independence.

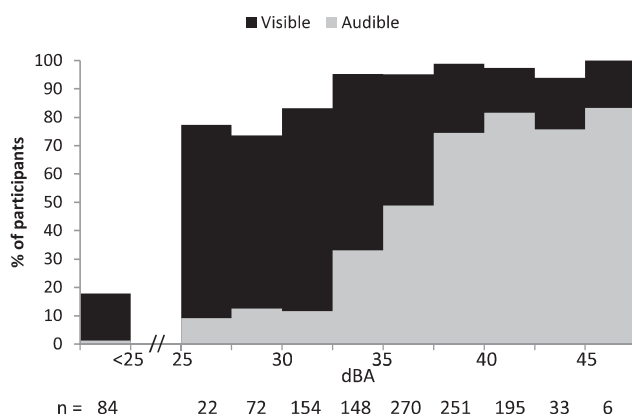


FIG. 1. Proportion of participants as a function of calculated outdoor A-weighted WTN levels. The figure plots the proportion of participants that reported wind turbines were visible from anywhere on their property or audible from inside or outside their homes from the total number of participants with valid responses living in each WTN level category.

Among the participants who reported hearing each specific noise source, the prevalence of spontaneously reporting road traffic, wind turbines, rail and aircraft was 84%, 71%, 66%, and 30%, respectively. A total of 102 participants (8.2%) indicated that there were no audible noise sources around their home. These participants lived in areas where the average WTN levels were 32.4 dB [standard deviation (SD) = 8.3] and the mean distance to the nearest turbine was 1.7 km (SD = 2.0) (data not shown).

Table IV also provides the observed prevalence rates for high (i.e., very or extreme) annoyance toward wind turbine features. The results suggest that there was a tendency for the prevalence of annoyance to increase with increasing WTN levels, with the rise in annoyance becoming evident when WTN levels exceeded 35 dB. The pattern was slightly different for visual annoyance among participants drawn from the ON sample, where there was a noticeable rise in annoyance among participants living in areas where WTN

TABLE IV. Perception of community noise and related variables.

Variable	Wind Turbine Noise (dB)					Overall	CMH <i>p</i> -value ^a
	<25	[25–30)	[30–35)	[35–40)	[40–46]		
<i>n</i>	84 ^b	95 ^b	304 ^b	521 ^b	234 ^b	1238 ^b	
Sensitivity to noise ^c	14 (16.7)	14 (14.7)	35 (11.6)	77 (14.8)	35 (15.1)	175 (14.2)	0.8175
Audible perception of transportation noise sources <i>n</i> (%)							
Road traffic	62 (73.8)	60 (63.2)	259 (85.2)	443 (85.0)	192 (82.1)	1016 (82.1)	0.0013
Aircraft	43 (51.2)	33 (34.7)	146 (48.0)	263 (50.5)	124 (53.0)	609 (49.2)	
Aircraft (ON)	32 (53.3)	31 (36.0)	120 (49.0)	220 (48.9)	82 (48.2)	485 (48.0)	0.2114 ^d
Aircraft (PEI)	11 (45.8)	2 (22.2)	26 (44.1)	43 (60.6)	42 (65.6)	124 (54.6)	0.0214 ^d
Rail ^e	30 (50.0)	27 (31.4)	73 (29.8)	90 (20.0)	7 (4.1)	227 (22.5)	<0.0001 ^d
Perception of wind turbines <i>n</i> (%)							
See wind turbines	15 (17.9)	70 (74.5)	269 (89.1)	505 (96.9)	227 (97.0)	1086 (87.9)	<0.0001
Hear wind turbines	1 (1.2)	11 (11.6)	67 (22.0)	319 (61.2)	189 (80.8)	587 (47.4)	<0.0001
Number of years hearing the WT <i>n</i> (%)							
Do not hear	83 (98.8)	84 (88.4)	237 (78.0)	202 (39.0)	45 (19.3)	651 (52.8)	<0.0001
<1 year	1 (1.2)	2 (2.1)	15 (4.9)	31 (6.0)	12 (5.2)	61 (4.9)	
≥1 year	0 (0.0)	9 (9.5)	52 (17.1)	285 (55.0)	176 (75.5)	522 (42.3)	
Notice vibrations/rattles indoors during WTN operations	0 (0.0)	3 (3.2)	8 (2.6)	28 (5.4)	19 (8.2)	58 (4.7)	0.0004
Highly concerned about physical safety	1 (1.2)	3 (3.2)	5 (1.6)	46 (8.9)	22 (9.6)	77 (6.3)	<0.0001
Formal complaint ^f	2 (2.4)	2 (2.1)	3 (1.0)	22 (4.2)	6 (2.6)	35 (2.8)	0.2578
Reporting a high (very or extreme) level of annoyance to wind turbine features, <i>n</i> (%)							
Noise	0 (0.0)	2 (2.1)	3 (1.0)	52 (10.0)	32 (13.7)	89 (7.2)	<0.0001
Visual	2 (2.4)	15 (16.0)	17 (5.6)	81 (15.5)	44 (18.9)	159 (12.9)	
Visual (ON)	2 (3.3)	15 (17.6)	17 (7.0)	76 (16.9)	36 (21.2)	146 (14.5)	<0.0001 ^d
Visual (PEI)	0 (0.0)	0 (0.0)	0 (0.0)	5 (7.0)	8 (12.7)	13 (5.8)	0.0268 ^d
Blinking lights	2 (2.4)	8 (8.5)	17 (5.6)	61 (11.7)	34 (14.6)	122 (9.9)	<0.0001
Shadow flicker	0 (0.0)	3 (3.2)	6 (2.0)	51 (9.8)	36 (15.5)	96 (7.8)	<0.0001
Vibrations/rattles	0 (0.0)	1 (1.1)	2 (0.7)	9 (1.7)	7 (3.0)	19 (1.5)	0.0198
Reporting a high (very or extreme) level of WTN annoyance by time of day, <i>n</i> (%)							
Morning	0 (0.0)	0 (0.0)	1 (0.3)	28 (5.4)	10 (4.3)	39 (3.2)	
Afternoon	0 (0.0)	0 (0.0)	1 (0.3)	26 (5.0)	14 (6.1)	41 (3.3)	
Evening	0 (0.0)	1 (1.1)	2 (0.7)	48 (9.2)	26 (11.3)	77 (6.3)	
Nighttime	0 (0.0)	1 (1.1)	2 (0.7)	48 (9.2)	26 (11.3)	77 (6.3)	
Reporting a high (very or extreme) level of WTN annoyance by season, <i>n</i> (%)							
Spring	0 (0.0)	1 (1.1)	1 (0.3)	45 (8.6)	22 (9.6)	69 (5.6)	
Fall	0 (0.0)	1 (1.1)	2 (0.7)	42 (8.1)	22 (9.6)	67 (5.5)	
Summer	0 (0.0)	2 (2.1)	4 (1.3)	50 (9.6)	31 (13.7)	87 (7.1)	
Winter	0 (0.0)	1 (1.1)	1 (0.3)	38 (7.3)	21 (9.2)	61 (5.0)	
Closing bedroom window to block outside noise during sleep <i>n</i> (%)							
	26 (31.3)	30 (31.6)	87 (28.7)	178 (34.3)	68 (29.2)	389 (31.6)	0.8106
Source identified as cause for closing window ^g <i>n</i> (%)							
Road traffic	15 (18.1)	13 (13.7)	47 (15.5)	77 (14.8)	24 (10.3)	176 (14.3)	0.1161
Rail	6 (10.2)	1 (1.2)	7 (2.9)	10 (2.2)	0 (0.0)	24 (2.4)	0.0013
Wind turbines	0 (0.0)	2 (2.1)	6 (2.0)	79 (15.2)	50 (21.6)	137 (11.1)	<0.0001
Other	12 (14.5)	20 (21.1)	54 (17.8)	65 (12.5)	14 (6.0)	165 (13.4)	0.0002
Perceived benefit from having wind turbines in the area <i>n</i> (%)							
Personal	3 (3.9)	2 (2.2)	11 (4.0)	47 (9.2)	47 (20.3)	110 (9.3)	
ON	0 (0.0)	1 (1.2)	6 (2.7)	44 (10.0)	36 (21.4)	87 (9.0)	<0.0001 ^d
PEI	3 (15.8)	1 (11.1)	5 (9.8)	3 (4.3)	11 (17.2)	23 (10.8)	0.1700 ^d
Community	20 (29.0)	14 (20.9)	62 (36.0)	136 (35.1)	79 (40.7)	311 (35.0)	0.0135

^aThe Cochran Mantel-Haenszel chi-square test is used to adjust for provinces unless otherwise indicated, *p*-values <0.05 are considered to be statistically significant.

^bColumns may not add to total due to missing data.

^cSensitivity to noise reflects the prevalence of participants that reported to be either very or extremely (i.e., highly) noise sensitive in general.

^dChi-square test of independence.

^eNobody reported hearing rail noise in PEI as there is no rail activity in PEI, therefore the percent is given as a percentage of ON participants only.

^fRefers to anyone in the participant's household ever lodging a formal complaint (including signing a petition) regarding noise from wind turbines.

^gReasons for closing bedroom windows due to aircraft noise was suppressed due to low cell counts (i.e., *n* <5 overall).

levels were between [25 and 30) dB. The prevalence of *household* complaints concerning wind turbines, which could include signing a petition regarding noise from wind turbines, was 2.8% overall and unrelated to WTN levels ($p=0.2578$). However, complaints were found to be greater among the PEI sample (13/224 = 5.8%), compared to ON (22/1010 = 2.2%) ($p=0.0050$).

Other notable observations from Table IV include the finding that the number of participants who self-reported to personally benefit in any way (e.g., rent, payments or indirect benefits such as community improvements) from having turbines in their area, was not equally distributed among provinces. In ON, reporting such benefits was significantly related to WTN categories ($p<0.0001$) and there was a gradual increase from the lowest WTN category (<25 dB: 0.0%) to the loudest WTN category ([40–46] dB: 21.4%), whereas in PEI benefits were statistically evenly distributed across the sample ($p=0.1700$).

Closing bedroom windows to block outside noise during sleep was equally prevalent across all WTN categories ($p=0.8106$); however, identifying WTs as the reason for closing the window was found to be related to WTN levels ($p<0.0001$). In the two loudest categories, [35–40) dB and [40–46] dB, 15.2% and 21.6% of participants identified WTN as the reason for closing bedroom windows, respectively, compared to $\leq 2.1\%$ in the other WTN categories (Table IV).

Figure 2 plots the fitted percentage highly annoyed by WTN category overall and for ON and PEI separately. WTN annoyance was observed to significantly increase when WTN levels exceeded ≥ 35 dB compared with lower exposure categories ($p<0.009$, in all cases). Overall, observed prevalences of noise annoyance increased from less than 2.1% in the three lowest WTN level categories to 10% in areas where WTN levels were between [35 and 40) dB and

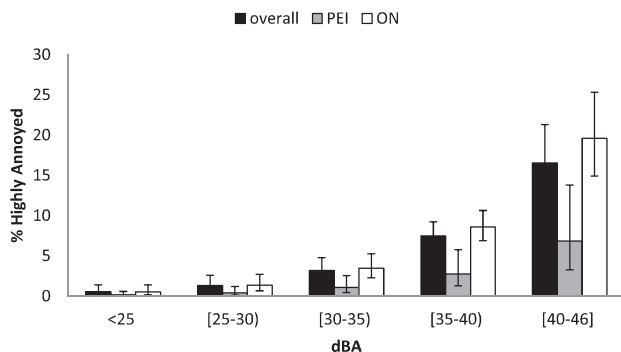


FIG. 2. Prevalence of high annoyance with wind turbine noise overall and by province as a function of calculated outdoor wind turbine noise levels. This illustrates the percentage of participants that reported to be either very or extremely (i.e., highly) bothered, disturbed or annoyed by WTN while at home over the last year. At home refers to either inside or outside the dwelling. Results are shown for participants from southwestern ON, PEI, and as an overall average. Fitted data are plotted along with their 95% confidence intervals. Results are shown as a function of calculated outdoor A-weighted WTN levels at the dwelling (dBA). WTN annoyance was observed to significantly increase when WTN levels exceeded ≥ 35 dB compared with lower exposure categories ($p<0.009$, in all cases). Additionally, annoyance was observed to be significantly higher in the southwestern ON sample compared to the PEI sample ($p=0.0015$), regardless of WTN level.

13.7% between [40 and 46] dB. Additionally, annoyance was observed to be significantly higher in the ON sample compared to the PEI sample. Across all WTN categories, the odds of being highly annoyed by WTN were 3.29 times greater in ON compared to PEI [95% confidence interval (CI), 1.47–8.68, $p=0.0015$]; however, the difference was most pronounced above 35 dB.

In addition to asking participants how annoyed they were toward WTN in general (i.e., without reference to their particular location), other questions were designed to assess annoyance as a function of location (i.e., indoors, outdoors). As shown in Fig. 3, the prevalence of high annoyance was significantly higher outdoors.

The prevalence of annoyance by time of day and season is provided in Table IV. For WTN levels below 30 dB, the prevalence of high annoyance was very low ($<1.2\%$) and similar for all times of day. Starting at 30 dB, the percentage highly annoyed during the evening and nighttime were significantly higher than the morning and afternoon; however this difference was most pronounced at WTN levels ≥ 35 dB. For WTN levels below 30 dB, the prevalence of high annoyance was very low ($<2.2\%$) and similar for all seasons. At WTN levels ≥ 35 dB, the prevalence of high annoyance during the summer was higher compared to all other seasons.

Noise annoyance toward road, aircraft and rail noise was also assessed in the questionnaire. It was of interest to determine how annoyance to these sources compared to WTN annoyance. In areas where WTN levels were <35 dB the greatest source of noise annoyance was road traffic. In WTN categories ≥ 35 dB, annoyance toward WTN exceeded all other sources ($p<0.0003$, in all cases) (see Fig. 4).

E. Self-reported health conditions and use of medication

Table V shows that subjectively reported sleep disturbance from any source while sleeping at home over the last year, in addition to a multitude of health effects, were found

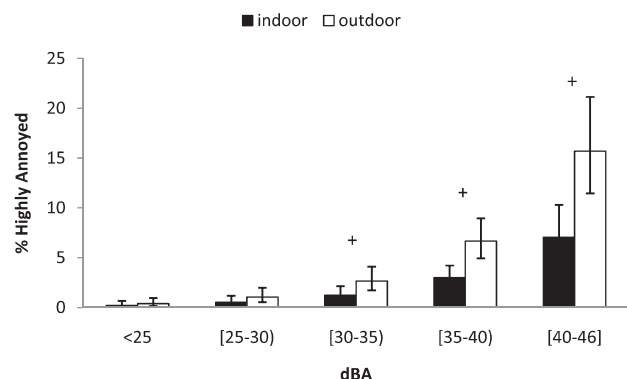


FIG. 3. Prevalence of high annoyance with wind turbine noise by location as a function of calculated outdoor wind turbine noise levels. Participants were asked to think about the last year or so and indicate how bothered, disturbed or annoyed they were by WTN while at home. The percentage of participants reporting to be either very or extremely (i.e., highly) bothered, disturbed or annoyed is shown as a function of calculated outdoor A-weighted WTN levels at the dwelling (dBA). Figure 3 presents the fitted results by location (i.e., indoors and outdoors) along with their 95% confidence intervals. + Indoor significantly different from outdoor ($p<0.001$).

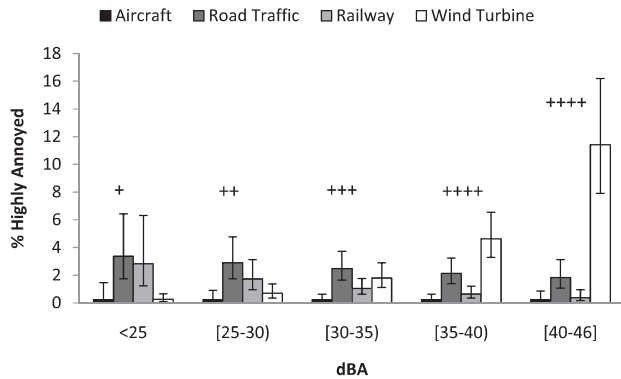


FIG. 4. Prevalence of high annoyance toward different noise sources as a function of calculated outdoor wind turbine noise levels. Illustrates the percentage of participants that reported to be either very or extremely (i.e., highly) bothered, disturbed or annoyed by road traffic, aircraft, rail and wind turbine noise (WTN) while at home over the last year. At home refers to either inside or outside the dwelling. Results represent fitted data along with their 95% confidence intervals and are shown as a function of calculated outdoor A-weighted WTN levels at the dwelling (dBA). +WTN significantly different from road traffic and rail noise ($p < 0.001$); ++WTN significantly different from road traffic ($p < 0.001$); +++WTN significantly different from aircraft noise ($p < 0.001$); ++++WTN significantly different from road traffic, rail, and aircraft noise ($p < 0.0003$).

to be unrelated to WTN levels. Similarly, medication use for high blood pressure, anxiety or depression was also found to be unrelated to WTN levels. Although sleep medication use was significantly related to WTN levels ($p = 0.0083$), the prevalence was *higher* among the two lowest WTN categories {<25 dB and [25–30] dB} (see Table V).

IV. DISCUSSION

The prevalence of self-reporting to be either “very” or “extremely” (i.e., highly) annoyed with several wind turbine features increased significantly with increasing A-weighted WTN levels. When classified by the prevalence of reported annoyance overall, and in areas where WTN levels exceeded 35 dB, annoyance was highest for visual aspects of wind turbines, followed by blinking lights, shadow flicker, noise and vibrations. Consistent with Pedersen *et al.* (2009), the increase in WTN annoyance was clearly evident when moving from [30–35] dB to [35–40] dB, where the prevalence of WTN annoyance increased from 1% to 10%. This continued to increase to 13.7% for areas where WTN levels were [40–46] dB. The prevalence of WTN annoyance was higher outdoors, during the summer, and during evening and nighttime hours. Pedersen *et al.* (2009) also found that annoyance with WTN was greater outdoors compared to indoors.

Despite a similar pattern of response between the ON and PEI samples, the self-reported WTN annoyance was 3.29 times greater in ON, a difference that was most pronounced at the two highest WTN categories. This difference is in contrast to the prevalence of *household* complaints related to wind turbines. Even though the overall prevalence of such complaints was low (i.e., 2.8%), complaints were more likely in PEI (5.8%) compared to ON (2.2%). The reasons for this difference despite greater reported annoyance in ON are unclear. Research has shown that there are several contingencies that must be met before someone that is highly

annoyed will complain (Michaud *et al.*, 2008). Such contingencies include knowing who to complain to, how to file a complaint and holding the belief that the complaint will result in positive change. The fact that the prevalence of complaints regarding wind turbines was unrelated to WTN levels is another indication that complaints do not always correlate well with changes in noise exposure (Fidell *et al.*, 1991). The motives underlying household complaints were not assessed in the present study, but the disparity found with annoyance could also be related to the wording used in the questionnaire. The prevalence of complaints was the one question where the respondent answered on behalf of the entire household.

More participants reported that they were highly annoyed by the visual aspects of wind turbines than by any other feature, even at higher WTN levels. Similar to WTN annoyance, the overall prevalence of annoyance with the visual impact of wind turbines was more than twice as high in the ON sample, and more prevalent across the exposure categories when compared to PEI. In the PEI sample, no participants reported visual annoyance in areas where WTN levels were below 35 dB. This is in contrast to a clear intensification in visual annoyance among the ON sample in areas where WTN levels were [25–30] dB. Exploring the variables that may underscore provincial differences was not within the scope of the current study. The questionnaire was not designed to probe underlying factors that may explain observed provincial differences; however, reported personal benefit from having wind turbines in the area was found to be different between the ON and PEI samples (Table IV).

Shepherd *et al.* (2011) assessed annoyance in response to WTN, but not in a manner that would permit comparisons with the Swedish (Pedersen and Persson Waye, 2004, 2007), Dutch (Janssen *et al.*, 2011; Pedersen *et al.*, 2009) or the current study. Shepherd *et al.* (2011) reported that 59% of participants living within 2 km of a wind turbine installation spontaneously identified wind turbines as an annoying noise source, with a mean annoyance rating of 4.59 (SD, 0.65) when the 5 category adjectival scale was analyzed as a numerical scale from 0 to 5. No exposure-response relationship could be assessed because the authors did not provide an analysis based on precise distance or as a function of WTN levels, which they reported to be between 20 and 50 dB among participants living within 2 km of a wind turbine. This encompasses the entire WTN level range in the CNHS. As such, the only tentative comparison that can be made between the current study and the Shepherd *et al.* (2011) study would be that the observed prevalence of highly annoyed (i.e., “very” or “extremely”) within 2 km of the nearest wind turbine was 7.0%. These data are not shown because the focus of the current study was on WTN levels and an analysis based solely on distance to the nearest turbine does not adequately account for WTN levels at any given dwelling. WTN is a more sensitive measure of exposure level because, in addition to the distance to the turbine, it accounts for topography, presence of large bodies of water, wind turbine characteristics, the layout of the wind farm and the number of wind turbines at any given distance.

TABLE V. Sample profile of health conditions.

Variable <i>n</i> (%)	Wind turbine noise (dB)					Overall	CMH ^a <i>p</i> -value
	<25	[25–30)	[30–35)	[35–40)	[40–46]		
<i>n</i>	84 ^b	95 ^b	304 ^b	521 ^b	234 ^b	1238 ^b	
Health worse vs last year ^c	17 (20.2)	12 (12.6)	46 (15.1)	90 (17.3)	51 (21.8)	216 (17.5)	0.1724
Migraines	18 (21.4)	24 (25.3)	56 (18.4)	134 (25.8)	57 (24.4)	289 (23.4)	0.2308
Dizziness	19 (22.6)	16 (16.8)	65 (21.4)	114 (21.9)	59 (25.2)	273 (22.1)	0.2575
Tinnitus	21 (25.0)	18 (18.9)	71 (23.4)	129 (24.8)	54 (23.2)	293 (23.7)	0.7352
Chronic pain	20 (23.8)	23 (24.2)	75 (24.8)	118 (22.6)	57 (24.5)	293 (23.7)	0.8999
Asthma	8 (9.5)	12 (12.6)	22 (7.2)	43 (8.3)	16 (6.8)	101 (8.2)	0.2436
Arthritis	23 (27.4)	38 (40.0)	98 (32.2)	175 (33.7)	68 (29.1)	402 (32.5)	0.6397
High blood pressure (BP)	24 (28.6)	36 (37.9)	81 (26.8)	166 (32.0)	65 (27.8)	372 (30.2)	0.7385
Medication for high BP	26 (31.3)	34 (35.8)	84 (27.6)	163 (31.3)	63 (27.0)	370 (29.9)	0.4250
Family history of high BP	44 (52.4)	49 (53.8)	132 (45.5)	254 (50.6)	121 (53.8)	600 (50.3)	0.6015
Chronic bronchitis/emphysema/COPD	3 (3.6)	10 (10.8)	17 (5.6)	27 (5.2)	14 (6.0)	71 (5.7)	0.7676
Diabetes	7 (8.3)	8 (8.4)	33 (10.9)	46 (8.8)	19 (8.2)	113 (9.1)	0.6890
Heart disease	8 (9.5)	7 (7.4)	31 (10.2)	32 (6.1)	17 (7.3)	95 (7.7)	0.2110
Highly sleep disturbed ^d	13 (15.7)	11 (11.6)	41 (13.5)	75 (14.5)	24 (10.3)	164 (13.3)	0.4300
Diagnosed sleep disorder	13 (15.5)	10 (10.5)	27 (8.9)	44 (8.4)	25 (10.7)	119 (9.6)	0.3102
Sleep medication	16 (19.0)	18 (18.9)	39 (12.8)	46 (8.8)	29 (12.4)	148 (12.0)	0.0083
Restless leg syndrome	7 (8.3)	16 (16.8)	37 (12.2)	81 (15.5)	33 (14.1)	174 (14.1)	
Restless leg syndrome (ON)	4 (6.7)	15 (17.4)	27 (11.0)	78 (17.3)	28 (16.5)	152 (15.0)	0.0629 ^e
Restless leg syndrome (PEI)	3 (12.5)	1 (11.1)	10 (16.9)	3 (4.2)	5 (7.8)	22 (9.7)	0.1628 ^e
Medication anxiety or depression	11 (13.1)	14 (14.7)	35 (11.5)	59 (11.3)	23 (9.8)	142 (11.5)	0.2470
QoL past month ^f							
Poor	9 (10.8)	3 (3.2)	21 (6.9)	29 (5.6)	20 (8.6)	82 (6.6)	0.9814
Good	74 (89.2)	92 (96.8)	283 (93.1)	492 (94.4)	213 (91.4)	1154 (93.4)	
Satisfaction with health ^f							
Dissatisfied	13 (15.5)	13 (13.7)	49 (16.1)	66 (12.7)	36 (15.4)	177 (14.3)	0.7262
Satisfied	71 (84.5)	82 (86.3)	255 (83.9)	455 (87.3)	198 (84.6)	1061 (85.7)	

^aThe Cochran Mantel-Haenszel chi-square test is used to adjust for provinces unless otherwise indicated, *p*-values <0.05 are considered to be statistically significant.

^bColumns may not add to total due to missing data.

^cWorse consists of the two ratings: “*Somewhat worse now*” and “*Much worse now*.”

^dHigh sleep disturbance consists of the two ratings: “*very*” and “*extremely*” sleep disturbed.

^eChi-square test of independence.

^fQuality of Life (QoL) and Satisfaction with Health were assessed with the two stand-alone questions on the WHOQOL-BREF. Reporting “*poor*” overall QoL reflects a response of “*poor*” or “*very poor*,” and “*good*” reflects a response of “*neither poor nor good*,” “*good*,” or “*very good*.” Reporting “*dissatisfied*” overall Satisfaction with Health reflects a response of “*very dissatisfied*” or “*dissatisfied*,” and “*satisfied*” reflects a response of “*neither satisfied nor dissatisfied*,” “*satisfied*,” or “*very satisfied*.” A detailed presentation of the results related to QoL is presented by Feder *et al.* (2015).

It was important to assess the extent to which the sample was homogeneously distributed, with respect to demographics and community noise exposure. The reason for this is that the validity of the exposure-response relationship is strengthened when the primary distinction across the sample is the exposure of interest; in this case, WTN levels. Demographically, some minor differences were found with respect to age, employment, type of dwelling and dwelling ownership; however, with the possible exception of employment, these factors showed no obvious pattern with WTN levels and none were strong enough to exert an influence on the overall results. At the design stage, there was some concern that selecting participants up to 10 km might result in an unequal exposure to community noise sources other than WTN. This may have an influence on the underlying response to WTN. Limited data availability did not permit the modeling of sound pressure levels from other noise sources as originally intended, however it was possible to model BNTS levels. Although Fields (1993)

concluded that background sound levels generally do not influence community annoyance, his review did not include wind turbines as a noise source and in the current study BNTS levels were calculated to be lower in areas where WTN levels were higher. Lower BNTS could contribute to a greater expectation of peace and quiet. Therefore, a limitation in the CHNS may be that the expectation of peace and quiet was not explicitly evaluated. This factor may influence the association between long-term sound levels and annoyance by an equivalent of up to 10 dB (ANSI, 1996; ISO, 2003b). The influence this factor may have had on the exposure-response relationship found specifically between WTN levels and the prevalence of reporting high annoyance with WTN in the CHNS is discussed in Michaud *et al.* (2016a).

In the absence of modeling, the audibility of road traffic, aircraft and rail noise provided a crude indication of exposure to these sources. In general, road traffic noise exposure was heard by the vast majority of the sample (82.1%).

Aircraft noise was uniformly audible in ON by about half the sample; in PEI however, hearing aircraft was more common in the higher WTN exposure categories (i.e., above 35 dB) where between 61% and 66% of the respondents indicated that they could hear aircraft. Future research may benefit from assessing the extent to which audible aircraft noise may have influenced the annoyance with WTN in PEI. Only when WTN levels were [40–46] dB was the audibility of wind turbines comparable to road traffic (i.e., both sources were audible by approximately 81% of participants). For these community noise sources, participants were asked how bothered, disturbed, or annoyed they were while at home over the last year or so. The findings are of interest in light of the source comparisons made by Pedersen *et al.* (2009) and Janssen *et al.* (2011), which placed WTN annoyance above all transportation noise sources when comparing them at equal sound levels. In the current study, the overall annoyance toward WTN (7.2%) was found to be higher in comparison to road (3.8%), aircraft (0.4%), and rail in ON (1.9%). Source comparisons need to be made with caution because the observed source differences in annoyance may result from an *actual* difference in sound pressure levels at the dwellings in this study. Modeling the sound levels from transportation noise sources in the current study would allow a more direct comparison between these sources and WTN annoyance at equivalent sound exposures. Another approach is to assess the relative community tolerance level of WTN with that reported for road and aircraft noise studies. This analysis indicates that there is a lower community tolerance level for WTN when compared to both road and aircraft noise at equivalent sound levels (Michaud *et al.*, 2016a).

The list of symptoms that are claimed to be caused by exposure to WTN is considerable (Chapman, 2013), but there is a lack of robust evidence from epidemiological studies to support these associations (Council of Canadian Academies, 2015; Knopper *et al.*, 2014; MassDEP MDPH, 2012; McCunney *et al.*, 2014; Merlin *et al.*, 2014). The results from the current study did not show any statistically significant increase in the self-reported prevalence of chronic pain, asthma, arthritis, high blood pressure, bronchitis, emphysema, chronic obstructive pulmonary disease (COPD), diabetes, heart disease, migraines/headaches, dizziness, or tinnitus in relation to WTN exposure up to 46 dB. In other words, individuals with these conditions were equally distributed among WTN exposure categories. Similarly, the prevalence of reporting to be highly sleep disturbed (for any reason) and being diagnosed with a sleep disorder were unrelated to WTN exposure. These self-reported findings are consistent with the conclusions reached following an analysis of objectively measured sleep among a subsample of the current study participants (Michaud *et al.*, 2016b). Medication use (for anxiety, depression, or high blood pressure) was unrelated to WTN levels. It is notable that the observed prevalence for many of the aforementioned health effects are remarkably consistent with large-scale national population-based studies (Innes *et al.*, 2011; Kroenke and Price, 1993; Morin *et al.*, 2011; O'Brien *et al.*, 1994; Shargorodsky *et al.*, 2010).

V. CONCLUDING REMARKS

Study findings indicate that annoyance toward all features related to wind turbines, including noise, vibrations, shadow flicker, aircraft warning lights and the visual impact, increased as WTN levels increased. The observed increase in annoyance tended to occur when WTN levels exceeded 35 dB and were undiminished between 40 and 46 dB. Beyond annoyance, the current study does not support an association between exposures to WTN up to 46 dB and the evaluated health-related endpoints. In some cases, there were clear differences between the southwestern ON and PEI participants; however, exploring the basis behind these differences fell outside the study scope and objectives. The CNHS supported the development of a model for community annoyance toward WTN, which identifies some of the factors that may influence this response (Michaud *et al.*, 2016a). At the very least, the observed differences reported between ON and PEI in the current study demonstrates that even at comparable WTN levels, the community response to wind turbines is not necessarily uniform across Canada. Future studies designed to intentionally explore the factors that underscore such differences may be beneficial.

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¹See supplementary material at <http://dx.doi.org/10.1121/1.4942391> for the univariate analysis results.

²Locations coded as out-of-scope were originally assigned the following categories: *Demolished for unknown reasons, vacant for unknown reasons, unoccupied, seasonal, >79 years of age, and other* (Michaud, 2015b; Health Canada, 2014). In an effort to address feedback and provide further clarification, the categories used to define out-of-scope locations were further defined elsewhere (Michaud, 2015a) with additional details provided in the current paper. Specifically, locations that were determined to be “demolished for unknown reasons” are presented separately in Table I as Code F. Locations that were originally defined as “unoccupied for unknown reasons” are now more precisely defined under Code B (i.e., inhabitable dwelling not occupied at time of survey, newly constructed dwelling, or unoccupied trailer in vacant trailer park). Furthermore, it was confirmed that 6 dwellings originally listed under Code B (Michaud, 2015a) were in fact GPS coordinates listed in error and have therefore been reassigned to Code A.

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Wind Turbines and Health

A Critical Review of the Scientific Literature

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Objective: This review examines the literature related to health effects of wind turbines. **Methods:** We reviewed literature related to sound measurements near turbines, epidemiological and experimental studies, and factors associated with annoyance. **Results:** (1) Infrasound sound near wind turbines does not exceed audibility thresholds. (2) Epidemiological studies have shown associations between living near wind turbines and annoyance. (3) Infrasound and low-frequency sound do not present unique health risks. (4) Annoyance seems more strongly related to individual characteristics than noise from turbines. **Discussion:** Further areas of inquiry include enhanced noise characterization, analysis of predicted noise values contrasted with measured levels postinstallation, longitudinal assessments of health pre- and postinstallation, experimental studies in which subjects are “blinded” to the presence or absence of infrasound, and enhanced measurement techniques to evaluate annoyance.

The development of renewable energy, including wind, solar, and biomass, has been accompanied by attention to potential environmental health risks. Some people who live in proximity of wind turbines have raised health-related concerns about noise from their operations. The issue of wind turbines and human health has also now been explored and considered in a number of policy, regulatory, and legal proceedings.

This review is intended to assess the peer-reviewed literature regarding evaluations of potential health effects among people living in the vicinity of wind turbines. It will include analysis and commentary of the scientific evidence regarding potential links to health effects, such as stress, annoyance, and sleep disturbance, among others, that have been raised in association with living in proximity to wind turbines. Efforts will also be directed to specific compo-

nents of noise associated with wind turbines such as infrasound and low-frequency sound and their potential health effects.

We will attempt to address the following questions regarding wind turbines and health:

1. Is there sufficient scientific evidence to conclude that wind turbines adversely affect human health? If so, what are the circumstances associated with such effects and how might they be prevented?
2. Is there sufficient scientific evidence to conclude that psychological stress, annoyance, and sleep disturbance can occur as a result of living in proximity to wind turbines? Do these effects lead to adverse health effects? If so, what are the circumstances associated with such effects and how might they be prevented?
3. Is there evidence to suggest that specific aspects of wind turbine sound such as infrasound and low-frequency sound have unique potential health effects not associated with other sources of environmental noise?

The coauthors represent professional experience and training in occupational and environmental medicine, acoustics, epidemiology, otolaryngology, psychology, and public health.

Earlier reviews of wind turbines and potential health implications have been published in the peer-reviewed literature¹⁻⁵ by state and provincial governments (Massachusetts, 2012, and Australia, 2014, among others) and trade associations.⁶

This review is divided into the following five sections:

1. Noise: The type associated with wind turbine operations, how it is measured, and noise measurements associated with wind turbines.
2. Epidemiological studies of populations living in the vicinity of wind turbines.
3. Potential otolaryngology implications of exposure to wind turbine sound.
4. Potential psychological issues associated with responses to wind turbine operations and a discussion of the health implications of continuous annoyance.
5. Governmental and nongovernmental reports that have addressed wind turbine operations.

METHODS

To identify published research related to wind turbines and health, the following activities were undertaken:

1. We attempted to identify and assess peer-reviewed literature related to wind turbines and health by conducting a review of PubMed, the National Library of Medicine's database that indexes more than 5500 peer-reviewed health and scientific journals with more than 21 million citations. Search terms were wind turbines, wind turbines and health effects, infrasound, infrasound and health effects, low-frequency sound, wind turbine syndrome, wind turbines and annoyance, and wind turbines and sleep disturbances.
2. We conducted a Google search for nongovernmental organization and government agency reports related to wind turbines and environmental noise exposure (see Supplemental Digital Content Appendix 1, available at: <http://links.lww.com/JOM/A179>).

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3. After identifying articles obtained via these searches, they were categorized into five main areas that are noted below (section D) and referred to the respective authors of each section for their review and analysis. Each author then conducted their own additional review, including a survey of pertinent references cited in the identified articles. Articles were selected for review and commentary if they addressed exposure and a health effect—whether epidemiological or experimental—or were primary exposure assessments.
4. Identified studies were categorized into the following areas:
 - I. Sound, its components, and field measurements conducted in the vicinity of wind turbines;
 - II. Epidemiology;
 - III. Effects of sound components such as infrasound and low-frequency sound on health;
 - IV. Psychological factors associated with responses to wind turbines;
 - V. Governmental and nongovernmental reports.
5. The authors are aware of reports and commentaries that are not in the scientific or medical peer-reviewed literature that have raised concern about potential health implications for people who live near wind turbines. These reports describe relatively common symptoms with numerous causes, including headache, tinnitus, and sleep disturbance. Because of the difficulties in comprehensively identifying non-peer-reviewed reports such as these, and the inherent uncertainty in the quality of non-peer-reviewed reports, they were not included in our analysis, aside from some books and government reports that are readily identified. A similar approach of excluding non-peer-reviewed literature in scientific reviews is used by the World Health Organization (WHO)'s International Agency for Research on Cancer (IARC) in its deliberations regarding identification of human carcinogens⁷. International Agency for Research on Cancer, however, critically evaluates exposure assessments not published in the peer-reviewed literature, if conducted with appropriate quality and in accordance with international standards and guidelines. International Agency for Research on Cancer uses this policy for exposure assessments because many of these efforts, although containing valuable data in evaluating health risks associated with an exposure to a hazard, are not routinely published. The USA National Toxicology Program also limits its critical analysis of potential carcinogens to the peer-reviewed literature. In our view, because of the critical effect of scientific studies on public policy, it is imperative that peer-reviewed literature be used as the basis. Thus, in this review, only peer review studies are considered, aside from exposure-related assessments.

RESULTS

Characteristics of Wind Turbine Sound

In this portion of the review, we evaluate studies in which sound near wind turbines has been measured, discuss the use of modeled sound levels in dose-response studies, and review literature on measurements of low-frequency sound and infrasound from operating wind turbines. We evaluate sound levels measured in areas, where symptoms have been reported in the context of proximity to wind turbines. We address methodologies used to measure wind turbine noise and low-frequency sound. We also address characteristics of wind turbine sound, sound levels measured near existing wind turbines, and the response of humans to different levels and characteristics of wind turbine sound. Special attention is given to challenges and methods of measuring wind turbine noise, as well as low-frequency sound (20 to 200 Hz) and Infrasound (less than 20 Hz).

Wind turbines sound is made up from both moving components and interactions with nonmoving components of the wind turbine (Fig. 1). For example, mechanical components in the nacelle can generate noise and vibration, which can be radiated from the structure, including the tower. The blade has several components that create aerodynamic noise, such as the blade leading edge, which contacts the wind first in its rotation, the trailing edge, and the blade tip. Blade/tower interactions, especially where the blades are downwind of the tower, can create infrasound and low-frequency sound. This tower orientation is no longer used in large wind turbines.⁸

Sound Level and Frequency

Sound is primarily characterized by its pitch or frequency as measured in Hertz (Hz) and its level as measured in decibels (dB). The frequency of a sound is the number of times in a second that the medium through which the sound energy is traveling (ie, air, in the case of wind turbine sound) goes through a compression cycle. Normal human hearing is generally in the range of 20 to 20,000 Hz. As an example, an 88-key piano ranges from about 27.5 to 4186 Hz with middle C at 261.6 Hz. As in music, ranges of frequencies can be described in "octaves," where the center of each octave band has a frequency of twice that of the previous octave band (this is also written as a "1/1 octave band"). Smaller subdivisions can be used such as 1/3 and 1/12 octaves. The level of sound pressure for each frequency band is reported in decibel units.

To represent the overall sound level in a single value, the levels from each frequency band are logarithmically added. Because human hearing is relatively insensitive to very low- and high-frequency sounds, frequency-specific adjustments or weightings are added to the unweighted sound levels before summing to the overall level. The most common of these is the A-weighting, which simulates the human response to various frequencies at relatively low levels (40 phon or about 50 dB). Examples of A-weighted sound levels are shown in Fig. 2.

Other weightings are cited in the literature, such as the C-weighting, which is relatively flat at the audible spectrum; G-weighting, which simulates human perception and annoyance of sound that lie wholly or partly in the range from 1 to 20 Hz; and Z-weighting, which does not apply any weighting. The weighting of the sound is indicated after the dB label. For example, an A-weighted sound level of 45 dB would be written as 45 dBA or 45 dB(A). If no label is shown, the weighting is either implied or unweighted.

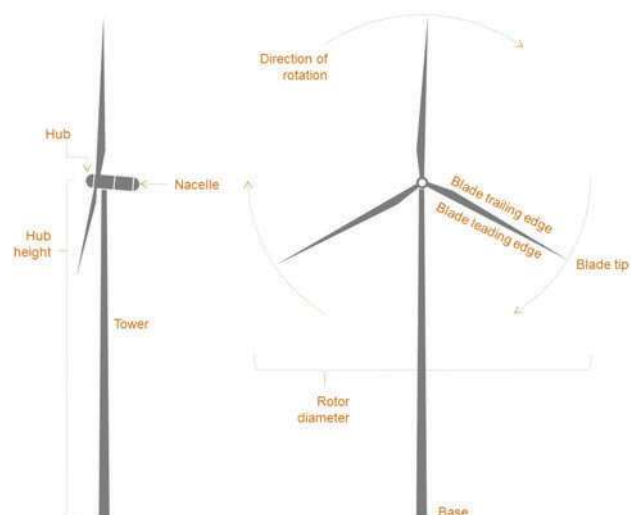


FIGURE 1 . Schematic of a modern day wind turbine.



FIGURE 2. Sample A-weighted sound pressure levels.

Beyond the overall level, wind turbine noise may be amplitude modulated or have tonal components. Amplitude modulation is a regular cycling in the level of pure tone or broadband sound. A typical three-bladed wind turbine operating at 15 RPM would have a modulation period or cycle length of about 1.3 seconds. Tones are frequencies or narrow frequency bands that are much louder than the adjacent frequencies in sound spectra. Prominent tones can be identified through several standards, including ANSI S12.9 Part 4 and IEC 61400-11. Relative high-, mid-, and low-frequency content can also define how the sound is perceived, as well as many qualitative factors unique to the listener. Consequently, more than just the overall levels can be quantified, and studies have measured the existence of amplitude modulation, prominent tones, and spectral content in addition to the overall levels.

Wind Turbine Sound Power and Pressure Levels

The sound *power* level is the intrinsic sound energy radiated by a source. It is not dependent on the particular environment of the sound source and the location of the receiver relative to the source. The sound *pressure* level (SPL), which is measured by a sound-level meter at a location, is a function of the sound *power* emitted by neighboring sources and is highly dependent on the environment and the location of the receiver relative to the sound source(s).

Wind turbine sound is typically broadband in character with most of the sound energy at lower frequencies (less than 1000 Hz). Although wind turbines produce sound at frequencies less than the 25 Hz 1/3 octave band, sound power data are rarely published below that frequency. Most larger, utility-scale wind turbines have sound power levels between 104 and 107 dBA. Measured sound levels because of wind turbines depend on several factors, including weather conditions, the number of turbines, turbine layout, local topography, the particular turbine used, distance between the turbines and the receiver, and local flora. Meteorological conditions alone can cause 7 to 14 dB variations in sound levels.⁹ Examples of the SPLs because of a single wind turbine with three different sound powers, and at various distances, are shown in Fig. 3 as calculated with ISO 9613-2.¹⁰ Measurement results of A-weighted, C-weighted, and G-weighted sound levels have confirmed that wind turbine sound attenuates logarithmically with respect to distance.¹¹

With respect to noise standards, Hessler and Hessler¹² found an arithmetic average of 45 dBA daytime and 40 dBA nighttime for governments outside the United States, and a nighttime average of 47.7 dBA for US state noise regulation and siting standards. The metrics for those levels can vary. Common metrics are the day-evening-night level (Lden), day-night level (Ldn), equivalent average level (Leq), level exceeded 90% of the time (L90), and median (L50). The application of how these are measured and the time period over which they are measured varies, meaning that, from a practical

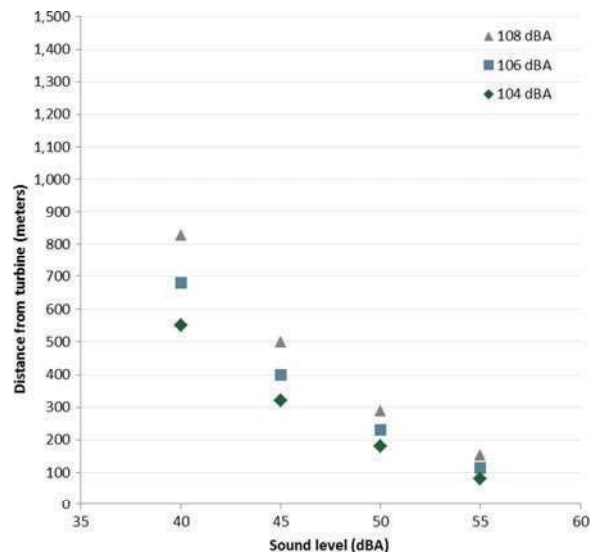


FIGURE 3. Sound levels at varying setbacks and turbine sound power levels—RSG Modeling, Using ISO 9613-2.

standpoint, sound-level limits are even more varied than the explicit numerical level. The Leq is one of the more commonly used metric. It is the logarithmic average of the squared relative pressure over a period of time. This results in a higher weighting of louder sounds.

Owing to large number of variables that contribute to SPLs because of wind turbines at receivers, measured levels can vary dramatically. At a wind farm in Texas, O'Neal et al¹³ measured sound levels with the nearest turbine at 305 m (1000 feet) and with four turbines within 610 m (2000 feet) at 50 to 51 dBA and 63 dBC (10-minute Leq), with the turbines producing sufficient power to emit the maximum sound power. During the same test, sound levels were 27 dBA and 47 dBC (10-minute Leq) inside a home that was located 290 m (950 feet) from the nearest turbine and within 610 m (2000 feet) of four turbines¹⁴ (see Fig. 4).

Bullmore et al¹⁵ measured wind turbine sound at distances from 100 to 754 m (330 to 2470 feet), where they found sound levels ranging from 40 to 55 dBA over various wind conditions. At typical receiver distances (greater than 300 m or 1000 feet), sound was attenuated to below the threshold of hearing at frequencies above the 1.25 kHz 1/3 octave band. In studies mentioned here, measurements were made with the microphone between 1 and 1.6 m (3 and 5 feet) above ground.

Wind Turbine Emission Characteristics

Low-Frequency Sound and Infrasound

Low-frequency sound is typically defined as sound from 20 to 200 Hz, and infrasound is sound less than 20 Hz. Low-frequency sound and infrasound measurement results at distances close to wind turbines (< 500 meters) typically show infrasound because of wind farms, but not above audibility thresholds (such as ISO 226 or as published by the authors^{11,14,16–20,149}). One study found sound levels 360 m and 200 m from a wind farm to be 61 dBG and 63 dBG, respectively. The threshold of audibility for G-weighted sound levels is 85 dBG. The same paper found infrasound levels of 69 dBG 250 m from a coastal cliff face and 76 dBG in downtown Adelaide, Australia.¹⁷ One study found that, even at distances less than 450 feet (136 m), infrasound levels were 80 dBG or less. At more typical receiver distances (greater than 300 m or 1000 feet), infrasound levels were 72 dBG or less. This corresponded to A-weighted sound

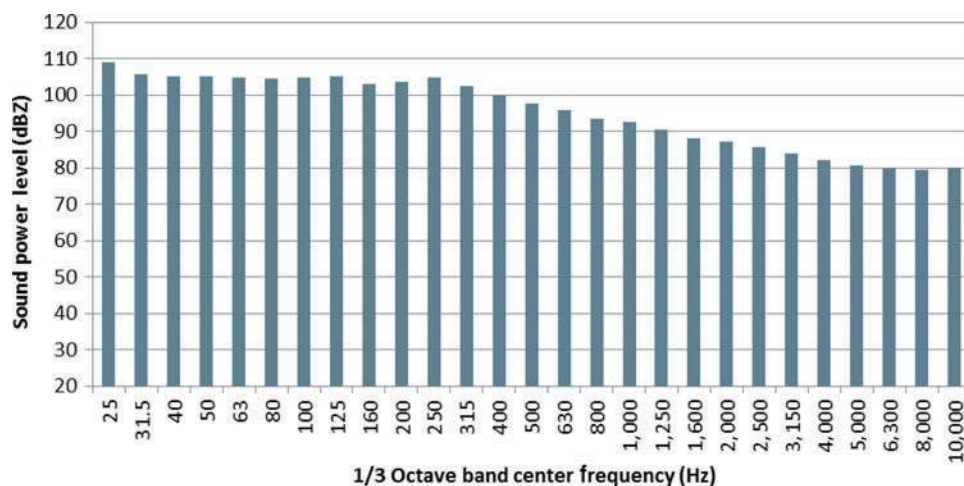


FIGURE 4. Sound power of the Siemens SWT 2.3-93 (TX) wind turbine¹⁴

levels of 56 and 49 dBA, respectively, higher than most existing regulatory noise limits.¹¹

Farther away from wind farms (1.5 km) infrasound is no higher than what would be caused by localized wind conditions, reinforcing the necessity for adequate wind-caused pseudosound reduction measures for wind turbine sound-level measurements.²¹

Low-frequency sound near wind farms is typically audible, with levels crossing the threshold of audibility between 25 and 125 Hz depending on the distance between the turbines and measurement location.^{11,14,18,19,22} Figure 5 shows the frequency spectrum of a wind farm measured at about 3500 feet compared with a truck at 50 feet, a field of insects and birds, wind moving through vegetation, and the threshold of audibility according to ISO 387-7.

Amplitude Modulation

Wind turbine sound emissions vary with blade velocity and are characterized in part by amplitude modulation, a broadband oscillation in sound level, with a cycle time generally corresponding to the blade passage frequency. The modulation is typically located in the 1/1 octave bands from 125 Hz to 2 kHz. Fluctuation magnitudes are typically not uniform throughout the frequency range. These fluctuations are typically small (2 to 4 dB) but under more unusual circumstances can be as great as 10 dB for A-weighted levels and as much as 15 dB in individual 1/3 octave bands.^{18,23} Stigwood et al²³ found that, in groups of several turbines, the individual modulations can often synchronize causing periodic increases in the modulation magnitude for periods of 6 to 20 seconds with occasional periods where the individual turbine modulations average each other out, minimizing the modulation magnitude. This was not always the case though, with periods of turbine synchronization occasionally lasting for hours under consistent high wind shear, wind strength, and wind direction.

Amplitude modulation is caused by many factors, including blade passage in front of the tower (shadowing), sound emission directivity of the moving blade tips, yaw error of the turbine blades (where the turbine blades are not perpendicular to the wind), inflow turbulence, and high levels of wind shear.^{18,23,24} Amplitude modulation level is not correlated with wind speed. Most occurrences of “enhanced” amplitude modulation (a higher magnitude of modulation) are caused by anomalous meteorological conditions.¹⁸ Amplitude modulation varies by site. Some sites rarely exhibit amplitude modulation, whereas at others amplitude modulation has been measured up to 30% of the time.⁹ It has been suggested by some that

amplitude modulation may be the cause of “infrasound” complaints because of confusing of amplitude modulation, the modulation of a broadband sound, with actual infrasound.¹⁸

Tonality

Tones are specific frequencies or narrow bands of frequencies that are significantly louder than adjacent frequencies. Tonal sound is not typically generated by wind turbines but can be found in some cases.^{19,25} In most cases, the tonal sound occurs at lower frequencies (less than 200 Hz) and is due to mechanical noise originating from the nacelle, but has also been found to be due to structural vibrations originating from the tower, and anomalous aerodynamic characteristics of the blades²⁶ (see Fig. 5).

Sound Levels at Residences where Symptoms Have Been Reported

One recent research focus has been the sound levels at (and in) the residences of people who have complained about sound levels emitted by turbines as some have suggested that wind turbine noise may be a different type of environmental noise.²⁷ Few studies have actually measured sound levels inside or outside the homes of people. Several hypotheses have been proposed about the characteristics of wind turbine noise complaints, including infrasound,²⁷ low-frequency tones,¹⁹ amplitude modulation,^{18,28} and overall noise levels.

Overall Noise Levels

Because of the large variability of noise sensitivity among people, sound levels associated with self-reported annoyance can vary considerably. (Noise sensitivity and annoyance are discussed in more detail later in this review.) People exposed to measured external sound levels from 38 to 53 dBA (10-minute or 1-hour Leq). Department of Trade and Industry,¹⁸ Walker et al,²⁷ Gabriel et al,²⁸ and van den Berg et al^{29,149} have reported annoyance. Sound levels have also been measured inside complainant residences at between 22 and 37 dBA (10-minute Leq).¹⁸

Low Frequency and Infrasonic Levels

Concerns have been raised in some settings that low-frequency sound and infrasound may be special features of wind turbine noise that lead to adverse health effects.³⁰ As a result, noise measurements in areas of operating wind turbines have focused specifically

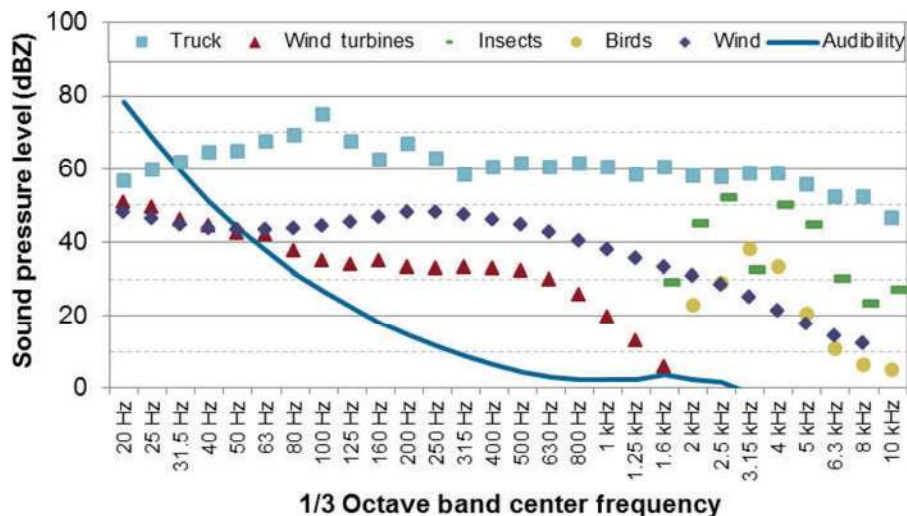


FIGURE 5. Comparison of frequency spectrum of a truck passby at 50 feet, wind turbines at 3500 feet, insects, birds, wind, and the threshold of audibility according to ISO 387-7.

on sound levels in the low-frequency range and occasionally the infrasonic range.

Infrasonic sound levels at residences are typically well below published audibility thresholds, even thresholds for those particularly sensitive to infrasound. Nevertheless, low-frequency sound typically exceeds audibility thresholds in a range starting between 25 and 125 Hz.^{18,19,22} In some cases, harmonics of the blade passage frequency (about 1 Hz, ie infrasound) have been measured at homes of people who have raised concerns about health implications of living near wind turbine with sound levels reaching 76 dB; however, these are well below published audibility thresholds.²⁷

Amplitude Modulation

Amplitude modulation has been suggested as a major cause of complaints surrounding wind turbines, although little data have been collected to confirm this hypothesis. A recent study of residents surrounding a wind farm that had received several complaints showed predicted sound levels at receiver distances to be 33 dBA or less. Residents were instructed to describe the turbine sound, when they found it annoying. Amplitude modulation was present in 68 of 95 complaints. Sound recorders distributed to the residents exhibited a high incidence of amplitude modulation.²⁸

Limited studies have addressed the percentage of complaints surrounding utility-scale wind farms, with only one comparing the occurrence of complaints with sound levels at the homes. The complaint rate among residents within 2000 feet (610 m) of the perimeter of five mid-western United States wind farms was approximately 4%. All except one of the complaints were made at residences, where wind farm sound levels exceeded 40 dBA.¹² The authors used the LA90 metric to assess wind farm sound emissions. LA90 is the A-weighted sound level that is exceeded 90% of the time. This metric is used to eliminate wind-caused spikes and other short-term sound events that are not caused by the wind farm.

In Northern New England, 5% of households within 1000 m of turbines complained to regulatory agencies about wind turbine noise.³¹ All complaints were included, even those that were related to temporary issues that were resolved. Up to 48% of the complainants were at wind farms, where at least one noise violation was found or a variance from the noise standard. A third of the all complaints were due to a single wind farm.

Sound Measurement Methodology

Collection of accurate, comparable, and useful noise data depends on careful and consistent methodology. The general method-

ology for environmental sound level monitoring is found in ANSI 12.9 Part 2. This standard covers basic requirements that include the type of measurement equipment necessary, calibration procedures, windscreen specifications, microphone placement guidance, and suitable meteorological conditions. Nevertheless, there are no recommendations for mitigating the effects of *high* winds (greater than 5 m/s) or measuring in the infrasonic frequency range (less than 20 Hz).³² Another applicable standard is IEC 61400-11, which provides a method for determining the sound power of individual wind turbines. The standard gives specifications for measurement positions, the type of data needed, data analysis methods, report content requirements, determination of tonality, determination of directivity, and the definitions and descriptors of different acoustical parameters.³³ The standard specifies a microphone mounting method to minimize wind-caused pseudosound, but some have found the setup to be insufficient under gusty wind conditions, and no recommendations are given for infrasound measurement.³⁴ Because the microphone is ground mounted, it is not suitable for long-term measurements.

Low-Frequency Sound and Infrasound Measurement

There are no standards currently in place for the measurement of wind turbine noise that includes the infrasonic range (ie, frequencies less than 20 Hz), although one is under development (ANSI/ASA S12.9 Part 7). Consequently, all current attempts to measure low-frequency sound and infrasound have either used an existing methodology, an adapted existing methodology, or proposed a new methodology.

The main problem with measuring low-frequency sound and infrasound in environmental conditions is wind-caused pseudosound due to air pressure fluctuation, because air flows over the microphone. With conventional sound-level monitoring, this effect is minimized with a wind screen and/or elimination of data measured during windy periods (less than 5 m/s [11 mph] at a 2-m [6.5 feet] height).³⁵ In the case of wind turbines, where maximum sound levels may be coincident with ground wind speeds greater than 5 m/s (11 mph), this is not the best solution. With infrasound in particular, wind-caused pseudosound can influence measurements, even at wind speeds down to 1 m/s.¹¹ In fact, many sound-level meters do not measure infrasonic frequencies.

A common method of dealing with infrasound is using an additional wind screen to further insulate the microphone from air flow.^{17,34,36} In some cases, this is simply a larger windscreen that further insulates the microphone from air flow.^{34,36} One author used a

windscreen with a subterranean pit to shelter the microphone, and another used wind resistant cloth.³⁴ A compromise to an underground microphone mounting is mounting the microphone close (20-cm height) to the ground, minimizing wind influence, or using a standard ground mounted microphone with mounting plate, as found in IEC 61400-11.³⁶ Low-frequency sound and infrasound differences between measurements made with dedicated specialized windscreens and/or measurement setup and standard wind screens/measurements setups can be quite large.^{11,37} Nevertheless, increased measurement accuracy can come at the cost of reduced accuracy at higher frequencies using some methods.³⁸

To further filter out wind-caused pseudosound, some authors have advocated a combination of microphone arrays and signal processing techniques. The purpose of the signal processing techniques is to detect elements of similarity in the sound field measured at the different microphones in the array.

Levels of infrasound from other environmental sources can be as high as infrasound from wind turbines. A study of infrasound measured at wind turbines and at other locations away from wind turbines in South Australia found that the infrasound level at houses near the wind turbines is no greater than that found in other urban and rural environments. The contribution of wind turbines to the infrasound levels is insignificant in comparison with the background level of infrasound in the environment.²¹

Conclusions

Wind turbine noise measurement can be challenging because of the necessity of measuring sound levels during high winds, and down to low frequencies. No widely accepted measurement methodologies address all of these issues, meaning that methods used in published measurements can differ substantially, affecting the comparability of results.

Measurements of low-frequency sound, infrasound, tonal sound emission, and amplitude-modulated sound show that infrasound is emitted by wind turbines, but the levels at customary distances to homes are typically well below audibility thresholds, even at residences where complaints have been raised. Low-frequency sound, often audible in wind turbine sound, typically crosses the audibility threshold between 25 and 125 Hz depending on the location and meteorological conditions.^{11,14,18,19,22} Amplitude modulation, or the rapid (once per second) and repetitive increase and decrease of broadband sound level, has been measured at wind farms. Amplitude modulation is typically 2 to 4 dB but can vary more than 6 dB in some cases (A-weighted sound levels).^{18,23}

A Canadian report investigated the total number of noise-related complaints because of operating wind farms in Alberta, Canada, over its entire history of wind power. Wind power capacity exceeds 1100 MW; some of the turbines have been in operation for 20 years. Five noise-oriented complaints at utility-scale wind farms were reported over this period, none of which were repeated after the complaints were addressed. Complaints were more common during construction of the wind farms; other power generation methods (gas, oil, etc) received more complaints than wind power. Farmers and ranchers did not raise complaints because of effects on crops and cattle.³⁹ An Australian study found a complaint rate of less than 1% for residents living within 5 km of turbines greater than 1 MW. Complaints were concentrated among a few wind farms; many wind farms never received complaints.¹⁴

Reviewing complaints in the vicinity of wind farms can be effective in determining the level and extent of annoyance because of wind turbine noise, but there are limitations to this approach. A complaint may be because of higher levels of annoyance (rather annoyed or very annoyed), and the amount of annoyance required for an individual to complain may be dependent on the personality of the person and the corresponding attitude toward the visual effect of the turbines, their respective attitudes toward wind energy, and whether

they derive economic benefit from the turbines. (All of these factors are discussed in more detail later in this report.)

Few studies have addressed sound levels at the residents of people who have described symptoms they consider because of wind turbines. Limited available data show a wide range of levels (38 to 53 dBA [10-minute or 1-hour Leq] outside the residence and from 23 to 37 dBA [10-minute Leq] inside the residence).^{18,25,27,28} The rate of complaints surrounding wind farms is relatively low; 3% for residents within 1 mile of wind farms and 4% to 5% within 1 km.^{12,31,39}

Epidemiological Studies of Wind Turbines

Key to understanding potential effects of wind turbine noise on human health is to consider relevant evidence from well-conducted epidemiological studies, which has the advantage of reflecting risks of real-world exposures. Nevertheless, environmental epidemiology is an observational (vs experimental) science that depends on design and implementation characteristics that are subject to numerous inherent and methodological limitations. Nevertheless, evidence from epidemiological studies of reasonable quality may provide the best available indication of whether certain exposures—such as industrial wind turbine noise—may be harming human health. Critical review and synthesis of the epidemiological evidence, combined with consideration of evidence from other lines of inquiry (ie, animal studies and exposure assessments), provide a scientific basis for identifying causal relationships, managing risks, and protecting public health.

Methods

Studies of greatest value for validly identifying risk factors for disease include well-designed and conducted cohort studies and case-control studies—provided that specific diseases could be identified—followed by cross-sectional studies (or surveys). Case reports and case series do not constitute epidemiological studies and were not considered because they lack an appropriate comparison group, which can obscure a relationship or even suggest one where none exists.⁴⁰ Such studies may be useful in generating hypotheses that might be tested using epidemiological methods but are not considered capable of demonstrating causality, a position also taken by international agencies such as the WHO.⁷

Epidemiological studies selected for this review were identified through searches of PubMed and Google Scholar using the following key words individually and in various combinations: “wind,” “wind turbine,” “wind farm,” “windmill,” “noise,” “sleep,” “cardiovascular,” “health,” “symptom,” “condition,” “disease,” “cohort,” “case-control,” “cross-sectional,” and “epidemiology.” In addition, general Web searches were performed, and references cited in all identified publications were reviewed. Approximately 65 documents were identified and obtained, and screened to determine whether (1) the paper described a primary epidemiological study (including experimental or laboratory-based study) published in a peer-reviewed health, medical or relevant scientific journal; (2) the study focused on or at least included wind turbine noise as a risk factor; (3) the study measured at least one outcome of potential relevance to health; and (4) the study attempted to relate the wind turbine noise with the outcome.

Results

Of the approximately 80 articles initially identified in the search, only 20 met the screening criteria (14 observational and six controlled human exposure studies), and these were reviewed in detail to determine the relative quality and validity of reported findings. Other documents included several reviews and commentaries^{3,4,6,41–49}; case reports, case studies, and surveys^{22,50–52}; and documents published in media other than peer-reviewed journals. One study published as part of a conference

proceedings did not meet the peer-reviewed journal eligibility criterion but was included because it seemed to be the first epidemiological study on this topic and an impetus for subsequent studies.⁵³

The 14 observational epidemiological studies were critically reviewed to assess their relative strengths and weaknesses on the basis of the study design and the general ability to avoid selection bias (eg, the selective volunteering of individuals with health complaints), information bias (eg, under- or overreporting of health complaints, possibly because of reliance on self-reporting), and confounding bias (the mixing of possible effects of other strong risk factors for the same disease because of correlation with the exposure).

Figure 6 depicts the 14 observational epidemiological studies published in peer-reviewed health or medical journals, all of which were determined to be cross-sectional studies or surveys. As can be seen from the figure, the 14 publications were based on analyses of data from only eight different study populations, that is, six publications were based on analyses of a previously published study (eg, Pedersen et al⁵⁴ and Bakker et al⁵⁵ were based on the data from Pedersen et al⁵⁶) or on combined data from previously published studies (eg, Pedersen and Larsman⁵⁷ and Pedersen and Waye⁵⁸ were based on the combined data from Pedersen and Waye^{59,60}; and Pedersen⁶¹ and Janssen et al⁶² were based on the combined data from Pedersen et al,⁵⁶ Pedersen and Waye,⁵⁹ and Pedersen and Waye⁶⁰). Therefore, in the short summaries of individual studies below, publications based on the same study population(s) are grouped.

Summary of Observational Epidemiological Studies

Possibly the first epidemiological study evaluating wind turbine sound and noise annoyance was published in the proceedings of the 1993 European Community Wind Energy Conference.⁵³ Investigators surveyed 574 individuals (159 from the Netherlands, 216 from Germany, and 199 from Denmark). Up to 70% of the people

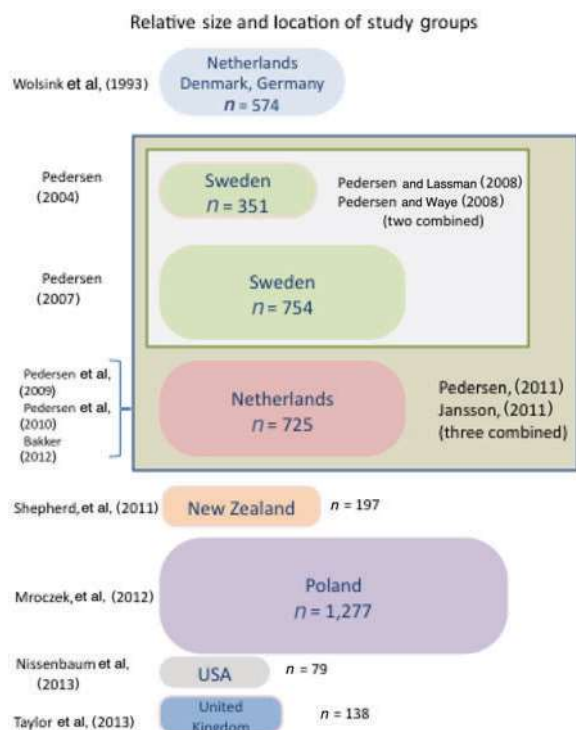


FIGURE 6. The 14 observational epidemiological studies published in peer-reviewed health or medical journals, all of which were determined to be cross-sectional studies or surveys.

resided near wind turbines for at least 5 years. No response rates were reported, so the potential for selection or participation bias cannot be evaluated. Wind turbine sound levels were calculated in 5 dBA intervals for each respondent, on the basis of site measurements and residential distance from turbines. The authors claimed that noise-related annoyance was weakly correlated with objective sound levels but more strongly correlated with indicators of respondents' attitudes and personality.⁵³

In a cross-sectional study of 351 participants residing in proximity to wind turbines (power range 150 to 650 kW), Pedersen (a coauthor of the Wolsink⁵³ study) and Persson and Waye⁵⁹ described a statistically significant association between modeled wind turbine audible noise estimates and self-reported annoyance. In this section, "statistically significant" means that the likelihood that the results were because of chance is less than 5%. No respondents among the 12 exposed to wind turbine noise less than 30 dBA reported annoyance with the sound; however, the percentage reporting annoyance increased with noise exceeding 30 dBA. No differences in health or well-being outcomes (eg, tinnitus, cardiovascular disease, headaches, and irritability) were observed. With noise exposures greater than 35 dBA, 16% of respondents reported sleep disturbance, whereas no sleep disturbance was reported among those exposed to less than 35 dBA. Although the authors observed that the risk of annoyance from wind turbine noise exposure increased statistically significantly with each increase of 2.5 dBA, they also reported a statistically significant risk of reporting noise annoyance among those self-reporting a negative attitude toward the visual effect of the wind turbines on the landscape scenery (measured on a five-point scale ranging from "very positive" to "very negative" opinion). These results suggest that attitude toward visual effect is an important contributor to annoyance associated with wind turbine noise. In addition to its reliance on self-reported outcomes, this study is limited by selection or participation bias, suggested by the difference in response rate between the highest-exposed individuals (78%) versus lowest-exposed individuals (60%).

Pedersen⁶⁰ examined the association between modeled wind turbine sound pressures and self-reported annoyance, health, and well-being among 754 respondents in seven areas in Sweden with wind turbines and varying landscapes. A total of 1309 surveys were distributed, resulting in a response rate of 57.6%. Annoyance was significantly associated with SPLs from wind turbines as well as having a negative attitude toward wind turbines, living in a rural area, wind turbine visibility, and living in an area with rocky or hilly terrain. Those annoyed by wind turbine noise reported a higher prevalence of lowered sleep quality and negative emotions than those not annoyed by noise. Because of the cross-sectional design, it cannot be determined whether wind turbine noise caused these complaints or if those who experienced disrupted sleep and negative emotions were more likely to notice and report annoyance from noise. Measured SPLs were not associated with any health effects studied. In the same year, Petersen et al reported on what they called a "grounded theory study" in which 15 informants were interviewed in depth regarding the reasons they were annoyed with wind turbines and associated noise. Responses indicated that these individuals perceived the turbines to be an intrusion and associated with feelings of lack of control and influence.⁶³ Although not an epidemiological study, this exercise was intended to elucidate the reasons underlying the reported annoyance with wind turbines.

Further analyses of the combined data from Pedersen and Waye^{59,60} (described above) were published in two additional papers.^{57,58} The pooled data included 1095 participants exposed to wind turbine noise of at least 30 dBA. As seen in the two original studies, a significant association between noise annoyance and SPL was observed. A total of 84 participants (7.7%) reported being fairly or very annoyed by wind turbine noise. Respondents reporting wind turbines as having a negative effect on the scenery were also

statistically significantly more likely to report annoyance to wind turbine noise, regardless of SPLs.⁵⁷ Self-reported stress was higher among those who were fairly or very annoyed compared with those not annoyed; however, these associations could not be attributed specifically to wind turbine noise. No differences in self-reported health effects such as hearing impairment, diabetes, or cardiovascular diseases were reported between the 84 (7.7%) respondents who were fairly or very annoyed by wind turbine noise compared with all other respondents.⁵⁸ The authors did not report the power of the study.

Pederson et al^{54–56} evaluated the data from 725 residents in the Netherlands living within 2.5 km of a site containing at least two wind turbines of 500 kW or greater. Using geographic information systems methods, 3727 addresses were identified in the study target area, for which names and telephone numbers were found for 2056; after excluding businesses, 1948 were determined to be residences and contacted. Completed surveys were received from 725 for a response rate of 37%. Although the response rate was lower than in previous cross-sectional studies, nonresponse analyses indicated that similar proportions responded across all landscape types and sound pressure categories.⁵⁵ Calculated sound levels, other sources of community noise, noise sensitivity, general attitude, and visual attitude toward wind turbines were evaluated. The authors reported an exposure–response relationship between calculated A-weighted SPLs and self-reported annoyance. Wind turbine noise was reported to be more annoying than transportation noise or industrial noise at comparable levels. Annoyance, however, was also correlated with a negative attitude toward the visual effect of wind turbines on the landscape. In addition, a statistically significantly decreased level of annoyance from wind turbine noise was observed among those who benefited economically from wind turbines, despite equal perception of noise and exposure to generally higher (greater than 40 dBA) sound levels.⁵⁶ Annoyance was strongly correlated with self-reporting a negative attitude toward the visual effect of wind turbines on the landscape scenery (measured on a five-point scale ranging from “very positive” to “very negative” opinion). The low response rate and reliance on self-reporting of noise annoyance limit the interpretation of these findings.

Results of further analyses of noise annoyance were reported in a separate report,⁵⁴ which indicated that road traffic noise had no effect on annoyance to wind turbine noise and vice versa. Visibility of, and attitude toward, wind turbines and road traffic were significantly related to annoyance from their respective noise source; stress was significantly associated with both types of noise.^{54,157}

Additional analyses of the same data were performed using a structural equation approach that indicated that, as with annoyance, sleep disturbance increased with increasing SPL because of wind turbines; however, this increase was statistically significant only at pressures of 45 dBA and higher. Results of analyses of the combined data from the two Swedish^{59,60} and the Dutch⁵⁶ cross-sectional studies have been published in two additional papers. Using the combined data from these three predecessor studies, Pedersen et al^{54,56} identified 1755 (ie, 95.9%) of the 1830 total participants for which complete data were available to explore the relationships between calculated A-weighted SPLs and a range of indicators of health and well-being. Specifically, they considered sleep interruption; headache; undue tiredness; feeling tense, stressed, or irritable; diabetes; high blood pressure; cardiovascular disease; and tinnitus.⁶¹ As in the precursor studies, noise annoyance indoors and outdoors was correlated with A-weighted SPLs. Sleep interruption seemed at higher sound levels and was also related to annoyance. No other health or well-being variables were consistently related to SPLs. Stress was not directly associated with SPLs but was associated with noise-related annoyance.

Another report based on these data (in these analyses, 1820 of the 1830 total participants) modeled the relationship between wind turbine noise exposure and annoyance indoors and outdoors.⁶²

The authors excluded respondents who benefited economically from wind turbines, then compared their modeled results with other modeled relationships for industrial and transportation noise; they claimed that annoyance from wind turbine noise at or higher than 45 dBA is associated with more annoyance than other noise sources.

Shepherd et al,⁶⁴ who had conducted an earlier evaluation of noise sensitivity and Health Related Quality of Life (HRQL),¹⁵³ compared survey results from 39 residents located within 2 km of a wind turbine in the South Makara Valley in New Zealand with 139 geographically and socioeconomically matched individuals who resided at least 8 km from any wind farm. The response rates for both the proximal and more distant study groups were poor, that is, 34% and 32%, respectively, although efforts were made to blind respondents to the study hypotheses. No indicator of exposure to wind turbine noise was considered beyond the selection of individuals based on the proximity of their residences from the nearest wind turbine. Health-related quality-of-life (HRQOL) scales were used to describe and compare the general well-being and well-being in the physical, psychological, and social domains of each group. The authors reported statistically significant differences between the groups in some HRQOL domain scores, with residents living within 2 km of a turbine installation reporting lower mean physical HRQOL domain score (including lower component scores for sleep quality and self-reported energy levels) and lower mean environmental quality-of-life (QOL) scores (including lower component scores for considering one's environment to be less healthy and being less satisfied with the conditions of their living space). No differences were reported for social or psychological HRQOL domain scores. The group residing closer to a wind turbine also reported lower amenity but not related to traffic or neighborhood noise annoyance. Lack of actual wind turbine and other noise source measurements, combined with the poor response rate (both noted by the authors as limitations), limits the inferential value of these results because they may pertain to wind turbine emissions.⁶⁴

Possibly the largest cross-sectional epidemiological study of wind turbine noise on QOL was conducted in an area of northern Poland with the most wind turbines.⁶⁵ Surveys were completed by a total of 1277 adults (703 women and 574 men), aged 18 to 94 years, representing a 10% two-stage random sample of the selected communities. Although the response rate was not reported, participants were sequentially enrolled until a 10% sample was achieved, and the proportion of individuals invited to participate but unable or refusing to participate was estimated at 30% (B. Mroczek, dr hab n. zdr., e-mail communication, January 2, 2014). Proximity of residence was the exposure variable, with 220 (17.2%) respondents within 700 m; 279 (21.9%) between 700 and 1000 m; 221 (17.3%) between 1000 and 1500 m; and 424 (33.2%) residing more than 1500 m from the nearest wind turbine. Indicators of QOL and health were measured using the Short Form–36 Questionnaire (SF-36). The SF-36 consists of 36 questions specifically addressing physical functioning, role-functioning physical, bodily pain, general health, vitality, social functioning, role-functioning emotional, and mental health. An additional question concerning health change was included, as well as the Visual Analogue Scale for health assessment. It is unclear whether age, sex, education, and occupation were controlled for in the statistical analyses. The authors report that, within all subscales, those living closest to wind farms reported the best QOL, and those living farther than 1500 m scored the worst. They concluded that living in close proximity of wind farms does not result in the worsening of, and might improve, the QOL in this region.⁶⁵

A small survey of residents of two communities in Maine with multiple industrial wind turbines compared sleep and general health outcomes among 38 participants residing 375 to 1400 m from the nearest turbine with another group of 41 individuals residing 3.3 to 6.6 km from the nearest wind turbine.⁶⁶ Participants completed questionnaires and in-person interviews on a range of

health and attitudinal topics. Prevalence of self-reported health and other complaints was compared by distance from the wind turbines, statistically controlling for age, sex, site, and household cluster in some analyses. Participants living within 1.4 km of a wind turbine reported worse sleep, were sleepier during the day, and had worse SF-36 Mental Component Scores compared with those living farther than 3.3 km away. Statistically significant correlations were reported between Pittsburgh Sleep Quality Index, Epworth Sleepiness Scale, SF-36 Mental Component Score, and log-distance to the nearest wind turbine. The authors attributed the observed differences to the wind turbines¹⁴⁷; methodological problems such as selection and reporting biases were overlooked. This study has a number of methodological limitations, most notably that all of the “near” turbine groups were plaintiffs in a lawsuit against the wind turbine operators and had already been interviewed by the lead investigator prior to the study. None of the “far” group had been interviewed; they were “cold called” by an assistant. This differential treatment of the two groups introduces a bias in the integrity of the methods and corresponding results. Details of the far group, as well as participation rates, were not noted.⁶⁶

In another study, the role of negative personality traits (defined by the authors using separate scales for assessing neuroticism, negative affectivity, and frustration intolerance) on possible associations between actual and perceived wind turbine noise and medically unexplained nonspecific symptoms was investigated via a mailed survey.⁶⁷ Of the 1270 identified households within 500 m of eight 0.6 kW micro-turbine farms and within 1 km of four 5 kW small wind turbine farms in two cities in the United Kingdom, only 138 questionnaires were returned, for a response rate of 10%. No association was noted between calculated and actual noise levels and nonspecific symptoms. A correlation between perceived noise and nonspecific symptoms was seen among respondents with negative personality traits. Despite the participant group’s reported representativeness of the target population, the low survey response rate precludes firm conclusions on the basis of these data.⁶⁷

In a study of residents living near a “wind park” in Western New York State, surveys were administered to 62 individuals living in 52 homes.⁶⁸ The wind park included 84 turbines. No association was noted between self-reported annoyance and short duration sound measurements. A correlation was noted between the measure of a person’s concern regarding health risks and reported measures of the prevalence of sleep disturbance and stress. While a cross-sectional study is based on self-reported annoyance and health indicators, and therefore limited in its interpretation, one of its strengths is that it is one of the few studies that performed actual sound measurements (indoors and outdoors).

A small but detailed study on response to the wind turbine noise was carried out in Poland.⁶⁹ The study population consisted of 156 people, age 15–82 years, living in the vicinity of 3 wind farms located in the central and northwestern parts of Poland. No exclusion criteria were applied, and each individual agreeing to participate was sent a questionnaire patterned after the one used in the Pederson 2004 and Pederson 2007 studies and including questions on living conditions, self-reported annoyance due to noise from wind turbines, and self-assessment of physical health and well-being (such as headaches, dizziness, fatigue, insomnia, and tinnitus). The response rate was 71%. Distance from the nearest wind turbine and modeled A-weighted SPLs were considered as exposure indicators. One third (33.3%) of the respondents found wind turbine noise annoying outdoors, and one fifth (20.5%) found the noise annoying while indoors. Wind turbine noise was reported as being more annoying than other environmental noises, and self-reported annoyance increased with increasing A-weighted SPLs. Factors such as attitude toward wind turbines and “landscape littering” (visual impact) influenced the perceived annoyance from the wind turbine noise. This study, as with most others, is limited by the cross-sectional design

and reliance on self-reported health and well-being indicators; however, analyses focused on predictors of self-reported annoyance, and found that wind turbine noise, attitude toward wind turbines, and attitude toward “landscape littering” explain most of the reported annoyance.

Other Possibly Relevant Studies

A publication based on the self-reporting of 109 individuals who “perceived adverse health effects occurring with the onset of an industrial wind turbine facility” indicated that 102 reported either “altered health or altered quality of life.” The authors appropriately noted that this was a survey of self-selected participants who chose to respond to a questionnaire specifically designed to attract those who had health complaints they attributed to wind turbines, with no comparison group. Nevertheless, the authors inappropriately draw the conclusion that “Results of this study suggest an underlying relationship between wind turbines and adverse health effects and support the need for additional studies.”^{46(p.336)} Such a report cannot provide valid evidence of any relationship for which there is no comparison and is of little if any inferential value.

Researchers at the School of Public Health, University of Sydney, in Australia conducted a study to explore psychogenic explanations for the increase around 2009 of wind farm noise and/or health complaints and the disproportionate corresponding geographic distribution of those complaints. They obtained records of complaints about noise or health from residents living near all 51 wind farms (1634 turbines) operating between 1993 and 2012 from wind farm companies and corroborated with documents such as government public enquiries, news media records, and court affidavits. Of the 51 wind farms, 33 (64.7%) had no record of noise or health complaints, including all wind farms in Western Australia and Tasmania. The researchers identified 129 individuals who had filed complaints, 94 (73%) of whom lived near six wind farms targeted by anti-wind advocacy groups. They observed that 90% of complaints were registered after anti-wind farm groups included health concerns as part of their advocacy in 2009. The authors concluded that their findings were consistent with their psychogenic hypotheses.

Discussion

No cohort or case-control studies were located in this updated review of the peer-reviewed literature. The lack of published case-control studies is less surprising and less critical because there has been no discrete disease or constellation of diseases identified that likely or might be explained by wind turbine noise. Anecdotal reports of symptoms associated with wind turbines include a broad array of nonspecific symptoms, such as headache, stress, and sleep disturbance, that afflicts large proportions of the general population and have many recognized risk factors. Retrospectively associating such symptoms with wind turbines or even measured wind turbine noise—as would be necessary in case-control studies—does not prevent recall bias from influencing the results.

Although cross-sectional studies and surveys have the advantage of being relatively simple and inexpensive to conduct, they are susceptible to a number of influential biases. Most importantly, however, is the fact that, because of the simultaneous ascertainment of both exposure (eg, wind turbine noise) and health outcomes or complaints, the temporal sequence of exposure–outcome relationship cannot be demonstrated. If the exposure cannot be established to precede the incidence of the outcome—and not the reverse, that is, the health complaint leads to increased perception of or annoyance with the exposure, as with insomnia headaches or feeling tense/stressed/irritable—the association cannot be evaluated for a possible causal nature.

Conclusions

A critical review and synthesis of the evidence available from the eight study populations studied to date (and reported in 14 publications) provides some insights into the hypothesis that wind turbine noise harms human health in those living in proximity to wind turbines. These include the following:

- No clear or consistent association is seen between noise from wind turbines and any reported disease or other indicator of harm to human health.
- In most surveyed populations, some individuals (generally a small proportion) report some degree of annoyance with wind turbines; however, further evaluation has demonstrated:
 - Certain characteristics of wind turbine sound such as its intermittence or rhythmicity may enhance reported perceptibility and annoyance;
 - The context in which wind turbine noise is emitted also influences perceptibility and annoyance, including urban versus rural setting, topography, and landscape features, as well as visibility of the wind turbines;
 - Factors such as attitude toward visual effect of wind turbines on the scenery, attitude toward wind turbines in general, personality characteristics, whether individuals benefit financially from the presence of wind turbines, and duration of time wind turbines have been in operation all have been correlated with self-reported annoyance; and
 - Annoyance does not correlate well or at all with objective sound measurements or calculated sound pressures.
- Complaints such as sleep disturbance have been associated with A-weighted wind turbine sound pressures of higher than 40 to 45 dB but not any other measure of health or well-being. Stress was associated with annoyance but not with calculated sound pressures.⁶¹
- Studies of QOL including physical and mental health scales and residential proximity to wind turbines report conflicting findings—one study (with only 38 participants living within 2.0 km of the nearest wind turbine) reported lower HRQOL among those living closer to wind turbines than respondents living farther away,⁶⁴ whereas the largest of all studies (with 853 living within 1500 m of the nearest wind turbine)⁶⁵ found that those living closer to wind turbines reported higher QOL and health than those living farther away.⁶⁵

Because these statistical correlations arise from cross-sectional studies and surveys in which the temporal sequence of the exposure and outcome cannot be evaluated, and where the effect of various forms of bias (especially selection/volunteer bias and recall bias) may be considerable, the extent to which they reflect causal relationships cannot be determined. For example, the claims such as “We conclude that the noise emissions of wind turbines disturbed the sleep and caused daytime sleepiness and impaired mental health in residents living within 1.4 km of the two wind turbines installations studied” cannot be substantiated on the basis of the actual study design used and some of the likely biases present.⁶⁸

Notwithstanding the limitations inherent to cross-sectional studies and surveys—which alone may provide adequate explanation for some of the reported correlations—several possible explanations have been suggested for the wind turbines–associated annoyance reported in many of these studies, including attitudinal and even personality characteristics of the survey participants.⁶⁷ Pedersen and colleague,⁵⁷ who have been involved in the majority of publications on this topic, noted “The enhanced negative response [toward wind turbines] could be linked to aesthetical response, rather than to multi-modal effects of simultaneous auditory and visual stimulation, and a risk of hindrance to psycho-physiological restoration could not be excluded.”^(p.389) They also found that wind turbines might

be more likely to elicit annoyance because some perceive them to be “intrusive” visually and with respect to their noise.⁶³ Alternative explanations on the basis of evaluation of all health complaints filed between 1993 and 2012 with wind turbine operators across Australia include the influence of anti-wind power activism and the surrounding publicity on the likelihood of health complaints, calling the complaints “communicated diseases.”⁵⁰

As noted earlier, the 14 papers meeting the selection criteria for critical review and synthesis were based on only eight independent study groups—three publications were based on the same study group from the Netherlands⁵⁶ and four additional publications were based on the combined data from the two Swedish surveys^{59,60} or from the combined data from all three. The findings across studies based on analyses of the same data are not independent observations, and therefore the body of available evidence may seem to be larger and more consistent than it should. This observation does not necessarily mean that the relationships observed (or the lack of associations between calculated wind turbines sound pressures and disease or other indicators of health) are invalid, but that consistency across reports based on the same data should not be overinterpreted as independent confirmation of findings. Perhaps more important is that all eight were cross-sectional studies or surveys, and therefore inherently limited in their ability to demonstrate the presence or absence of true health effects.

Recent controlled exposure laboratory evaluations lend support to the notion that reports of annoyance and other complaints may reflect, at least in part, preconceptions about the ability of wind turbine noise to harm health^{50,69,70} or even the color of the turbine⁷¹ more than the actual noise emission.

Sixty years ago, Sir Austin Bradford Hill delivered a lecture entitled “Observations and Experiment” to the Royal College of Occupational Medicine. In his lecture, Hill stated that “The observer may well have to be more patient than the experimenter—awaiting the occurrence of the natural succession of events he desires to study; he may well have to be more imaginative—sensing the correlations that lie below the surface of his observations; and he may well have to be more logical and less dogmatic—avoiding as the evil eye the fallacy of ‘*post hoc ergo propter hoc*,’ the mistaking of correlation for causation.”^{72(p.1000)}

Although it is typical and appropriate to point out the obvious need for additional research, it may be worth emphasizing that more research of a similar nature—that is, using cross-sectional or survey approaches—is unlikely to be informative, most notably for public policy decisions. Large, well-conducted prospective cohort studies that document baseline health status and can objectively measure the incidence of new disease or health conditions over time with the introduction would be the most informative. On the contrary, the phenomena that constitute wind turbine exposures—primarily noise and visual effect—are not dissimilar to many other environmental (eg, noise of waves along shorelines) and anthropogenic (eg, noise from indoor Heating Ventilation and Air Conditioning or road traffic) stimuli, for which research and practical experience indicate no direct harm to human health.

Sound Components and Health: Infrasound, Low-Frequency Sound, and Potential Health Effects

Introduction

This section addresses potential health implications of infrasound and low-frequency sound because claims have been made that the frequency of wind turbine sound has special characteristics that may present unique health risks in comparison with other sources of environmental sound.

Wind turbines produce two kinds of sound. Gears and generators can make mechanical noise, but this is less prominent than the

TABLE 1. Human Thresholds for Different Frequencies

Frequency (Hz)	Threshold (dB SPL)
100	27
25	69
10	97

SPL, sound pressure level.

aerodynamic noise of the blades, whose tips may have velocities in excess of 200 mph. Three-bladed turbines often rotate about once every 3 seconds; their “blade-pass” frequency is thus about 1 Hz (Hz: cycle per second). For this reason, the aerodynamic noise often rises and falls about once per second, and some have described the sounds as “whooshing” or “pulsing.”

Several studies^{42,73,74} have shown that at distances of 300 m or more, wind turbine sounds are below human detection thresholds for frequencies less than 50 Hz. The most audible frequencies (those whose acoustic energies exceed human thresholds the most) are in 500 to 2000 Hz range. At this distance from a single wind turbine, overall levels are typically 35 to 45 dBA.^{75,76} These levels can be audible in a typical residence with ambient noise of 30 dBA and windows open (a room with an ambient level of 30 dBA would be considered by most people to be quiet or very quiet). In outdoor environments, sound levels drop about 6 dB for every doubling of the distance from the source, so one would predict levels of 23 to 33 dBA, that is, below typical ambient noise levels in homes, at a distance of 1200 m. For a wind farm of 12 large turbines, Møller and Pedersen⁷⁷ predicted a level of 35 dBA at a distance of 453 m.

As noted earlier in this report, sound intensity is usually measured in decibels (dB), with 0 dB SPL corresponding to the softest sounds young humans can hear. Nevertheless, humans hear well only within the frequency range that includes the frequencies most important for speech understanding—about 500 to 5000 Hz. At lower frequencies, hearing thresholds are much higher.⁷³ Although frequencies lower than 20 Hz are conventionally referred to as “infrasound,” sounds in this range can in fact be heard, but only when they are extremely intense (a sound of 97 dB SPL has 10 million times as much energy as a sound of 27 dB; see Table 1).

Complex sounds like those produced by wind turbines contain energy at multiple frequencies. The most complete descriptions of such sounds include dB levels for each of several frequency bands (eg, 22 to 45 Hz, 45 to 90 Hz, 90 to 180 Hz, . . . , 11,200 to 22,400 Hz). It is simpler, and appropriate in most circumstances, to specify overall sound intensity using meters that give full weight to the frequencies people hear well, and less weight to frequencies less than 500 Hz and higher than 5000 Hz. The resulting metric is “A-weighted” decibels or dBA. Levels in dBA correlate well with audibility; in a very quiet place, healthy young people can usually detect sounds less than 20 dBA.

Low-Frequency Sound and Infrasound

Low-frequency noise (LFN) is generally considered frequencies from 20 to 250 Hz, as described earlier in more detail in subsection “Low Frequency and Infrasonic Levels.” The potential health implications of low-frequency sound from wind turbines have been investigated in a study of four large turbines and 44 smaller turbines in the Netherlands.¹⁶ In close proximity to the turbines, infrasound levels were below audibility. The authors suggested that LFN could be an important aspect of wind turbine noise; however, they did not link measured or modeled noise levels with any health outcome measure, such as annoyance.

A literature review of infrasound and low-frequency sound concluded that low-frequency sound from wind turbines at residences did not exceed levels from other common noise sources, such as traffic.⁴² The authors concluded that a “statistically significant association between noise levels and self-reported sleep disturbance was found in two of the three [epidemiology] studies.”^(p.1) It has been suggested that LFN from wind turbines causes other and more serious health problems, but empirical support for these claims is lacking.⁴²

Sounds with frequencies lower than 20 Hz (ie, infrasound) may be audible at very high levels. At even higher levels, subjects may experience symptoms from very low-frequency sounds—ear pressure (at levels as low as 127 dB SPL), ear pain (at levels higher than 145 dB), chest and abdominal movement, a choking sensation, coughing, and nausea (at levels higher than 150 dB).^{78,79} The National Aeronautics and Space Administration considered that infrasound exposures lower than 140 dB SPL would be safe for astronauts; American Conference of Governmental Industrial Hygienists recommends a threshold limit value of 145 dB SPL for third-octave band levels between 1 and 80 Hz.⁷⁹ As noted earlier, infrasound from wind turbines has been measured at residential distances and noted to be many orders of magnitude below these levels.

Whenever wind turbine sounds are audible, some people may find the sounds annoying, as discussed elsewhere in this review. Some authors, however, have hypothesized that even inaudible sounds, especially at very low frequencies, could affect people by activating several types of receptors, including the following:

1. Outer hair cells of the cochlea⁸⁰;
2. Hair cells of the normal vestibular system,⁸¹ especially the otolith organs⁸²;
3. Hair cells of the vestibular system after its fluid dynamics have been disrupted by infrasound⁸⁰;
4. Visceral graviceptors acting as vibration sensors.⁸¹

To evaluate these hypotheses, it is useful to review selected aspects of the anatomy and physiology of the inner ear (focusing on the differences between the cochlea and the vestibular organs), vibrotactile sensitivity to airborne sound, and the types of evidence that, while absent at present, could in theory support one or more of these hypotheses.

How the Inner Ear Works

The inner ear contains the cochlea (the organ of hearing) and five vestibular organs (three semicircular canals and two otolith organs, transmitting information about head position and movement). The cochlea and the vestibular organs have one important feature in common—they both use hair cells to convert sound or head movement into nerve impulses that can then be transmitted to the brain. Hair cells are mechanoreceptors that can elicit nerve impulses only when their stereocilia (or sensory hairs) are bent.

The anatomy of the cochlea ensures that its hair cells respond well to airborne sound and poorly to head movement, whereas the anatomy of the vestibular organs optimizes hair cell response to head movement and minimizes response to airborne sound. Specifically, the cochlear hair cells are not attached to the bony otic capsule, and the round window permits the cochlear fluids to move more freely when air-conducted sound causes the stapes to move back and forth in the oval window. Conversely, the vestibular hair cells are attached to the bony otic capsule, and the fluids surrounding them are not positioned between the two windows and thus cannot move as freely in response to air-conducted sound. At the most basic level, this makes it unlikely that inaudible sound from wind turbines can affect the vestibular system.

Responding to Airborne Sound

Airborne sound moves the eardrum and ossicles back and forth; the ossicular movement at the oval window then displaces inner ear fluid, causing a movement of membranes in the cochlea, with bending of the hair cell stereocilia. Nevertheless, this displacement of the cochlear hair cells depends on the fact that there are two windows separating the inner ear from the middle ear, with the cochlear hair cells positioned between them—whenever the oval window (the bony footplate of the stapes, constrained by a thin annular ligament) is pushed inward, the round window (a collagenous membrane lined by mucous membrane) moves outward, and vice versa. When the round window is experimentally sealed,⁸³ the cochlea's sensitivity to sound is reduced by 35 dB.

The vestibular hair cells are not positioned between the two cochlear windows, and therefore airborne sound-induced inner ear fluid movement does not efficiently reach them. Instead, the vestibular hair cells are attached to the bone of the skull so that they can respond faithfully to head movement (the cochlear hair cells are not directly attached to the skull). As one might expect, vestibular hair cells can respond to head vibration (bone-conducted sound), such as when a tuning fork is held to the mastoid. Very intense airborne sound can also make the head vibrate; people with severe conductive hearing loss can hear airborne sound in this way, but only when the sounds are made 50 to 60 dB more intense than those audible to normal people.

The cochlea contains two types of hair cells. It is often said that we hear with our inner hair cells (IHCs) because all the “type I” afferent neurons that carry sound-evoked impulses to the brain connect to the IHCs. The outer hair cells (OHCs) are important as “preamplifiers” that make it possible to hear very soft sounds; they are exquisitely tuned to specific frequencies, and when they move they create fluid currents that then displace the stereocilia of the IHCs.

Although more numerous than the IHCs, the OHCs receive only very scanty afferent innervation, from “type II” neurons, the function of which is unknown. Salt and Hullar⁸⁰ have pointed out that OHCs generate measurable electrical responses called cochlear microphonics to very low frequencies (eg, 5 Hz) at levels that are presumably inaudible to the animals and have hypothesized that the type II afferent fibers from the OHCs might carry this information to the brain. Nevertheless, it seems that no one has ever recorded action potentials from type II cochlear neurons, nor have physiological responses other than cochlear microphonics been recorded in response to inaudible sounds.^{84,85} In other words, as Salt and Hullar⁸⁰ acknowledge, “The fact that some inner ear components (such as the OHC) may respond to [airborne] infrasound at the frequencies and levels generated by wind turbines does not necessarily mean that they will be perceived or disturb function in any way.”^(p.19)

Responses of the Vestibular Organs

As previously noted, vestibular hair cells are efficiently coupled to the skull. The three semicircular canals in each ear are designed to respond to head rotations (roll, pitch, yaw, or any combination). When the head rotates, as in shaking the head to say “no,” the fluid in the canals lags behind the skull and bends the hair cells. The otolith organs (utricle and saccule) contain calcium carbonate crystals (otoconia) that are denser than the inner ear fluid, and this allows even static head position to be detected; when the head is tilted, gravitational pull on the otoconia bends the hair cells. The otolith organs also respond to linear acceleration of the head, as when a car accelerates.

Many people complaining about wind turbines have reported dizziness, which can be a symptom of vestibular disorders; this has led to suggestions that wind turbine sound, especially inaudible infrasound, can stimulate the vestibular organs.^{81,82} Pierpont⁸¹ introduced a term “Wind Turbine Syndrome” based on a case series of 10

families who reported symptoms that they attributed to living near wind turbines. The author invited people to participate if they thought they had symptoms from living in the vicinity of wind turbines; this approach introduces substantial selection bias that can distort the results and their corresponding significance. Telephone interviews were conducted; no medical examination, diagnostic studies or review, and documentation of medical records were conducted as part of the case series. Noise measurements were not provided. Nonetheless, the author described a collection of nonspecific symptoms that were described as “Wind Turbine Syndrome.” The case series, at the time of preparation of this review, has not been published in the peer-reviewed scientific literature. Although not medically recognized, advocates of this “disorder” suggest that wind turbines produce symptoms, such as headaches, memory loss, fatigue, dizziness, tachycardia, irritability, poor concentration, and anxiety.⁸⁶

To support her hypotheses, Pierpont cited a report by Todd et al⁸⁷ that demonstrated human vestibular responses to bone-conducted sound at levels below those that can be heard. But as previously noted, this effect is not surprising because the vestibular system is designed to respond to head movement (including head vibration induced by direct contact with a vibrating source). The relevant issue is how the vestibular system responds to airborne sound, and here the evidence is clear. Vestibular responses to airborne sound require levels well above audible thresholds.^{88,89} Indeed, clinical tests of vestibular function using airborne sound use levels in excess of 120 dB, which raise concerns of acoustic trauma.⁹⁰

Salt and Hullar⁸⁰ acknowledge that a normal vestibular system is unlikely to respond to inaudible airborne sound—“Although the hair cells in other sensory structures such as the saccule may be tuned to infrasonic frequencies, auditory stimulus coupling to these structures is inefficient so that they are unlikely to be influenced by airborne infrasound.”^(p.12) They go on to hypothesize that infrasound may cause endolymphatic hydrops, a condition in which one of the inner ear fluid compartments is swollen and may disturb normal hair cell function. But here, too, they acknowledge the lack of evidence—“... it has never been tested whether stimuli in the infrasound range cause endolymphatic hydrops.”^(p.19) In previous research, Salt⁹¹ was able to create temporary hydrops in animals using airborne sound, but only at levels (115 dB at 200 Hz) that are many orders of magnitude higher than levels that could exist at residential distances from wind turbines.

Human Vibrotactile Sensitivity to Airborne Sound

Very loud sound can cause head and body vibration. As previously noted, a person with absent middle ear function but an intact cochlea may hear sounds at 50 to 60 dB SPL. Completely deaf people can detect airborne sounds using the vibrotactile sense, but only at levels far above hearing threshold, for example, 128 dB SPL at 16 Hz.⁹² Vibrotactile sensation depends on receptors in the skin and joints.

Pierpont⁸¹ hypothesized that “visceral graviceptors,”^{93,94} which contain somatosensory receptors, could detect airborne infrasound transmitted from the lungs to the diaphragm and then to the abdominal viscera. These receptors would seem to be well suited to detect body tilt or perhaps whole-body vibration, but there is no evidence that airborne sound could stimulate sensory receptors in the abdomen. Airborne sound is almost entirely reflected away from the body; when Takahashi et al⁹⁵ used airborne sound to produce chest or abdominal vibration that exceeded ambient body levels, levels had to exceed 100 dB at 20 to 50 Hz.

Further Studies of Note

The influence of preconception on mood and physical symptoms after exposure to LFN was examined by showing 54 university

students one of two series of short videos that either promoted or dispelled the notion that sounds from wind turbines had health effects, then exposing subjects to 10 minutes of quiet period followed by infrasound (40 dB at 5 Hz) generated by computer software, and assessing mood and a series of physical symptoms.⁶⁹ In a double-blind protocol, participants first exposed to either a “high-expectancy” presentation included first-person accounts of symptoms attributed to wind turbines or a “low-expectancy” presentation showed experts stating scientific positions indicating that infrasound does not cause symptoms. Participants were then exposed to 10 minutes of infrasound and 10 minutes of sham infrasound. Physical symptoms were reported before and during each 10-minute exposure. The study showed that healthy volunteers, when given information designed to invoke either high or low expectations that exposure to infrasound causes symptom complaints, reported symptoms that were consistent with the level of expectation. These data demonstrate that the participants’ expectations of the wind turbine sounds determined their patterns of self-reported symptoms, regardless of whether the exposure was to a true or sham wind turbine sound. The concept known as a “nocebo” response, essentially the opposite of a placebo response, will be discussed in more detail later in this report. A nocebo response refers to how a preconceived negative reaction can occur in anticipation of an event.⁹⁶

A further study assessed whether positive or negative health information about infrasound generated by wind turbines affected participants’ symptoms and health perceptions in response to wind farm sound.⁷⁰ Both physical symptoms and mood were evaluated after exposure to LFN among 60 university students first shown high-expectancy or low-expectancy short videos intended to promote or dispel the notion that wind turbines sounds impacted health. One set of videos presented information indicating that exposure to wind turbine sound, particularly infrasound, poses a health risk, whereas the other set presented information that compared wind turbine sound to subaudible sound created by natural phenomena such as ocean waves and the wind, emphasizing their positive effects on health. Students were continuously exposed during two 7-minute listening sessions to both infrasound (50.4 dB, 9 Hz) and audible wind farm sound (43 dB), which had been recorded 1 km from a wind farm, and assessed for mood and a series of physical symptoms. Both high-expectancy and low-expectancy groups were made aware that they were listening to the sound of a wind farm and were being exposed to sound containing both audible and subaudible components and that the sound was at the same level during both sessions. Participants exposed to wind farm sound experienced a placebo response elicited by positive preexposure expectations, with those participants who were given expectations that infrasound produced health benefits reporting positive health effects. They concluded that reports of symptoms or negative effects could be nullified if expectations could be framed positively.

University students exposed to recorded sounds from locations 100 m from a series of Swedish wind turbines for 10 minutes were assessed for parameters of annoyance.⁹⁷ Sound was played at a level of 40 dBAeq (the “eq” refers to the average level over the 10-minute exposure). After the initial exposure, students were exposed to an additional 3 minutes of noise while filling out questionnaires. Authors reported that ratings of annoyance, relative annoyance, and awareness of noise were different among the different wind turbine recordings played at equivalent noise levels. Various psychoacoustic parameters (sharpness, loudness, roughness, fluctuation strength, and modulation) were assessed and then grouped into profiles. Attributes such as “lapping,” “swishing,” and “whistling” were more easily noticed and potentially annoying, whereas “low frequency” and “grinding” were associated with less intrusive and potentially less annoying sounds.

Adults exposed to sounds recorded from a 1.5 MW Korean wind turbine were assessed for the degree of noise annoyance.⁹⁸ Over

a 40-minute period, subjects were exposed to a series of 25 random 30-second bursts of wind turbine noise, separated by at least 10 seconds of quiet between bursts. Following a 3-minute quiet period, this pattern was repeated. Participants reported their annoyance on a scale of 1 to 11. Authors found that the amplitude modulation of wind turbine noise had a statistically significant effect on the subjects’ perception of noise annoyance.

The effect of psychological parameters on the perception of noise from wind turbines was also assessed in Italian adults from both urban and rural areas. Recorded sounds from different distances (150 m, 250 m, and 500 m) away from wind turbines were played while pictures of wind turbines were shown and subjects described their reaction to the pictures.⁷¹ Pictures differed in color, the number of wind turbines, and distance from wind turbines. Pictures had a weak effect on individual reactions to the number of wind turbines; the color of the wind turbines influenced both visual and auditory individual reactions, although in different ways.

Epilepsy and Wind Turbines

Rapidly changing visual stimuli, such as flashing lights or oscillating pattern changes, can trigger seizures in susceptible persons, including some who never develop spontaneous seizures; stimuli that change at rates of 12 to 30 Hz are most likely to trigger seizures.⁹⁹ Rotating blades (of a ceiling fan, helicopter, or wind turbine) that interrupt light can produce a flicker, leading to a concern that wind turbines might cause seizures. Nevertheless, large wind turbines (2 MW or more) typically rotate at rates less than 1 Hz; with three blades, the frequency of light interruption would be less than 3 Hz, a rate that would pose negligible risk to developing a photoepileptic seizure.¹⁰⁰

Smedley et al¹⁰¹ applied a complex simulation model of seizure risk to wind turbines, assuming worst-case conditions—a cloudless day, an observer looking directly toward the sun with wind turbine blades directly between the observer and the sun, but with eyes closed (which scatters the light more broadly on the retina); they concluded that there would be a risk of seizures at distances up to nine times the turbine height, but only when blade frequency exceeds 3 Hz, which would be rare for large wind turbines. Smaller turbines, typically providing power for a single structure, often rotate at higher frequencies and might pose more risk of provoking seizures. At the time of preparation of this report, there has been no published report of a photoepileptic seizure being triggered by looking at a rotating wind turbine.

Sleep and Wind Turbines

Sleep disturbance is relatively common in the general population and has numerous causes, including illness, depression, stress, and the use of medications, among others. Noise is well known to be potentially disruptive to sleep. The key issue with respect to wind turbines is whether the noise is sufficiently loud to disrupt sleep. Numerous environmental studies of noise from aviation, rail, and highways have addressed sleep implications, many of which are summarized in the WHO’s position paper on Nighttime Noise Guidelines.¹⁰² (Fig. 7). This consensus document is based on an expert analysis of environmental noise from sources other than wind turbines, including transportation, aviation, and railway noise. The WHO published the figure (Fig. 7) to indicate that significant sleep disturbance from environmental noise begins to occur at noise levels greater than 45 dBA. This figure is based on an analysis of pooled data from 24 different environmental noise studies, although no wind turbine-related noise studies were included in the analysis. Nonetheless, the studies provide substantial data on environmental noise exposure that can be contrasted with noise levels associated with wind turbine operations to enable one to draw reasonable inferences.

In contrast to the WHO position, an author in an editorial claimed that routine wind turbine operations that result in noise

levels less than 45 dBA can have substantial effects on sleep, with corresponding adverse health effects.¹⁰³ Another author, however, challenged the basis of the assertion by pointing out that Hanning had ignored 17 reviews on the topic with alternative perspectives and different results.¹⁰⁴

Sleep disturbance is a potential extra-auditory effect of noise, and research has shown a link between wind turbine noise and sleep disruption.^{4,55,61,64,105} As with the other variables reviewed, quantifying sleep quality is typically done with coarse measures. In fact, this reviewer identified no studies that used a multi-item validated sleep measure. Research studies typically rely on a single item (sometimes answered yes/no) to measure sleep quality. Such coarse measurement of sleep quality is unfortunate because impaired sleep is a plausible pathway by which wind turbine noise exposure may impact both psychological well-being and physical health.

Disturbed sleep can be associated with adverse health effects.¹⁰⁶ Awakening thresholds, however, depend on both physical and psychological factors. Signification is a psychological factor that refers to the meaning or attitude attached to a sound. Sound with high signification will awaken a sleeper at lower intensity than sound lacking signification.¹⁰⁶ As reviewed above, individuals often attach attitudes to wind turbine sound; as such, wind turbine sleep disruption may be impacted by psychological factors related to the sound source.

Shepherd et al⁶⁴ found a significant difference in perceived sleep quality between their wind farm and comparison groups, with the wind farm group reporting worse sleep quality. In the wind farm group, noise sensitivity was strongly correlated with sleep quality. In both the wind farm and comparison groups, sleep quality showed similar strong positive relationships with physical HRQL and psychological HRQL. Pedersen⁶¹ found that sound-level exposure was associated with sleep interruption in two of three studies reviewed; however, the effect sizes associated with sound exposure were minimal.

Bakker et al⁵⁵ found that noise exposure was related to sleep disturbance in quiet areas ($d = 0.40$) but not for individuals in noisy areas ($d = 0.02$). Nevertheless, when extreme sound exposure groups were composed,⁵⁵ data showed that individuals living in high sound areas (greater than 45 dBA) had significantly greater sleep disruption than subjects in low sound areas (less than 30 dBA). Annoyance rat-

ings were more strongly associated with sleep disruption.⁵⁵ Furthermore, when⁵⁵ structural equation models (SEMs) were applied, the direct association between sound level and sleep disruption was lost and annoyance seemed to mediate the effect of wind turbine sound on sleep disturbance. Across the reviewed studies it seems that sleep disruption was associated with sound-level exposure; however, the associations were weak and annoyance ratings were more strongly and consistently associated with self-reported sleep disruption.

Conclusions

Infrasound and low-frequency sound can be generated by the operation of wind turbines; however, neither low-frequency sound nor infrasound in the context of wind turbines or in experimental studies has been associated with adverse health effects.

Annoyance, Wind Turbines, and Potential Health Implications

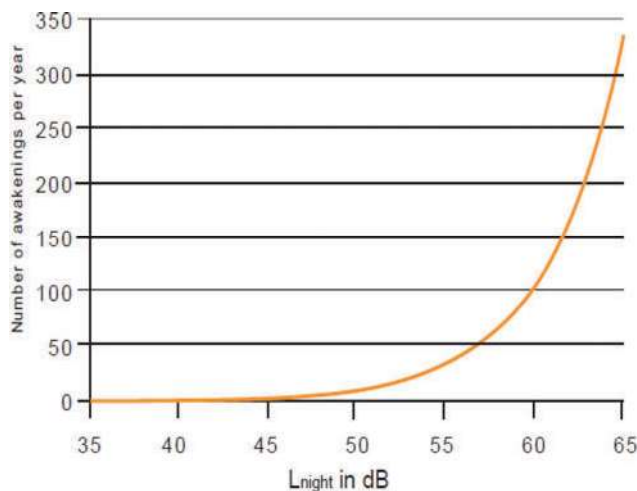
The potential effect of noise on health may occur through both physiological (sleep disturbance) and psychological pathways. Psychological factors related to noise annoyance reported in association with wind turbine noise will be reviewed and analyzed. A critique of the methodological adequacy of the existing wind turbine research as it relates to psychological outcomes will be addressed.

As noted earlier, “annoyance” has been used as an outcome measure in environmental noise studies for many decades. Annoyance is assessed via a questionnaire. Because annoyance has been associated under certain circumstances with living in the vicinity of wind turbines, this section examines the significance of annoyance, risk factors for reporting annoyance in the context of wind turbines, and potential health implications.

For many years, it has been recognized that exposure to high noise levels can adversely affect health^{107,108} and that environmental noise can adversely affect psychological and physical health.¹⁰⁹ Key to evaluating the health effects of noise exposure—like any hazard—is a thorough consideration of noise intensity and duration. When outcomes are broadened to include more subjective qualities like annoyance and QOL, additional psychological factors must be studied.

Noise-related annoyance is a subjective psychological condition that may result in anger, disappointment, dissatisfaction, withdrawal, helplessness, depression, anxiety, distraction, agitation, or exhaustion.¹¹⁰ Annoyance is primarily identified using standardized self-report questionnaires. Well-established psychiatric conditions like major depressive disorder are also subjective states that are most often identified by self-report questionnaires. Despite its subjective nature, noise annoyance was included as a negative health outcome by the WHO in their recent review of disease burden related to noise exposure.¹¹⁰ The inclusion of annoyance with conditions like cardiovascular disease reinforces its status as a legitimate primary health outcome for environmental noise research.

This section reviews the literature on the effect of wind turbines, including noise-related annoyance and its corresponding effect on health, QOL, and psychological well-being. “Quality of life” is a multidimensional concept that captures subjective aspects of an individual’s experience of functioning, well-being, and satisfaction across the physical, mental, and social domains of life. The WHO defines QOL as “an individual’s perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns. It is a broad ranging concept affected in complex ways by the person’s physical health, psychological status, personal beliefs, social relationships and their relationship to salient features of their environment”.^{111(p1404)} Numerous well-validated QOL measures are available, with the SF-12 and SF-36¹¹² and the WHO Quality of Life—Short Form (WHOQOL-BREF¹¹³) being among the most commonly used. Quality of life measures have been widely



Source: Miedema, Passchier-Vermeer and Vos, 2003

FIGURE 7. Worst-case prediction of noise-induced behavioral awakenings. Adapted from WHO¹⁰² (Chapter 3); Miedema et al.¹⁶³

adopted as primary outcomes for clinical trials and cost-effectiveness research.

Meta-analysis is a quantitative method for summarizing the relative strength of an effect or relationship as observed across multiple independent studies.¹¹⁴ The increased application of meta-analysis has had a considerable effect on how literature reviews are approached. Currently, more than 20 behavioral science journals require that authors report measures of effect size along with tests of significance.¹¹⁵ The use of effect size indicators enhances the comparability of findings across studies by changing the reported outcome statistics to a common metric. In behavioral health, the most frequently used effect size indicators are the Cohen d ¹¹⁶ and r the zero-order (univariate) correlation coefficient.¹¹⁵ An additional advantage of reporting outcomes as effect size units is that benchmarks exist for judging the magnitude of these (significant) differences. Studies reviewed below report an array of statistical analyses (the t test, analysis of variances, odds ratios, and point-biserial and biserial correlations), some of which are not suitable for conversion into the Cohen d ; thus, following the recommendations of McGrath and Meyer,¹¹⁵ r will be used as the common effect size measure for evaluating studies. As reference points, r between 0.10 and 0.23 represents small effects, r between 0.24 and 0.36 represents medium effects, and r of 0.37 and greater represent large effects.¹¹⁵ Although these values offer useful guidelines for comparing findings, it is important to realize that, in health-related research, very small effects with $r < 0.10$ can be of great importance¹¹⁷.

Noise Sensitivity

Noise sensitivity is a stable and normally distributed psychological trait,¹¹⁸ but predicting who will be annoyed by sound is not a straightforward process.¹¹⁹ Noise sensitivity has been raised as a major risk factor for reporting annoyance in the context of environmental noise.¹⁵⁴ Noise sensitivity is a psychological trait that affects how a person reacts to sound. Despite lacking a standard definition, people can usually reliably rate themselves as low (noise tolerant), average, or high on noise sensitivity questionnaires; those who rate themselves as high are by definition noise sensitive.

Noise-sensitive individuals react to environmental sound more easily, evaluate it more negatively, and experience stronger emotional reactions than noise tolerant people.^{120–122,146,150–152,156} Noise sensitivity is not related to objectively measured auditory thresholds,¹²³ intensity discrimination, auditory reaction time, or power-function exponents for loudness.¹¹⁸ Noise sensitivity reflects a psycho-physiological process with neurocognitive and psychological features. Noise-sensitive individuals have noise “annoyance thresholds” approximately 10 dB lower than noise tolerant individuals.¹²¹ Noise sensitivity has been described as increasing a person’s risk for experiencing annoyance when exposed to sound at low and moderate levels.^{4,155}

Noise-Related Annoyance

Noise sensitivity and noise-related annoyance are moderately correlated ($r = 0.32$ ¹¹⁸) but not isomorphic. The WHO¹¹⁰ defines noise annoyance as a subjective experience that may include anger, disappointment, dissatisfaction, withdrawal, helplessness, depression, anxiety, distraction, agitation, or exhaustion. A survey of an international group of noise researchers indicated that noise-related annoyance is multifaceted and includes both behavioral and emotional features.¹²⁴ This finding is consistent with Job’s¹²⁰ definition of noise annoyance as a state associated with a range of reactions, including frustration, anger, dysphoria, exhaustion, withdrawal, and helplessness.

Annoyance and Wind Turbine Sounds

As noted elsewhere in this review, Pedersen and colleagues^{56,59,60,63} conducted the world’s largest epidemiological

studies of people living in the vicinity of wind turbines. These studies have been discussed in detail in the epidemiological studies section of this review. Other authors have also addressed annoyance in the context of living near wind turbines.^{55,59,125,126} Pedersen⁶¹ later compared findings from the three cross-sectional epidemiological studies to identify common outcomes. Across all three studies, SPLs were associated with annoyance outside (r between 0.05 and 0.09) and inside of the people’s homes (r between 0.04 and 0.05). These effect sizes were all less than the small effect boundary of 0.10, meaning that sound levels played a minor role in annoyance. The percentages of people reporting annoyance with wind turbine noise ranged from 7% to 14% for indoor exposure and 18% to 33% for outside exposure.^{56,59} These rates are similar to those reported for exposure to other forms of environmental noise.¹²⁷

The dynamic nature of wind turbine sound may make it more annoying than other sources of community noise according to Pedersen et al.⁵⁶ They compared self-reported annoyance from other environmental noise exposure studies (aircraft, railways, road traffic, industry, and shunting yards) with annoyance from wind turbine sound. Proportionally, more subjects were annoyed with wind turbine sound at levels lower than 50 dB than with all other sources of noise exposure, except for shunting yards. Pedersen and Waye^{105,126} reported that the sound characteristics of swishing ($r = 0.70$) and whistling ($r = 0.62$) were highly correlated with annoyance to wind turbine sound. Others have reported similar findings. One author has suggested that wind turbine sound may have acoustic qualities that may make it more annoying at certain noise levels.⁷⁸ Other theories for symptoms described in association with living near wind turbines have also been proposed.¹⁴⁰

Annoyance associated with wind turbine sounds tends to show a linear association. Sound levels, however, explain only between 9% ($r = 0.31$) and 13% ($r = 0.36$) of the variance in annoyance ratings.^{55,59} Therefore, SPLs seem to play a significant, albeit limited, role in the experience of annoyance associated with wind turbines, a conclusion similar to that reached by Knopper and Ollson.⁴

Nonacoustical Factors Associated With Annoyance

Although noise levels and noise sensitivity affect the risk of a person reporting annoyance, nonacoustic factors also play a role, including the visual effect of the turbines, whether a person derives economic benefit from the turbines and the type of terrain where one lives.^{4,148} Pedersen and Waye⁵⁹ assessed the effect of visual/perceptual factors on wind turbine-related annoyance; all of the variables described above were significantly related to self-reported annoyance after controlling for SPLs. Nevertheless, when these variables were evaluated simultaneously, only attitude to the visual effect of the turbines remained significantly related to annoyance ($r = 0.41$, which can be interpreted as a large effect) beyond sound exposure. Pedersen and Waye¹²⁶ also found visual effect to be a significant factor in addition to sound exposure for self-reported annoyance to wind turbine sounds. Pedersen et al⁵⁶ explored the effect of visual attitude on wind turbine sound-related annoyance. Logistic regression showed that sound levels, noise sensitivity, attitudes toward wind turbines, and visual effect were all significant independent predictors of annoyance. Nevertheless, visual attitudes showed an effect size of $r = 0.27$ (medium effect), whereas noise sensitivity had an r of 0.09. Other authors have also found the visual effect of wind turbines to be related to annoyance ratings.¹²⁸ Results from multiple studies support the conclusion that visual effect contributes to wind turbine annoyance,⁴ with this review finding visual effect to have an effect size in the medium to large range. Nevertheless, given that noise sensitivity and visual attitude are consistently correlated ($r = 0.19$ and $r = 0.26$, respectively),^{56,59} it is possible that visual effect enhances annoyance through multisensory (visual and auditory) activation of the noise-sensitivity trait.

Economic Benefit, Wind Turbines, and Annoyance

Some studies have indicated that people who derive economic benefit from wind turbines are less likely to report annoyance. Pedersen et al⁵⁶ found that people who benefited economically ($n = 103$) from wind turbines reported significantly less annoyance despite being exposed to relatively high levels of wind turbine noise. The annoyance mitigating effect of economic benefit was replicated in Bakker et al.⁵⁵ The mitigation effect of economic benefit seems to be within the small effect size range ($r = 0.15$).⁵⁵ In addition, because receiving economic benefit represents a personal choice to have wind turbines on their property in exchange for compensation, the involvement of subject selection factors (ie, noise tolerance) requires additional study.

Annoyance, Quality of Life, Well-being, and Psychological Distress

The largest cross-sectional epidemiological study of wind turbine noise on QOL was conducted in northern Poland.⁶⁵ Surveys were completed by 1277 adults (703 women and 574 men), aged 18 to 94 years, representing a 10% two-stage random sample of the selected communities. Although the response rate was not reported, participants were sequentially enrolled until a 10% sample was achieved, and the proportion of individuals invited to participate but unable or refusing to participate was estimated at 30% (B. Mroczek, personal communication). Proximity of residence was the exposure variable, with 220 (17.2%) respondents within 700 m, 279 (21.9%) between 700 and 1000 m, 221 (17.3%) between 1000 and 1500 m, and 424 (33.2%) residing more than 1500 m from the nearest wind turbine. Several indicators of QOL, measured using the SF-36, were analyzed by proximity to wind turbines. The SF-36 consists of 36 questions divided into the following subscales: physical functioning, role-functioning physical, bodily pain, general health, vitality, social functioning, role-functioning emotional, and mental health. An additional question concerning health change was included, as well as the Visual Analogue Scale for health assessment. It is unclear whether age, sex, education, and occupation were controlled. The authors report that within all subscales, those living closest to wind farms reported the best QOL, and those living farther than 1500 m scored the worst. They concluded that living in close proximity to wind farms does not result in worsening of the QOL.⁶⁵ The authors recommend that subsequent research evaluate the reasons for the higher QOL and health indicators associated with living in closer proximity to wind farms. They speculated that these might include economic factors such as opportunities for employment with or renting land to the wind farm companies.

Individuals living closer to wind farms reported higher levels of mental health ($r = 0.11$), physical role functioning ($r = 0.07$), and vitality ($r = 0.10$) than did those living farther away.⁶⁵ Nevertheless, the implications of the study⁶⁵ are unclear, as the authors did not estimate sound-level exposure or obtain noise annoyance ratings from their subjects. Overall, with the exception of the study by Mroczek et al,⁶⁵ noise annoyance demonstrated a consistent small to medium effect on QOL and psychological well-being.

A study a year earlier of 39 individuals in New Zealand came to different conclusions than the Polish study.¹²⁹ Survey results from 39 residents located within 2 km of a wind turbine in the South Makara Valley in New Zealand were compared with 139 geographically and socioeconomically matched individuals who resided at least 8 km from any wind farm. The response rates for both the proximal and more distant study groups were poor, that is, 34% and 32%, respectively, although efforts were made to blind respondents to the study hypotheses. No other indicator of exposure to wind turbines was included beyond the selection of individuals from within 2 km or beyond 8 km of a wind turbine, so actual or calculated wind turbine noise exposures were not available. Subjective HRQOL scales were

used to describe and compare the self-reported physical, psychological, and social well-being for each group. Health-related quality of life measures are believed to provide an alternative approach to direct health assessment in that decrements in well-being are assumed to be sensitive to and reflect possible underlying health effects. The authors reported statistically significant differences between the groups in some HRQOL domain scores, with residents living within 2 km of a turbine installation reporting lower mean physical HRQOL domain score (including lower component scores for sleep quality and self-reported energy levels) and lower mean environmental QOL scores (including lower component scores for considering one's environment to be less healthy and being less satisfied with the conditions of their living space). The wind farm group scored significantly lower on physical HRQL ($r = 0.21$), environmental QOL ($r = 0.19$), and overall HRQL ($r = 0.10$) relative to the comparison group. Although the psychological QOL ratings were not significantly different ($P = 0.06$), the wind farm group also scored lower on this measure ($r = 0.16$). In the wind farm group, noise sensitivity was strongly correlated with noise annoyance ($r = 0.44$), psychological HRQL ($r = 0.40$), and social HRQOL ($r = 0.35$). These correlations approach or exceed the large effect size boundary ($r > 0.37$ suggested by Cohen).

There were no differences seen for social or psychological HRQOL domain scores. The turbine group also reported lower amenity scores, which are based on responses to two general questions—"I am satisfied with my neighborhood/living environment," and "My neighborhood/living environment makes it difficult for me to relax at home." No differences were reported between groups for traffic or neighborhood noise annoyance. Lack of actual wind turbine and other noise source measurements, combined with the low response rate (both noted by the authors as limitations), limits the inferential value of this study because it might pertain to wind turbine emissions.

Across three studies, Pedersen⁶¹ found that outdoor annoyance with turbine sound was associated with tension and stress ($r = 0.05$ to 0.06) and irritability ($r = 0.05$ to 0.08), qualities associated with psychological distress. Bakker et al⁵⁵ also found that psychological distress was significantly related to wind turbine sound ($r = 0.16$), reported outside annoyance ($r = 0.18$) and inside annoyance ($r = 0.24$). Taylor et al⁶⁷ found that subjects living in areas with a low probability of hearing turbine noise reported significantly higher levels of positive affect than those living in moderate or high noise areas ($r = 0.24$), suggesting greater well-being for the low noise group.

Personality Factors and Wind Turbine Sound

Personality psychologists use five bipolar dimensions (neuroticism, extraversion-introversion, openness, agreeableness, and conscientiousness) to organize personality traits.¹³⁰ Two of these dimensions, neuroticism and extraversion-introversion, have been studied in relation to noise sensitivity and annoyance. Neuroticism is characterized by negative emotional reactions, sensitivity to harmful cues in the environment, and a tendency to evaluate situations as threatening.¹³¹ Introversion (the opposite pole of extraversion) is characterized by social avoidance, timidity, and inhibition.¹³¹ A strong negative correlation has been shown between noise sensitivity (self-ratings) and self-rated extraversion,¹²³ suggesting that introverts are more noise sensitive. Introverts experience a greater disruption in vigilance when exposed to low-intensity noise than do extroverts.¹³² Extroverts and introverts differ in terms of stimulation thresholds with introverts being more easily overstimulated than extroverts.¹³³ Despite these studies, the potential link between broad personality domains and noise annoyance remains unclear.

Taylor et al⁶⁷ explored the role of neuroticism, attitude toward wind turbines, negative oriented personality (NOP) traits (negative affectivity, frustration intolerance), and self-reported nonspecific

somatic symptoms (NSS) in reaction to wind turbine noise. Despite one of the few peer-reviewed studies of personality and noise sensitivity, it only achieved a 10% response rate, which raises questions as to the representativeness of the findings. Nonetheless, the study sample reported a moderately positive attitude toward wind turbines in general and seemed representative of the local community. In the study by Taylor et al,⁶⁷ zero-order correlations showed that estimated sound levels were significantly related to perceived turbine noise ($r = 0.33$) and reduced positive affect ($r = -0.32$) but not to non-specific symptoms ($r = 0.002$), whereas neuroticism and NOP traits were significantly related to NSS (r of 0.44 and 0.34, respectively). Multivariate analysis suggested that high NOP traits moderated the relationship between perceived noise and the report of NSS; that is, subjects with higher NOP traits reported significantly more NSS than did subjects low in NOP across the range of perceived loudness of noise.

Nocebo Response

The nocebo response refers to new or worsening symptoms produced by negative expectations.^{96,134} When negatively worded pretreatment information (“could lead to a slight increase in pain”) was given to a group of chronic back pain patients, they reported significantly more pain ($r = 0.38$) and had worse physical performance ($r = 0.36$).⁹⁶ These effect sizes are within the moderate to large ranges and reflect a meaningful adverse effect for the negative information contributing to the nocebo response. The effect of providing negative information regarding wind turbines prior to exposure to infrasound has been experimentally explored. Crichton et al¹³⁵ exposed college students to sham and true infrasound under high-expectancy (ie, adverse health effects from wind turbines) and low-expectancy (ie, no adverse health effects) conditions. The high-expectancy group received unfavorable information from TV and Internet accounts of symptoms associated with wind farm noise, whereas the low-expectancy group heard experts stating that wind farms would not cause symptoms. Symptoms were assessed pre- and postexposure to actual and sham infrasound. The high-expectancy group reported significantly more symptoms ($r = 0.37$) and greater symptom intensity ($r = 0.37$) following both sham and true infrasound exposure ($r = 0.65$ and 0.48 , respectively). The effect sizes were similar to those found in medical research on the nocebo response. These findings demonstrate that exposing individuals to negative information can increase symptom reporting immediately following exposure. The inclusion of information from TV and the Internet suggests that similar reactions may occur in real-world settings.

A study by Deignan et al¹³⁶ analyzed newspaper coverage of wind turbines in Canada and found that media coverage might contribute to nocebo responses. Newspaper coverage contained fright factor words like “dread,” “poorly understood by science,” “inequitable,” and “inescapable exposure”; the use of “dread” and “poorly understood by science” had increased from 2007 to 2011. These results document the use of fright factor words in the popular coverage of wind turbine debates; exposure to information containing these words may contribute to nocebo reactions in some people.

Wind turbines, similar to multiple technologies, such as power lines, cell phone towers, and WiFi signals, among others, have been associated with clusters of unexplained symptoms. Research suggests that people are increasingly worried about the effect of modern life (in particular emerging technologies) on their health (modern health worries [MHW]).¹³⁷ Modern Health Worries are moderately correlated with negative affect ($r = 0.23$) and, like the nocebo response, are considered psychogenic in origin. The expansion of wind turbine energy has been accompanied by substantial positive and negative publicity that may contribute to MHW and nocebo responses among some people exposed to this information. Health concerns have also been raised about the potential of electromagnetic fields

associated with wind turbine operations; however, a recent study indicated that magnetic fields in the vicinity of wind turbines were lower than those produced by common household items.¹³⁸

Chapman et al⁵⁰ explored the pattern of formal complaints (health and noise) made in relation to 51 wind farms in Australia from 1993 to 2012. The authors suggest that their study is a test of the psychogenic (nocebo or MHW) hypothesis. The findings showed that very few complaints were formally lodged; only 129 individuals in Australia formally or publically complained during the time period studied, and the majority of wind farms had no complaint made against them. The authors found that complaints increased around 2009 when “wind turbine syndrome” was introduced. On the basis of these findings, the authors conclude that nocebo effects likely play an important role in wind farm health complaints. But the authors do report that the vast majority of complaints (16 out of 18) were filed by individuals living near large wind farms ($r = 0.32$). So while few individuals complain, those who do almost exclusively live near large wind farms. Nevertheless, it is important to note that filing a formal or public complaint is a complex sociopolitical action, not a health-related outcome. Furthermore, analysis of data provided in Table 2 of the Chapman⁵² study shows that the strongest predictor of a formal complaint was the presence of an opposition group in the area of the wind farm. A review of Table 2 shows that opposition groups were present in 15 of the 18 sites that filled complaints, whereas there was only one opposition group in the 33 areas that did not file a complaint ($r = 0.82$). Therefore, the relevance of this study for understanding health effects of wind turbines is limited. Chapman has also addressed the multitude of reasons why some Australian home owners may have left their homes and attributed the decision to wind turbines.⁵² Gross¹³⁸ provides a community justice model designed to counter the potential for nocebo or psychogenic response to wind farm development. This method was pilot tested in one community and showed the potential to increase the sense of fairness for diverse community members. No empirical data were gathered during the pilot study so the effect of method cannot be formally evaluated.

Conclusions

Annoyance is a recognized health outcome measure that has been used in studies of environmental noise for many decades. Noise levels have been shown to account for only a modest portion of self-reported annoyance in the context of wind turbines ($r = 0.35$).⁴ Noise sensitivity, a stable psychological trait, contributes equally to exposure in explaining annoyance levels ($r = 0.37$). Annoyance associated with wind turbine noise shows a consistent small to medium adverse effect on self-rated QOL and psychological well-being. Given the coarseness of measures used in many studies, the magnitude of these findings are likely attenuated¹³⁹ and underestimate the effect of annoyance on QOL. Visual effect increases annoyance beyond sound exposure and noise sensitivity, but at present there is insufficient research to conclude that visual effect operates separately from noise sensitivity because the two variables are correlated. Wind turbine development is subject to the same global psychogenic health worries and nocebo reactions as other modern technologies.¹⁴⁰

Economic benefit mitigates the effect of wind turbine sound; however, research is needed to clarify the potential confounding role of (self) selection in this finding. The most powerful multivariate model reviewed⁵⁹ accounted for approximately 50% ($r = 0.69$) of the variance in reported annoyance, leaving 50% unexplained. Clearly other relevant factors likely remain unidentified. Nevertheless, it is not unusual for there to be a significant percentage of unexplained variance in biomedical or social science research. For example, a meta-analysis of postoperative pain (a subjective experience), covering 48 studies and 23,037 subjects, found that only 54% ($r = 0.73$) of the variance in pain ratings could be explained by the variables included in the studies.¹⁴¹ Wind turbine development is subject to

the same global psychogenic health worries and nocebo reactions as other modern technologies.¹⁴² Therefore, communities, government agency, and companies would be well advised to adopt an open, transparent, and engaging process when debating the potential effect of wind turbine sites.¹⁴³ The vast majority of findings reviewed in this section were correlational and, therefore, do not imply causality, and that other as of yet unidentified (unmeasured) factors may be associated with or responsible for these findings.

DISCUSSION

Despite the limitations of available research related to wind turbines and health, inferences can be drawn from this information, if used in concert with available scientific evidence from other environmental noise studies, many of which have been reviewed and assessed for public policy in the WHO's Nighttime Noise Guidelines.¹⁰² A substantial database on environmental noise studies related to transportation, aviation, and rail has been published.¹⁴² Many of these studies have been used to develop worldwide regulatory noise guidelines, such as those of the WHO,¹⁰² which have proposed nighttime noise levels primarily focused on preventing sleep disturbance.

Because sound and its components are the potential health hazards associated with living near wind turbines, an assessment of other environmental noise studies can offer a valuable perspective in assessing health risks for people living near wind turbines. For example, one would not expect adverse health effects to occur at lower noise levels if the same effects do not occur at higher noise levels. In the studies of other environmental noise sources, noise levels have been considerably higher than those associated with wind turbines. Noise differences as broad as 15 dBA (eg, 55 dBA in highways vs 40 dBA from wind turbines) have been regularly reported.¹⁴² In settings where anthropogenic changes are perceived, indirect effects such as annoyance have been reported, and these must also be considered in the evaluation of health effects.

We now attempt to address three fundamental questions posed at the beginning of this review related to potential health implications of wind turbines.

Is there available scientific evidence to conclude that wind turbines adversely affect human health? If so, what are the circumstances associated with such effects and how might they be prevented?

The epidemiological and experimental literature provides no convincing or consistent evidence that wind turbine noise is associated with any well-defined disease outcome. What is suggested by this literature, however, is that varying proportions of people residing near wind turbine facilities report annoyance with the turbines or turbine noise. It has been suggested by some authors of these studies that this annoyance may contribute to sleep disruption and/or stress and, therefore, lead to other health consequences. This self-reported annoyance, however, has not been reported consistently and, when observed, arises from cross-sectional surveys that inherently cannot discern whether the wind turbine noise emissions play any direct causal role. Beyond these methodological limitations, such results have been associated with other mediating factors (including personality and attitudinal characteristics), reverse causation (ie, disturbed sleep or the presence of a headache increases the perception of and association with wind turbine noise), and personal incentives (whether economic benefit is available for living near the turbines).

There are no available cohort or longitudinal studies that can more definitively address the question about causal links between wind turbine operations and adverse health effects. Nevertheless, results from cross-sectional and experimental studies, as well as studies of other environmental noise sources, can provide valuable information in assessing risk. On the basis of the published cross-sectional epidemiological studies, "annoyance" is the main outcome

measure that has been raised in the context of living in the vicinity of wind turbines. Whether annoyance is an adverse health effect, however, is disputable. "Annoyance" is not listed in the International Classification of Diseases (10th edition), although it has been suggested by some that annoyance may lead to stress and to other health consequences, such as sleep disturbance. This proposed mechanism, however, has not been demonstrated in studies using methods capable of elucidating such pathways.

The authors of this review are aware of the Internet sites and non-peer-reviewed reports, in which some people have described symptoms that they attribute to living near wind turbines. The quality of this information, however, is severely limited such that reasonable assessments cannot be made about direct causal links between the wind turbines and symptoms reported. For example, inviting only people who feel they have symptoms because of wind turbines to participate in surveys and asking people to remember events in the past in the context of a current concern (ie, postturbine installation) introduce selection and recall biases, respectively. Such major biases compromise the reliability of the information as used in any rigorous causality assessment. Nonetheless, consistent associations have been reported between annoyance, sleep disturbance, and altered QOL among some people living near wind turbines. It is not possible to properly evaluate causal links of these claims in the absence of a thorough medical assessment, proper noise studies, and a valid study approach. The symptoms reported tend to be nonspecific and associated with various other illnesses. Personality factors, including self-assessed noise sensitivity, attitudes toward wind energy, and nocebo-like reactions, may play a role in the reporting of these symptoms. In the absence of thorough medical evaluations that include a characterization of the noise exposure and a diagnostic medical evaluation, confirmation that the symptoms are due to living near wind turbines cannot be made with any reliability. In fact, the use of a proposed case definition that seemed in a journal not indexed by PubMed can lead to misleading and incorrect assessments of people's health, if performed in the absence of a thorough diagnostic evaluation.¹⁴³ We recommend that people who suspect that they have symptoms from living near wind turbines undergo a thorough medical evaluation to identify all potential causes of and contributors to the symptoms. Attributing symptoms to living near wind turbines in the absence of a comprehensive medical evaluation is not medically appropriate. It is in the person's best interest to be properly evaluated to ensure that recognized and treatable illnesses are recognized.

Available scientific evidence does not provide support for any bona fide-specific illness arising out of living in the vicinity of wind turbines. Nonetheless, it seems that an array of factors contribute to some proportion of those living in proximity to wind turbines, reporting some degree of annoyance. The effect of prolonged annoyance—regardless of its source or causes—may have other health consequences, such as increasing stress; however, this cannot be demonstrated with the existing scientific literature on annoyance associated with wind turbine noise or visibility.

Is there available scientific evidence to conclude that psychological stress, annoyance, and sleep disturbance can occur as a result of living in proximity to wind turbines? Do these effects lead to adverse health effects? If so, what are the circumstances associated with such effects and how might they be prevented?

Available research is not suitable for assessing causality because the major epidemiological studies conducted to date have been cross-sectional, data from which do not allow the evaluation of the temporal relationship between any observed correlated factors. Cross-sectional studies, despite their inherent limitations in assessing causal links, however, have consistently shown that some people living near wind turbines are more likely to report annoyance than

those living farther away. These same studies have also shown that a person's likelihood of reporting annoyance is strongly related to their attitudes toward wind turbines, the visual aspect of the turbines, and whether they obtain economic benefit from the turbines. Our review suggests that these other risk factors play a more significant role than noise from wind turbines in people reporting annoyance.

The effect of annoyance on a person's health is likely to vary considerably, based on various factors. To minimize these reactions, solutions may include informative discussions with area residents before developing plans for a wind farm along with open communications of plans and a trusted approach to responding to questions and resolving noise-related complaints.

Is there evidence to suggest that specific aspects of wind turbine sound such as infrasound and low-frequency sound have unique potential health effects not associated with other sources of environmental noise?

Both infrasound and low-frequency sound have been raised as possibly unique health hazards associated with wind turbine operations. There is no scientific evidence, however, including results from field measurements of wind turbine-related noise and experimental studies in which people have been purposely exposed to infrasound, to support this hypothesis. Measurements of low-frequency sound, infrasound, tonal sound emission, and amplitude-modulated sound show that infrasound is emitted by wind turbines, but that the levels at customary distances to homes are well below audibility thresholds, even at residences where people have reported symptoms that they attribute to wind turbines. These levels of infrasound—as close as 300 m from the turbines—are not audible. Moreover, experimental studies of people exposed to much higher levels of infrasound than levels measured near wind turbines have not indicated adverse health effects. Because infrasound is associated more with vibratory effects than high-frequency sound, it has been suggested that the vibration from infrasound may be contributing to certain physical sensations described by some people living near wind turbines. These sensations are difficult to reconcile in light of field studies that indicated that infrasound at distances more than 300 m for a wind turbine meet international standards for preventing rattling and other potential vibratory effects.¹³

Areas for Further Inquiry

In light of the limitations of available studies for drawing definitive conclusions and the need to address health-related concerns associated with wind turbines raised by some nearby residents, each author discussed potential areas of further inquiry to address current data gaps. These recommendations primarily address exposure characterization, health endpoints, and the type of epidemiological study most likely to lead to informative results regarding potential health effects associated with living near wind turbines.

Noise From Wind Turbines

As with any potential occupational or environmental hazard, further efforts at exposure characterization, that is, noise and its components such as infrasound and low-frequency sound, would be valuable. Ideally, uniform equipment and standardized methods of measurement can be used to enable comparison with results from published studies and evaluate adherence to public policy guidelines.

Efforts directed at evaluating models used to predict noise levels from wind turbines—in contrast to actual measured noise levels—would be valuable and may be helpful in informing and reassuring residents involved in public discussions related to the development of wind energy projects. Efforts at fine tuning noise models for accuracy to real-world situations can be reassuring to public health officials charged with evaluating potential health effects of noise. The development and the use of reliable and portable noise measuring devices to address components of noise near residences and

evaluating symptoms and compliance with noise guidelines would be valuable.

Epidemiology

Prospective cohort studies would be most informative for identifying potential health effects of exposure to wind turbine noise before and after wind turbines are installed and operating. Ideally, substantially large populations would be evaluated for baseline health status, and subsequently part of the population would become exposed to wind turbines and part would remain unexposed, as in an area where large wind turbine farms are proposed or planned. The value of such studies is in the avoidance of several forms of bias such as recall bias, where study participants might, relying on recall, under- or overreport risk factors or diseases that occurred sometime in the past. As has been noted by several authors, the level of attention given the topic of wind turbines and possible health effects in the news and the Internet makes it difficult to study any population truly “blinded” to the hypotheses being evaluated. The main advantage of prospective cohort studies with a pre- and post-wind turbine component is the direct ability to compare changes in disease and health status among individuals subsequently exposed to wind turbine noise with those among similar groups of people not exposed. These conditions are not readily approximated by any other study approach. A similar but more complex approach could include populations about to become exposed to other anthropogenic stimuli, such as highways, railroads, commercial centers, or other power generation sources.

We note that additional cross-sectional studies may not be capable of contributing meaningfully and in fact might reinforce biases already seen in many cross-sectional studies and surveys.

Sound and Its Components

Several types of efforts can be undertaken to test hypotheses proposed about inaudible sound being a risk for causing adverse health effects. It would be simple, at least conceptually, to expose blinded subjects to inaudible sounds, especially in the infrasound range, to determine whether they could detect the sounds or whether they developed any unpleasant symptoms. Ideally, these studies would use infrasound levels that are close to hearing thresholds and comparable with real-world wind turbine levels at residential distances. Crichton et al^{135,144} have begun such studies, finding that subjects could not detect any difference between infrasound and sham “exposures.” The infrasound stimulus used, however, was only 40 dB at 5 Hz, more than 60 dB lower than hearing threshold and lower than levels measured at some residences near wind turbines.

The possibility of adverse effects from inaudible sound could also be tested in humans or animals in long-term studies. To date, there seem to be no reports of adverse effects in people exposed to wind turbine noise that they could never hear (such reports would require careful controls), nor are any relevant animal studies known to the authors of this review.

Controlled human exposure studies have been used to gain insight into the effects of exposure to LFN from wind turbines. Human volunteers are exposed for a short amount of time under defined conditions, sometimes following various forms of preconditioning, and different response metrics evaluated. Most of these studies addressed wind turbine noise annoyance but no direct health indicator; however, one study addressed visual reaction to the color of wind turbines in pictures,⁷¹ and another evaluated physical symptoms in response to wind turbine noise.^{135,144}

Efforts to document a potential effect of infrasound on health have been unsuccessful, including searches for responses to sound from cochlear type II afferent neurons or responses to inaudible airborne sound from the vestibular system. But in other cases, the relevant experiments (can inaudible sound cause endolymphatic hydrops?) seem not to have been conducted to date. This seemingly

improbable hypothesis, however, could be tested in guinea pigs, which reliably develops endolymphatic hydrops in response to other experimental interventions.

Psychological Factors

This review has demonstrated that a complex combination of noise and personal factors contributes to some people reporting annoyance in the context of living near wind turbines. Further efforts at characterizing and understanding these issues can be directed to improvements in measurement of sound perception, data analysis, and conceptualization.

We suggest improvements in the quality and standardization of measurement for important constructs like noise sensitivity and noise annoyance across studies. We also suggest eliminating the use of single-item “measures” for primary outcomes.

Data analysis should ideally include effect size measures in all studies to supplement the significance testing (some significant differences are small when sample sizes are large). This will help improve the comparability of findings across studies.

Integrate noise sensitivity, noise annoyance, and QOL into a broader more comprehensive theory of personality or psychological functioning, such as the widely accepted five-factor model of personality.

SUMMARY

1. Measurements of low-frequency sound, infrasound, tonal sound emission, and amplitude-modulated sound show that infrasound is emitted by wind turbines. The levels of infrasound at customary distances to homes are typically well below audibility thresholds.
2. No cohort or case-control studies were located in this updated review of the peer-reviewed literature. Nevertheless, among the cross-sectional studies of better quality, no clear or consistent association is seen between wind turbine noise and any reported disease or other indicator of harm to human health.
3. Components of wind turbine sound, including infrasound and low-frequency sound, have not been shown to present unique health risks to people living near wind turbines.
4. Annoyance associated with living near wind turbines is a complex phenomenon related to personal factors. Noise from turbines plays a minor role in comparison with other factors in leading people to report annoyance in the context of wind turbines.

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Health Effects Related to Wind Turbine Sound, Including Low-Frequency Sound and Infrasound

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Abstract A narrative review of observational and experimental studies was conducted to assess the association between exposure to wind turbine sound and its components and health effects in the general population. Literature databases Scopus, Medline and Embase and additional bibliographic sources such as reference sections of key publications and journal databases were systematically searched for peer-reviewed studies published from 2009 to 2017. For the period until early 2015 only reviews were included, while for the period between January 2015 and January 2017 all relevant publications were screened. Ten reviews and 22 studies met the inclusion criteria. Most studies examined subjective annoyance as the primary outcome, indicating an association between exposure levels and the percentage highly annoyed. Sound from wind turbines leads to a higher percentage of highly annoyed when compared to other sound sources. Annoyance due to aspects, like shadow flicker, the visual (in) appropriateness in the landscape and blinking lights, can add to the noise annoyance. There is no evidence of a specific effect of the low-frequency component nor of infrasound. There are indications that the rhythmic pressure pulses on a building can lead to additional annoyance indoors. Personal characteristics such as noise sensitivity, privacy issues and social acceptance, benefits and attitudes, the local situation and the conditions of planning a wind farm also play a role in reported annoyance. Less data are available to evaluate the effects of wind turbines on sleep and long-term health effects. Sleep disturbance as well as other health effects in the vicinity of wind turbines was found to be related to annoyance, rather than directly to exposure.

Keywords Health effects · Wind turbine sound · Infrasound · Low-frequency noise · Observational studies · Experimental studies

1 Introduction

Globally, the use of sustainable sources of energy such as biomass, water power, solar and wind energy is increasing in order to reduce the use of fossil fuel. Worldwide targets are set for an increase in sustainable energy. As a result, it can be expected that the number of wind farms will keep growing

in the years to come and more people will have them in their immediate living environment. Most people have a positive attitude towards alternative energy sources; for example, in the Netherlands in 2006 90% of the population was positive about solar energy and 79%¹ was positive about wind energy. However, although the benefits at national and global level are recognized, viz. a reduction in atmospheric carbon dioxide concentration, at a local level people often oppose wind farm plans. The awareness of the consequences of a wind farm can lead to intense, and sometimes emotional discussions about the need for wind energy, the suitability of the area, the visual and aesthetic aspects and noise-related issues

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¹ Special Eurobarometer, Attitudes towards energy. European Commission (2006).

are not uncommon. Health effects of living in the vicinity of the turbines are often part of the discussion. The association between wind turbines and human responses is a complex one, and many factors play a role in the public debate. At the local level attention is often focused on the potentially negative health effects of living near a wind turbine.

This paper addresses the state of the art regarding health effects related to wind turbine sound and is based on a manuscript prepared at the request of the Noise and NIR Division of the Swiss Federal Office for the Environment (Bundesamt für Umwelt). Although several excellent reviews on this topic have been published, we think it is worthwhile to publish this narrative review because several large studies have been completed after publication of the most recent meta-analysis [1]. Also, this review addresses the effects to living in the vicinity of wind turbines (WT's) in a broader physical and social context and includes the evidence for possible health effects of the low-frequency and infrasound components. And finally, we made an effort to write a text that is accessible for a broader audience.

In this text we use the word 'sound' when it refers to sound in a neutral sense. The sound of WT's is not always perceived as negative as the word 'noise' (meaning: unwanted sound) would suggest. The term WT noise is quite common but in our opinion only correct when it refers to negative effects, such as in 'noise annoyance'. When it does, we may also use the word 'noise'.

In line with the definition of health as 'a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity' of the World Health Organization (WHO) [2], noise annoyance and sleep disturbance are considered here as health effects [3]² [4].

Because this review aims at a broad audience, it might be useful to explain briefly WT sound itself. We therefore start in Sects. 1.1 to 1.3 with an explanation of the sound produced by and heard from a wind turbine and what sound levels occur in practice. After a description of methods used in this review in Sects. 2 and 3 first summarizes the evidence from existing reviews. This is followed by a more detailed description of studies not covered in these reviews. In both parts the key issue is how sound from a wind turbine can affect people, especially neighbouring residents, and in what way and to what degree other factors are important to take into account. This is repeated in Sect. 4 for sound at (very) low frequencies that allegedly can affect people in other ways than 'normal' sound does. Here we use the term 'normal' sound casually when it is easily recognizable as sound and can be heard; this

does not include infrasound or low levels of other sound that are normally considered to be inaudible.

Our conclusions from reading and interpreting all the scientific information are summarized in Sect. 5 that concludes the main text.

1.1 Sound Production and Character

An overview of wind turbine sound sources can be found in a number of publications such as [5–8]. For the tall, modern turbines most sound comes from flowing air in contact with the wind turbine blades: aerodynamical sound. The most important contributions are related to the atmospheric turbulence hitting the blades (inflow turbulence sound) and air flowing at the blade surface (trailing edge sound).

- Turbulence at the rear or trailing edge of a blade is generated because the air flow at the blade surface develops into a turbulent layer. The frequency with the highest (audible) sound energy content is usually in the range of a few hundred Hz up to around 1000–2000 Hz. At the blade tips conditions are somewhat different due to air flowing towards the tip, but this tip noise is very similar to trailing edge noise and usually not distinguished as a relevant separate source.
- Inflow turbulence is generated because the blade cuts through turbulent eddies that are present in the inflowing air (wind). This sound has a maximum sound level at around 10 Hz.
- Thickness sound results from the displacement of air by a moving blade and is insignificant for sound production when the air flows smoothly around the blade. However, rapid changes in forces on the blade result in sudden sideways movements of the blade and sound pulses in the infrasound region. This leads to the typical wind turbine sound 'signature' of sound level peaks at frequencies between about 1–10 Hz. These peaks cannot be heard, but can be seen in measurements.

Inflow turbulence sound is important in the low- and middle-frequency range, overlapping with trailing edge sound at medium and higher frequencies. As both are highly speed dependent, sound production is high where the speed is high and highest near the fast rotating tips of the blades. Wind turbine sound can sometimes be tonal, i.e. one can hear a specific pitch. This can be mechanical sound from the gear box and other devices in the turbine which was a relevant source for early turbines. Another possible source is an irregularity on a blade, but this is apparently rare and can be mended.

When the sound penetrates into a dwelling, the building construction will attenuate the higher frequencies better than the lower frequencies. As a result, indoor levels will be lower and the sound inside is of a lower pitch, as higher frequencies

² Although high annoyance is not classified as a disease in the International Classification of Disease (ICD-9; ICD-10), it does affect the well-being of many people and therefore may be considered to be a health effect falling within the WHO definition of health.

are more reduced than low frequencies. This is true for every sound coming from outside. Wind turbine sound changes over time. An important feature is the variation of the sound at the rhythm of the rotating blades. This variation in synchrony with the blade passing frequency is also called the amplitude modulation (AM) of the sound [6,9–12].

1.2 Human Hearing

Most environmental sounds with a level of 40 dBA will approximately have the same loudness for human hearing because the A-weighting (that is implied by the A in dBA) is based on the loudness curve of 40 phon (which equals 40 dB at 1000 Hz). Such a low to moderate loudness is comparable with actual wind turbine sound levels at many residences near wind farms. Therefore, A-weighting should give a (nearly) correct estimate of the loudness of a sound. With hearing tests this was confirmed in the Japanese wind turbine sound study [13]. A-weighting is less correct at lower sound levels; application of A-weighting to low levels (roughly < 30 dBA) may allow for more low-frequency sound. Of course, this concerns sound levels that are already low and usually will comply with limits. It is because of the combination of our hearing capacities at different frequencies and the sound level of the different wind turbine sources that trailing edge sound is the most dominant sound when outside and not too far from a wind turbine. The sound will shift to lower frequencies at larger distances or indoors, and then inflow turbulent sound can be more important.

When a sound is ‘subaudible’, the level of that sound is below the hearing threshold and thus below the level it can be audible. Usually the ‘normal’ threshold (hearing threshold of young adults without hearing problems, according to the international standard ISO 326) is used. As there is a variation between individuals, the normal threshold is the hearing threshold separating the 50% best hearing from the 50% that hear less well. For an individual often that normal hearing threshold is taken as an indication, but for that person of course the individual hearing threshold is relevant. Hearing acuity may differ considerably between persons. Hearing generally deteriorates with age, but this is typically less so at lower frequencies when compared to higher frequencies.

1.3 Sound Levels in Practice

For a modern turbine, the maximum sound power level is in the range between 100 and 110 dBA. ‘Sound power’ is the total amount of sound radiated from a source. For a listener on the ground close to a turbine, the outdoor sound level will not be more than about 55 dBA. At residential locations this is often less and in most studies there are few people, if any, exposed to an average sound level of over 45 dBA. For a wind turbine, maximum sound levels are not much

higher than average sound levels. For two turbine types in a temperate climate, it was shown that the sound level from these two types at high power is 1–3 dB above the sound level averaged over a long time [14].

Measurements on many types of modern wind turbines show that most sound energy is radiated at low and infrasound frequencies and less at higher frequencies (approximately 100–2000 Hz). However, because of the lower sensitivity of human hearing at low frequencies, audibility is greater at the higher frequencies. In the last decades wind turbines have become bigger and onshore wind turbines now can have several megawatts (MW) electric power. 2 MW turbines produce 9–10 dB more sound power when compared to 200 kW turbines [15,16]. Over time the amount of low-frequency sound (10–160 Hz) increases at nearly the same rate as the total sound level. Depending on what the reference situation is, this is somewhat less according to one author [15], somewhat more according to the other [16].

1.4 Aspects Other than Sound

Apart from sound, visual aspects, safety and vibrations related to wind turbines may also have an impact on the environment and the people living in it. Economic benefit, intrusion in privacy and acceptance of the wind turbines and other sources of disturbance are relevant to understand levels of annoyance. Also, personal and contextual aspects can determine the level of annoyance due to wind turbines.

2 Method

2.1 Data Sources and Search

This paper summarizes the present knowledge available about the association between wind turbine sound and health. It is based on several literature searches and reviews recently performed in the Netherlands [17,18] and updated with literature until February 2017, using the same method. Some papers from the most recent conference on Wind Turbine Noise (May 2017) have also been added to the overview in Sect. 4.

For this review a systematic literature search was performed at three moments in time (2000–2012; 2012–2015; and 2015–2017) using the same protocol. Observational as well as experimental studies described in the peer review literature in the period between 2009 and 2017 were included. Language was restricted to German, English, French and Dutch. The databases Scopus, Medline and Embase (note: only 2015–2017) were searched because these studies do not appear in the available reviews yet and they are of high value as they build on earlier evidence. The search strategy is described in Table 1.

Table 1 Key search terms and search profile

1	(Wind turbine* or wind farm* or windmill* or wind park* or wind power or wind energy).ti. (550)
2	Turbine noise*.tw. and wind/ (33)
3	(Power plants/ or energy-generating sources/ or electric power supplies/) and wind/ (187)
4	(Low frequency noise* or low frequency sound* or infrasound or infrasonic noise* or infrasonic sounds or infrasonic frequencies or low frequency threshold or (noise* adj4 low frequenc*).ti. (500)
5	1 or 2 or 3 or 4 (1113)
6	(Wind turbine* or wind farm* or windmill* or wind park* or wind power or wind energy).ab. (803)
7	(Low frequency noise* or low frequency sound* or infrasound or infrasonic noise* or infrasonic sounds or infrasonic frequencies or low frequency threshold or (noise* adj4 low frequenc*).ab. (1487)
8	Noise*.ti. (26930)
9	(6 or 7) and 8 (498)
10	(Impact or perception* or perceive* or health* or well-being or “quality of life” or syndrome*).ti. (1456358)
11	(Annoyance or annoying or annoyed or aversion or stress or complaints or distress or disturbance or adversely affected or concerns or worries or noise problems or noise perception or noise reception or noise sensitivity or (sensitivity adj3 noise) or sound pressure level* or sleep disturbance* or sleep quality or cognitive performance or emotions or anxiet* or attitude*).tw. (1260490)
12	(Social barrier* or social acceptance or popular opinion* or public resistance or (living adj4 vicinity) or (living adj4 proximity) or (residing adj4 vicinity) or (residing adj4 proximity) or living close or “living near” or residents or neighbors or neighbours).tw. (105942)
13	(Soundscape or landscape or visual annoyance or visual interference or visual perception or visual impact or visual preferences or visual assessment or visual effects or perceptual attribute*).tw. (41227)
14	(Effects adj4 population) or dose-response relationship* or exposure-response relationship* or dose response or exposure response or human response or health effects or health aspects or health outcome*).tw. (136924)
15	(Flicker or reflection).ti. (10980)
16	Environmental exposure/ or noise/ae or environmental pollution/ae (79725)
17	Loudness perception/ or psychoacoustics/ or auditory perception/ or auditory threshold/ or sensory thresholds/ or visual perception/ or motion perception/ (130572)
18	Sleep disorders/ or emotions/ or anger/ or anxiety/ or quality of life/ or epilepsy/ or attitude/ or affect/ or pressure/ or aesthetics/ or social environment/ or risk factors/ (1232239)
19	(Physiopathology or adverse effects).fs. (3235762)
Language: English or Dutch or French or German	
Search period: 2009–2017	
Duplicates removed	
Exclude animals/not humans	

We aimed to include low-frequency sound and infrasound in this review, but there are less publications and reviews specifically addressing this part of the spectrum. Also, the (alleged or studied) effects of infrasound and low-frequency sound are different from the effects of ‘normal’ sound. As a consequence, this topic is reviewed separately and is based on all relevant publications from the literature search (Fig. 1).

2.2 Inclusion Criteria

Only studies were included in which it was mentioned in the title, abstract or summary that the association was studied between the sound or noise of wind turbines and a reaction or

effect concerning health or well-being. Also, studies addressing participation during the building process were accepted for review. This implied that the association between exposure to wind turbine (low-frequency) sound and annoyance, health, well-being or activity disturbance in the adult population was studied.

For a first selection the following criteria were used. Inclusion: papers address human health effects, perception, opinion, concern in relation to wind turbines. Exclusion: papers address non-human effects such as ecosystem effects, animals, papers solely about technical aspects of the wind turbines, papers regarding health effects of sound but not related to wind turbines. This resulted in total in 202 possi-

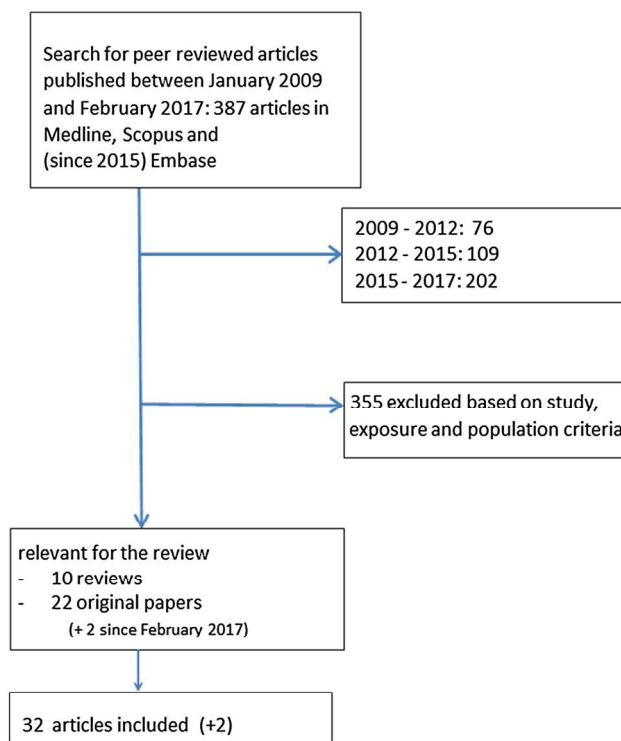


Fig. 1 Flowchart of selection process

bly relevant studies for the period between January 2015 and February 2017.

The papers for the period from January 2015 to February 2017 were grouped in seven categories: review, health effects, case studies, offshore, low-frequency sound/infrasound, visual aspects, social and not relevant. All reviews and health effects studies were included for full paper examination. All low-frequency sound/infrasound studies were examined for inclusion in the separate review. Offshore studies were a priori excluded; papers from the other categories were reconsidered after reading the abstracts.

Lastly, after full examination of the reviews and low-frequency sound/infrasound and health effect papers by the two authors, a final decision was made about inclusion in this review.

2.3 Procedure and Study Quality Assessment

This review is primarily based on results from epidemiological studies at population level and smaller-scale laboratory experiments.

The results have been divided into three sections. The difference in material between both periods (up to and since 2015) resulted in two sections: first we review the reviews (Sect. 3.1), and then we review original studies most of which are from the second period (3.2). The effects of infrasound

and low-frequency sound are summarized in a third part (Sect. 4).

The main results are summarized per outcome. For the key studies, the study design and outcomes are discussed in more detail. For this review primarily scientific publications are used, from both peer-reviewed journals and conference proceedings. In some cases results are discussed which were described in non-scientific ('grey') literature. Also, some publications are mentioned that are often used in the debate (discourse) about the risks of living in the vicinity of wind turbines.

As usual, all material from the selected literature has been read and analysed, but not necessarily included as reference, e.g. because the study was less relevant than originally thought or in case of doubling with other references (e.g. a conference paper and an article from the same authors and study). A meta-analysis on (part of) the data was not considered in the time frame of this assignment.

3 Results

Annoyance and sleep disturbance are the most frequently studied health effects of wind turbine sound as is also the case for sound from other sources. After a short explanation of the health effects addressed in the literature, the overall conclusions from key reviews are summarized. Then the main findings for annoyance, sleep disturbance and other health effects are described in more detail, sometimes referring to the underlying publications. The influence of personal, situational and contextual factors on these effects is also included. Then in Sect. 3.2 the most recent original studies (2015–2017) are described separately in more detail while following the same structure.

Effects that are mentioned as specific effects of infrasound and/or low-frequency sound are treated in Sect. 4.

3.1 Evidence Until Early 2017: Reviews

People can experience annoyance or irritation, anger or disturbance from wind turbine sound, or when they feel that their environmental quality and quality of life deteriorates due to the siting of wind turbines near their homes.

The number of publications on wind turbine sound and its health effects has increased considerably in the past 10 years, including peer-reviewed articles, conference papers and policy documents (Table 2).

A remarkable number of nineteen reviews were published in the period between 2009 and 2017. These include systematic reviews as well as policy preparing reviews. Some reviews were dismissed after reading the full text, since they were highly anecdotal, no health impact was estimated, incomplete or only concerned occupational exposure, etc.

Table 2 Reviews (2009–2017) selected for this paper

First author year and reference	Studies included		Time range	Exposure	Outcomes	Meta-analysis
	Number of studies evaluated	Number of participants				
Knopper, (2011) [21]	15 studies	Na	2003 and 2011	Aspects of wind turbines broadly	Physiological and self-reported health effects, annoyance, stress, sleep disturbance, insomnia, anxiety	No
Harrison, (2015) [27]	Review of reviews	Na	2015	Low-frequency noise, levels < 100 dB SPL	Wind turbine syndrome. Vertigo, nausea and nystagmus, aural fullness, hyperacusis, and tinnitus	No
Ellenbogen (MPED), (2012) [22,23]	4 studies (peer-reviewed and 4 non-peer-reviewed)	Na	2011	Aspects of wind turbines broadly: noise, shadow flicker, visual aspects, ice throw	Annoyance, sleep, health effects (self-reported, diagnosed)	No
Merlin, (2013) [19]	7 studies	2309 (79–754)	1981–2012	Infrasound/noise, electromagnetic interference, shadow flicker, blade glint	Adverse health effects (broad)	Yes
SHC, (2013) [20]	Na			Noise (including low-frequency noise, infrasound and vibrations) shadow flicker electromagnetic fields	Adverse health effects (broad)	No
Schmidt, (2014) [24]	36 studies	300–3000	2014	A-weighted sound exposure, < 30 dB >, infrasound, LFN, distance	Health, annoyance, tinnitus, vertigo, epilepsy, headache	No
MacCunney, (2014) [25]	20/14 studies	Na	2014	Distance, exposure, LFN infrasound	Sleep, cardiovascular, health, symptom, condition, disease	No
Knopper, (2014) [26]	60 studies	Na	2014	Noise, environmental change(s), wind, farm(s), infrasound, wind turbine(s), LFN, EMF, neighbourhood change	Annoyance, sleep disturbance, epilepsy, stress, health effect (wind turbine, syndrome)	No, due to methodological, heterogeneity
Council of Canadian Academies, (2015) [28]	38 studies	Na	2009–2014	WT noise: a weighted SPL, infrasound, low-frequency sound and amplitude modulation	Annoyance sleep disturbance, tress, tension, health-related quality of life, vibroacoustic disease, cardiovascular system, endocrine system, immune system, musculoskeletal system, nervous system (general), nervous system (auditory), psychological health, respiratory system	No
Onakpoya, (2016) [1]	8 studies	2433	2000–2014	> and < 40 dB, distance	Annoyance and sleep disturbance	Yes

The remaining ten recent and leading reviews and policy documents (described in 11 manuscripts: [1, 19–28] draw comparable conclusions about the health effects of wind turbine sound: in general, an association is found between annoyance and the level of wind turbine sound. Also, an association between sound level and sleep disturbance is considered plausible, even though a direct relation is uncertain because of the limited number of studies with sometimes contradictory results. Perceived stress is related to chronic annoyance or to the feeling that environmental quality and quality of life has diminished due to the placement of wind turbines, and there is sufficient evidence that stress can negatively affect people's health and well-being in people living in the vicinity of wind turbines [20].

Next to sound, vibration, shadow flicker, warning lights and other visual aspects have been examined in the reviews. There are no studies available yet about the long-term health effects. Such longitudinal studies (studies comparing the situation at different moments in time) might be useful to gain more insight in the causal pathways of the different factors. However, they can still only examine the strength of temporal associations across a range of relevant variables and to establish causal relations will remain problematic in this area.

Most recently, Onakpoya et al. [1] reanalysed the data from eight cross sectional studies, selected on strict quality requirements and including a total of 2433 participants. Effects considered were annoyance, sleep disturbance and quality of life. Evidence supports the earlier conclusion that there is an association between exposure to wind turbine sound and an increased frequency of annoyance and sleep problems, after adjustment for key variables as visual aspects, attitudes and background sound levels. The strength of evidence was the most convincing for annoyance, followed by sleep disturbance, when comparing participants at exposure levels below and above 40 dB. The findings are in line with Schmidt and Klokke [24] and Janssen et al. [29]. In contrast to these authors, Merlin et al. [19] consider annoyance a response to wind turbines and not a (health) effect as such.

Personal and contextual factors can influence annoyance. There is consensus in the literature that visual aspects, attitudes towards wind turbines in the landscape and towards the people responsible for wind farms, the process around planning and construction and economic interest can all in their own way affect levels of annoyance. However, actual evidence for this is still limited.

The next sections will describe the state of the art in more detail per health effect. Note that the description is limited to the effects of wind turbine sound in the 'normal' frequency range. Findings from studies, addressing suggested specific impacts of the low-frequency component and infrasound distinct from 'normal' sound are summarized separately in Sect. 4.

3.1.1 Noise Annoyance

In many countries the assessment of the sound of wind turbines is based on average, A-weighted sound levels (see Sect. 1.2). It is generally accepted that annoyance from wind turbines occurs at lower levels than is the case for traffic or industrial sound. Based on Dutch and Swedish data, an exposure–effect relation was derived between calculated sound exposure levels expressed in Lden (day–evening–night level) and the percentage highly annoyed, for indoor as well as outdoor exposures. Later research in Japan and Poland have confirmed these results and obtained similar results [30, 31]. The relation between wind turbine sound and annoyance can be compared with those for road, rail and aircraft sound. This comparison is presented in Fig. 2 where the 'aircraft Europe' data are from the European HYENA study [32], the wind turbine data are from Janssen et al. [29], and the other data are from Miedema and Vos [33] for industrial sound and from Miedema and Oudshoorn [34] for air, road and rail transportation sound. The more recent HYENA study has shown that at a number of big European airports noise annoyance has increased when compared to the older data from Miedema and Oudshoorn [34]. Figure 2 shows that sound from wind turbines leads to a higher percentage of highly annoyed people when compared to other sound sources. The relation resembles that of air traffic sound, but near airports there are higher sound levels and a correspondingly higher percentage of highly annoyed. The relations for transport sound in Fig. 2 have been derived for large numbers of persons from many countries, but the actual percentage for a specific place or situation can be very different, for wind turbines as well as other sources.

Some think that it is too early to define exposure–effect relations for wind turbines [20, 35]. According to them, the influence of context (like residential factors, trust in

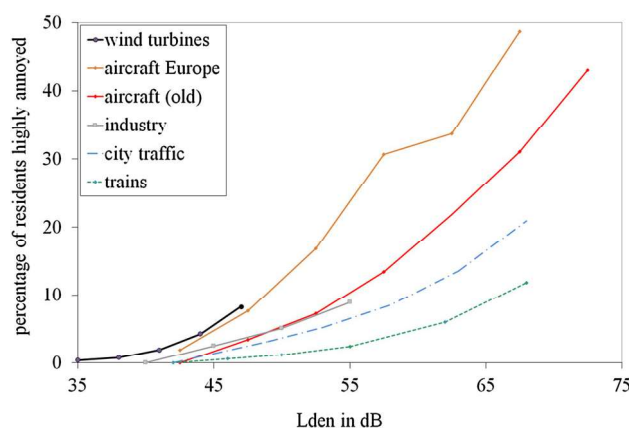


Fig. 2 Comparison of the percentage highly annoyed residents from sound of wind turbines, transportation and industry (approach adapted from Janssen et al. [51]); see text for explanation of legend

authorities and the planning process, situational factors) and personal factors (such as noise sensitivity and attitude) is so strong that the exposure–effect relation can only (or at best) give an indication of the percentage of highly annoyed at the local level [22,23]. This is not unique to wind turbines, but is to some degree—also true for other sound sources and in part explains why in specific places or situations the actual percentage of annoyed persons can differ from the relations in Fig. 2. Michaud et al. [36] compared the results from five studies and found there was a 7.5 dB variation in wind turbine sound levels that led to the same percentage of annoyed persons.

What makes wind turbine sound so annoying?

In a Dutch survey [37] 75% of the respondents indicated that the terms ‘swishing/lashing’ gave the best description of wind turbine sound, irrespective of their being annoyed or not [37]. Laboratory studies have consistently shown that the periodic variation in the sound of wind turbines adds to the annoyance. In the study of Persson Waye and Öhrström [38] it was found that wind turbine sounds described as ‘swishing’, ‘lapping’ or ‘whistling’ were more annoying while the least annoying sounds were described as ‘grinding’ and ‘low frequency’ [38]. In the UK research was performed near three dwellings where people complained about wind turbine sound. Rather than the low-frequency component of the sound amplitude modulation or the rhythmic character was the most conspicuous aspect of the sound [39]. In a later UK study Large and Stigwood [40] concluded that amplitude modulation is an important aspect of the intrusiveness of wind turbine sound. More recently Yoon et al. [12] stated that there is a strong possibility that amplitude modulation is the main reason why wind turbine sound is easily detectable and relatively annoying.

Whether the type of environment affects the levels of annoyance is not yet clear. It can be assumed that people in rural areas are more likely to hear and see wind turbines than in more built-up urban areas with more buildings and a less open view. However, Dutch research showed that the percentage of highly annoyed people was equally high in rural and urban areas [37] although the correlation with the wind turbine sound level was less strong in the built-up area [41]. An important moderator was the existence of a busy road nearby, reducing the percentage annoyed by wind turbine sound annoyance in rural areas only. In a Swedish study it was found that residents in rural areas reported more annoyance in rural areas than in urban environments, possibly due to their expectation that the rural area would be quiet [42]. In a recent study Qu et al. [43] found that the level of annoyance from wind turbine sound in urban and suburban areas was less than reported in the Swedish, Dutch, Polish and Canadian studies in rural areas.

3.1.2 Sleep Disturbance

Good sleep is essential for physical and mental health. Sound is one of the factors that can disturb sleep or affect the quality of sleep. Several biological reactions to night time sound from different sources have been described in the literature: increased heart rate, waking up, difficulty in falling asleep and more body movements (motility) during sleep [4]. The night noise guidelines of the WHO are not specifically aimed at noise from wind turbines, but cover a range of (other) noise sources. It is conceivable that the relatively small but frequently occurring sound peaks just above the threshold for sleep disturbance due to the rhythmic character of wind turbine sound cause sleep disturbance [44]. A Dutch study found that wind turbine sound did not affect self-reported sleep onset latency but did negatively influence the ability to keep sleeping [37,41]. An increase in sound level above 45 dBA increased the probability of awakening. This was not the case for people who obtained economic benefit from the wind turbines, but this might also have been an age effect (co-owners of the turbines were younger). These findings of the study in the Netherlands are in line with the conclusions which the WHO drew from the review of scientific literature the relation between transport sound and sleep [4]. According to the WHO, sleep disturbance can occur at an average sound level at the facade at night (L_{night}) of 40 dB and higher [4].

A direct association between wind turbine sound and sleep disturbance can only be determined when there is a measurable reaction to the sound. Such an immediate influence is only plausible when the sound level is sufficiently high and as yet has not been convincingly shown for wind turbine sound [23,45]. An indirect effect has been shown between self-reported sleep disturbance and annoyance from wind turbine sound, but not between sleep disturbance and the sound levels per se [41]. Research has shown that also for other sound sources there is a high correlation between self-reported sleep disturbance and annoyance from noise [46].

Several more recent studies show an association between quality of life and sleep disturbance and the distance of a dwelling to a wind turbine [47,48]. Differences in perceived quality of life were associated with annoyance and self-reported sleep disturbance in residents. These results are highly comparable with those found for air and road traffic, e.g. see [49].

3.1.3 Other Health Effects Due to Sound

In an Australian report [50] the number of people living in the vicinity of wind turbines with serious health complaints was estimated to be 10–15%. However, according to literature reviews on the health effects of wind turbines [1, 19, 20, 23–25, 28] there is no evidence for health effects caused by wind turbines in people living in the vicinity of wind turbines, other

than annoyance and self-reported sleep disturbance and the latter is inconclusive. There was, however, a clear correlation between annoyance and self-reported sleep disturbance in one study [41]. Based on existing field studies, there is insufficient evidence that living near a wind turbine is the direct cause of health effects such as mental health problems, headaches, pain, stiffness or diseases such as diabetes, cardiovascular disease, tinnitus and hearing damage.

3.1.4 Influence of Situational and Personal Factors

Research in the past decade has shed some light on the question why some people are more disturbed by wind turbines than others. Next to physical aspects, personal and contextual aspects influence the level of annoyance. Often these aspects are referred to as non-acoustic factors, complementary to the acoustic factors (the ‘decibels’). Because the term non-acoustic refers to a broad range of aspects, and as a result is very unspecific, we prefer the term personal and contextual factors [51]. They can be subdivided in the following categories (with some exemplary aspects in brackets):

- Situational factors (visual aspects frequency of sound events, meteorological circumstances, other sound sources, distance to amenities and attractiveness of the area).
- Demographic and socio-economic factors (age, gender, income, level of education);
- Personal factors (fear or worry in relation to source, noise sensitivity, economic benefit from the source);
- Social factors (expectation, attitudes towards producers or government, media coverage);

There is a lot of variation in the aspects studied and also the strength of the evidence varies strongly. Without pretending to be exhaustive, those aspects documented in the reviews on wind turbine sound up to 2015 are discussed in more detail below.

3.1.4.1 Visual Aspects

Modern wind turbines are visible from a considerable distance because they rise high and change the landscape. Due to the movement of their rotor blades, wind turbines are more salient in the landscape than objects that do not move. The rotating blades draw our attention and can cause variations in light intensity when the blades block or reflect sunlight. The visual and auditory aspects have been shown to be highly interrelated [19,36,52] and are therefore hard to unravel with respect to their effects. Annoyance from visual aspects may add to or even reinforce annoyance from noise (and vice versa). Noise and visual annoyance are strongly related as was also described above. It has been suggested [20] that people who see the wind turbines from their homes are more

worried about the health effect of continuous exposure and as a consequence also report more annoyance [20].

3.1.4.2 Economic Aspects

Economic aspects can also affect annoyance from wind turbines. In a study of Pedersen et al. [52] in the Netherlands, some 14% of the respondents benefited from one or more wind turbines, in particular enterprising farmers who lived in general closer to the turbines and were exposed to higher sound levels than the remaining respondents. The percentage of annoyed persons in this group was low to very low, despite the higher exposure and the use of the same terms to describe the typical characteristics of wind turbine sound. In the study this group was described as ‘healthy farmers’: on average they were younger, more often male and had a higher level of education when compared to those not having economic benefits and reported less problems with health and sleep. However, it might not only be the benefit, but differences in attitude and perception as well as having more control over the placement of the turbines that might play a role [37].

3.1.4.3 Noise Sensitivity

Being noise sensitive refers to an internal state determined by physiological, psychological, attitudinal aspect, lifestyle and activities of a person that increases the reactivity to sound in general. Noise sensitivity has a strong genetic component (i.e. hereditary), but can also be a consequence of a disease (e.g. migraine) or trauma. Also, serious anxiety disorders can go together with an increased sensitivity to sound and possibly lead to a feeling of panic [53]. Only a few studies have addressed this issue in relation to wind turbine sound. An early example is the study of Shepherd et al. [47] in New Zealand, in which two groups were compared (a ‘turbine group’ versus a control group). Noise sensitivity was measured with a single question informing whether people considered themselves as noise sensitive. In the turbine group a strong association was found between noise sensitivity and annoyance and a weak association in the control group. This is indicative of an interaction effect of exposure and sensitivity on annoyance. This has also been documented for other sound sources [54]. According to a case report from Thorne [50], a relatively high proportion of residents near two wind farms in Australia were noise sensitive. Self-selection into a ‘quiet area’ by noise sensitive people can be a plausible explanation.

3.1.4.4 Social Aspects

For the social acceptance of wind turbine projects by a local community, the Belgian Superior Health Council [20] stated it is crucial how the community evaluates the consequences for their future quality of life. The communication and relation between the key parties (residents, municipality and project developer) are very important. Disturbance by wind

turbines is a complex problem, in which the objective (physical) exposure and personal factors play a role, but also policy, psychology, communication and a feeling of justice.

When planning and participation are experienced as unjust or inadequate, public support will soon deteriorate, also among people who were originally neutral or in favour of the wind farm [55]. When residents feel they have been insufficiently heard, they feel powerless and experience a lack of control over their own environmental quality and quality of life. Worry or concern can be reduced by an open and honest procedure in which residents can contribute to the decisions in a positive way [56]. Already in the early phase of wind energy, research from Wolsink [57] and later from Breukers [58] showed that collaboration with emphasis on local topics was more successful than a policy aimed at as much wind energy as possible and a non-participatory approach.

Pedersen et al. [52] found that people who perceive the wind turbines as intruding and a threat to their privacy (motion, sound, visual) reported more annoyance. When people feel attached to their environment ('place attachment'), the wind farm can form a threat to that location and can create resistance [59]. Also, a feeling of helplessness and procedural injustice can develop when people feel they have no real say in the planning process. Potentially, this plays a role especially in rural areas where people choose to live because of tranquillity; for them the wind park can form an important threat (visual and auditory). Based on renewable energy projects in the UK, Walker and Devine-Wright [60] concluded that the more people participated in project development, the higher was the public support for renewable energy in general.

3.2 Evidence Since 2015 Based on New Studies

In the period between January 2015 and 2017, 22 relevant publications were identified in peer-reviewed literature. These are 10 on field studies [36,61–69], 7 on experiments [12,70–75], 3 on a prospective cohort study [76–78], 1 panel study [79] and 1 qualitative analysis of interviews and discourse [80]. After the systematic literature search, two relevant papers from the most recent International Wind Turbine Noise Conference (Rotterdam 2017) were included [43,81].

Two major studies were (partly) reported in this period and not included in the reviews, one in Canada [16,61–65] and one in Japan [66,67]. The study from Health Canada [36,61–65] was performed with 1238 adult residents living at varying distances from wind turbines. A-weighted sound levels outdoors were calculated as well as C-weighted levels, and additional measurements were made at a number of locations. A strong point of the study is the high response rate of 79%. The results were presented in six publications, addressing effects on sleep, stress, quality of life, noise annoyance and health effects and a separate paper on the effect of

shadow flicker on annoyance. Also, two papers were published describing the assessment of sound levels near wind turbines and near receivers [82,83]. The Japanese study by Kakeyama et al. [66,67] pertains a field study with structured face-to-face interviews at 34 study sites and 16 control sites. Wind turbine sound levels were estimated based on previous measurements at some sites and expressed in LAeq. Outcomes studied were sleep deprivation, sleep disturbance and physical and mental health symptoms (Table 3).

The next sections describe the state of the art in more detail per health effect as in 3.1. Note again that the description is limited to the effects of wind turbine sound in the 'normal' frequency range. Findings from studies addressing suggested specific impacts of the low-frequency component and infrasound distinct from 'normal' sound are summarized separately in Sect. 4.

3.2.1 Noise Annoyance

In one of his papers about the Health Canada study, Michaud et al. [61] describe the findings on annoyance, self-reported health and medication use. In line with earlier findings the study confirms that the percentage of highly annoyed increased significantly with increasing wind turbine sound levels. The effect was highest for annoyance with visual aspects of wind turbines, followed by blinking lights, shadow flicker, sound and vibrations.

An Iranian study of Abasssi et al. [68] included 53 workers divided in three job groups with repairing, security and administration tasks. The exposure level to wind turbine sound of employees at each job group was measured as an 8-h equivalent sound level as is usual in working conditions. Outcome measures included annoyance, sleep, psychological distress and health complaints. Noise sensitivity, age, job stress and shift work were accounted for. Annoyance was associated with measured sound levels but lower than found in residential studies. The other health outcomes did not show a significant association. It is not clear how this relates to residential conditions as the situations are quite different and different factors are involved.

In the period 2015–2017 several laboratory studies have addressed the effects of wind turbine sound and annoyance. In a listening test among 60 people, after a pilot in 12 people, an association was found by Schäffer et al. [70] between road traffic and wind turbine sound level or variations in sound level due to amplitude modulation and annoyance. Attitude towards wind turbines and noise sensitivity were important confounders, and the frequency of the amplitude modulation (higher for the wind turbine sound) seemed to play an important role.

The relative contribution of the typical characteristics of wind turbine sound, and particularly the rhythmic character or amplitude modulation (AM) was studied in several exper-

Table 3 Overview of the studies published after January 2015 and selected for this review

First author, year and reference	Studies included						
	Country	Number of participants	Design	Quality	Exposure	Outcomes	Effect
Michaud, (2016a) [61]	Canada	1238	Survey	objective and subjective measures	A waited SPL outdoors estimated + C-weighted	Annoyance, sleep disturbance, stress or psychological	The prevalence of self-reporting to be either 'very' or 'extremely' (i.e. highly) annoyed with several wind turbine, features increased significantly with increasing A-weighted levels
Michaud, (2016b) [62]	Canada	1238	Mixed	Objective and subjective measures	SPL 31–48 dB estimated + measurements on location	Sleep (actimeter), subjective sleep indicators	No effect on any of the sleep indicators
Michaud, (2016c) [63]	Canada	1238	Survey	Objective and subjective measures	A waited SPL outdoors estimated + C-weighted	Perceived stress scale (PSS) scores, hair cortisol concentrations, resting blood pressure and heart rate	The findings do not support an association between exposure to WTN up to 46 dBA and elevated self-reported and objectively defined measures of stress
Michaud, (2016d) [36]	Canada	1238	Survey	Objective and subjective measures	A waited SPL outdoors estimated + C-weighted	Noise annoyance, wind turbine perceptions, (including concern for physical safety) and a whole range of personal and situational aspects	Annoyance determined by other wind turbine-related, annoyances, personal benefit, noise sensitivity, physical safety concerns, property ownership and province: the community tolerance level (CTL) to WTN is 11 and 26 dB less than to other sources
Jalali, (2016a) [76]	Canada	T1–43, T2–31	Prospective cohort Before after	Objective and subjective measures		Annoyance, QoL subjective health, mental health	Significant effect on mental health and annoyance and symptoms. Interaction with negative attitude, worry about housing prize and visual complaints
Jalali, (2016b) [77]	Canada	16/2 nights	Prospective cohort Before after	Objective and subjective measures	Distance only	Sleep indicators with polysomnographic	No major change in sleep after placement of WT's
Jalali, (2016c) [78]	Canada		Prospective cohort Before after	Objective and subjective measures	Distance only	Pittsburg sleep quality, Epworth Sleepiness Scale and the Insomnia Severity Index	WT placement was associated with increased poor sleep quality, daytime sleepiness and rates of insomnia (expressed in th score on the PSQI and the ESS and the ISI. There was a strong association with negative attitude, worry about property values and WT visibility

Table 3 continued

First author, year and reference	Country	Number of participants	Design	Quality	Exposure	Outcomes	Effect
Schäffer, (2016) [70]	Germany and Switzerland	60	Laboratory study	Test in j 12 pp of noise stimuli	WT < 55 versus traffic outdoor levels > 40 normal fluctuations due to weather conditions	Annoyance (short term) modifying effect of noise characteristics	Difference found but (much) smaller than Janssen and Michaud, AM next to noise level
Feder, (2015) [64]	Canada	1238	Field study	Objective and subjective measures	22–11 km and estimates based on ISO9613-1 and ISO9613-for each dwelling, dBA and dBC	WHO QoL annoyance, symptoms, sleep quality, perceived stress, life, style behaviours and prevalent chronic disease	No effects on QoL subscales below 46dB
Chrichton, (2015) [71]	New Zealand	60	Laboratory study	Students/no control group	Up to 43 dB NZ standard for WT infra sound	Annoyance	Effect only in negative expectation group, interaction with NS
Blanes-Vidal, (2016) [69]	Denmark/USA	454	Cross sectional	Na	Distance to WT and number of turbines	Ideopathic symptoms	Effects on fatigue, difficulty concentrating, headache all disappeared after adjustment for noise exposure and odour from other sources
Ionannidou, (2016) [72]	Denmark	19	Laboratory study	Na	Amplitude modulation elements 60 dBA 30 s M (approach van den Berg)	Annoyance	Check
Abassi, (2015) [68]	Iran	53	Field study	Na	8-h equivalent sound level (LAeq, 8 h) based on ISO 9612:2009	Annoyance, sleep psychological distress, health complaints	Annoyance associated with measured levels but lower than found in residential studies possibly due to economic benefits
Tonin, (2016) [74]	Australia	72	Laboratory study	More men	Infrasound exposure double blind (sham noise)	Annoyance, symptoms	Effects mediated by high/low expectancy
Hafke-Dys, (2016) [73]	Poland	21	Laboratory study	Control condition without modulation	Broadband and narrowband noise. With modulations typical, for WT (3, 6 and 9dB) based on Rentegehem	Annoyance	Interaction between noise type (broadband) and AM on annoyance. WT noise is perceived as less annoying when AM freq. is < 4 Hz
Yoon, (2016) [12]	Korea	24	Laboratory study	Control group	Amplitude modulation	Perceived loudness	Combined effect of noise levels and AM on noise perception

Table 3 continued

First author, year and reference	Studies included							
	Country	Number of participants	Design	Quality	Exposure	Outcomes	Effect	
Botterill, (2016) [80]	Australia	Na	Interviews and discourse analysis	Na	Na	Topics mentioned most often in the discourse	Health and property values came forward as main topics	
Kageyama, (2016) [66,67]	Japan	1079	Face-to-face structured interviews	Control sites! (16) versus 34 exp. sites	L _{Aeq} estimated based on some measurement sites, median 36–40 and 35 at control sites	Insomnia, physical and mental health, sensitivity to noise and visual annoyance	Odds ratio (OR) of insomnia was significantly higher when the noise exposure level exceeded 40dB, self-reported sensitivity and visual annoyance independently associated with insomnia. OR of poor health only significant for, noise sensitivity and visual annoyance	
Maffei, (2015) [75]	Italy	40	Listening, experiments	Exp versus control	Sound recordings of about 5 min were made at five distances	Noise recognition	Recognition is congruent with the increase of the distance and the decrease of the values of sound, equivalent levels and loudness	
Krekel, (2016) [79]	France/Germany	30	Panel data	Na	(i) The exact geographical coordinates, (ii) the exact construction, dates and (iii) information on the size of the installation	Satisfaction with life	Geographical distribution of well-being merged with WT locations. Well-being data merged with	
Voicescu, (2016) [65]	Canada	1238	Survey	Objective and subjective measures	Shadow flicker (SF) combined with noise estimates expressed in maximum minutes per day (SFm), modelled and based on distance	Annoyance, health complaints including dizziness	Annoyance associated with SF annoyance to other wind turbine-related features, concern for physical safety and noise sensitivity. Reported dizziness was also retained in the final model (all significant)	

Table 3 continued

First author, year and reference	Studies included						
	Country	Number of participants	Design	Quality	Exposure	Outcomes	Effect
Yano, (2015) [30]	Japan	1079	Face-to-face interview	Control group (332) in areas with no wind turbines	Extra/interpolated from measured night time noise level ($L_{Aeq,n}$); distance for visual exposure	Noise annoyance, visual disturbance, perception of shadow flicker (SF)	$L_{Aeq,n}$ and distance significantly related to noise annoyance; distance more strongly associated with noise annoyance than level. Most annoyance reported at night-time. Visual annoyance not significantly related to distance. SF indoor and SF outdoor significantly related to distance. SF outdoor more prominent in mountainous area (compared to flat). Interaction between noise annoyance and visual annoyance/SF outdoor, not with visibility and SF indoors
Qu, (2017) [43]	England + Scotland	357	Survey in (sub)urban areas	No attribution to wind turbines in control group (96)	Calculated (maximum?) A-weighted wind turbine sound pressure level (SPL) on most exposed facade	Awareness of and annoyance with wind turbine noise, self-reported sleep disturbance, prevalence of specific health problems, general health, subjective well-being	SPL positively associated with noise annoyance. SPL not associated with sleep, but degree of noise annoyance significantly increased possibility of sleep disturbance. Visibility of wind turbine from both window and garden significantly increased odds of less deep sleep. In case group, annoyance with wind turbine noise significantly influenced prevalence of health problems: psychological problems significantly and positively associated with being annoyed by wind turbine noise, but not with SPL itself. Positive associations were found between SPL and adverse health problems, including nausea and dizziness. Dizziness and ear discomfort related to SPL in control group

iments. Ionannidou et al. [72] report on a study among 19 volunteers in which the effect of changes over time in the amplitude modulation of wind turbine sound on annoyance was investigated. The changes could either be the frequency of the modulation, the depth (or strength) of the modulation or a change in depth over time. The study confirms earlier results that AM leads to a higher annoyance rating. A higher modulation frequency (from 0.5 to 2 Hz) also resulted in a higher rating, but the effect was not significant. There was also a higher annoyance rating when the modulation depth increased intermittently, but again this was not significant. Because of the limited statistical power of these tests (because of the low number of participants and the limited time), it was recommended to investigate the variations in AM for a longer period and in a field setting.

A study from Hafke-Dys et al. [73] among 21 volunteers again concerned the effect of amplitude modulation on annoyance. In this study sounds with several modulation conditions were compared to a non-modulation condition. The test sounds used were (1) sound from moving cars, passing at a rate of 1–4 per second; (2) broadband sound with the same spectrum as wind turbines and (3) narrowband sound that could be modulated at 1, 2 and 4 Hz. All three types of sound had modulation depths typical for wind turbines at 3, 6 and 9 dB similar to Van Renterghem et al. [84], or zero (no modulation). Results showed that AM did increase annoyance in the case of broadband sound and passing cars, but not for the narrow band sound. The modulated sound was more annoying with increasing modulation frequency, in agreement with an expected highest sensitivity for modulated sounds at 4 Hz. Large, modern wind turbines modulate their sound at a frequency close to 1 Hz. The effect of AM on annoyance was less for the broadband sound than for passing cars. The main difference between these two sounds was the spectral content, with the broadband sound having more low-frequency sound than the passing cars. The authors conclude that this result supports the Japanese study [13] in which it was demonstrated ‘that low frequency components are not the most significant problem when it comes to the annoyance perception of wind turbine noise’.

Yoon et al. [12] studied the reaction to modulation of wind turbine sound in 12 people. Findings show again that there is an association between AM and level of annoyance. The authors conclude that there is a strong possibility that amplitude modulation is the main cause of two typical properties of wind turbine sound: that it is easily detectable and highly annoying at relatively lower sound levels than other noise sources. They add that this does not mean that these properties can be fully explained by the amplitude modulation.

Crichton and Petrie [71] studied 60 volunteers at exposure levels up to 43 dBA (the New Zealand standard limit) in combination with infrasound (9 Hz, 50 dB). In one group, the participants were shown a video about the health risk of

wind turbine infrasound, and in the second group a video on health benefits was shown. An effect on annoyance was found only in the group expecting to be negatively affected, and in this group noise sensitivity increased the likelihood of being annoyed. In the group expecting a positive effect, there was far less annoyance and almost no influence from noise sensitivity.

In a later publication from the Japanese study, it was found that within 860 m from a wind farm 10% of the residents were annoyed by shadow flicker while within 780 m 10% of the residents were highly annoyed by wind turbine sound [81]. The authors concluded that a minimum distance (or ‘setback’) between residences and wind farms should be considered from an aural and visual point of view.

3.2.2 Sleep Disturbance

Michaud et al. [62] reported on sleep disturbance from a field study involving 742 of the 1238 respondents (as described under 3.2) wearing an actimeter, to measure relevant sleep indicators during 3–7 consecutive nights after the interviews. Outdoor wind turbine sound levels were calculated following international standards. Neither self-reported sleep quality, diagnosed sleep disorders nor objective measures such as sleep onset latency, awakenings and sleep efficiency showed an immediate association with exposure levels up to 46 dB after adjustment for relevant confounders such as age, caffeine use, body mass index (BMI) and health condition. This partly contrasts with earlier findings on subjective sleep measures [47]. No study addressed objective sleep measures in relation to wind turbines before. However, it should be mentioned that the method of actigraphy is limited as compared to more elaborate polysomnographic measures as were employed by Jalali et al. [76] and described below. In the Health Canada study having to close the window in order to guarantee an undisturbed sleep had by far the strongest influence on annoyance [61]. This could be a reason that no relation between wind turbine sound level and sleep disturbance was found: if persons disturbed at night by wind turbine sound would close their bedroom window, the result could be that they are less disturbed at night by the sound as such, although they could be annoyed because they had to close the window. The results do not directly support or negate this explanation. However, those closing their bedroom windows was eight times more likely to be annoyed. At higher wind turbine sound levels, people more often gave wind turbines as a reason for closing the bedroom window [61].

Kakeyama et al. [66,67] showed a significant association between sound levels above 40 dB and sleeping problems (insomnia). These findings are in contrast with those reported by Michaud et al. [62] who did not observe an immediate association between sound exposure levels up to 46 dBA

and subjective and objective indicators for sleep. The earlier findings of Bakker [41] regarding subjective sleep indicators showed that sleep disturbance seemed to be related to sound level only when no other factors were included. When annoyance with wind turbine sound was included, then sleep disturbance was related to that annoyance and not anymore to sound level. Earlier, Pedersen and Persson [42] also concluded on an association between annoyance and sleep disturbance rather than a direct effect of sound level.

Jalali et al. [77] measured sleep disturbance in a group of 16 people for 2 consecutive nights using a polysomnographic method including a range of sleep and physiological parameters such as sleep onset, duration, movement during sleep, awakening, EEG activity. Sound measurements over the whole frequency range (0.5–20,000 Hz) were performed in the bedroom as well as outdoor, while accounting for weather conditions, wind speed and temperature. Factors that were taken into account were attitude, sensitivity, visibility, distance within 1000 m and windows open versus closed. Results showed no major changes in the sleep of participants who had new wind turbines in their community. There were no significant changes in the average indoor (31 dBA) and outdoor sound levels (40–45 dBA before, 38–42 dBA after) before and after the wind turbines became operational. None of the participants reported waking up to close their windows because of the outside noise. The lack of an effect might be explained by the limited measurements (two nights) or the low indoor sound levels that almost equalled the threshold value for sleep disturbance of 30 dBA.

In another paper Jalali et al. [78] report on the association between measured wind turbine sound levels and subjective sleep quality as measured with the Pittsburgh sleep quality index. Results show only an indirect association with attitude towards the wind turbines and concern about reduced housing values and the visibility of the turbine from the properties. The results confirm the strong psychological component and individual differences in sleep disturbance from wind turbine sound.

3.2.3 Other Health Effects Due to Sound

From the Canadian study Michaud et al. [61] concluded that, except for annoyance, the results do not support an association between exposure to wind turbine sound up to 46 dBA and the evaluated health-related end points, such as mental health problems, headaches, pain, stiffness, or diseases such as diabetes, cardiovascular disease, tinnitus and hearing damage. Michaud et al. [63] also studied the association between wind turbine sound level and objective stress indicators (cortisol, heart rate) and perceived stress (PPS index). These stress indicators were weakly associated with each other, but analysis showed no significant association between exposure to wind turbine sound (up to 46 dBA) and self-reported

or objective measures of stress. The authors remarked that there was also no association between stress indicators and noise annoyance, which does not support the hypothesis that stress can be a consequence of chronic annoyance. The only wind turbine-related variable that had an influence on stress was high annoyance with the blinking lights on top of the wind turbines [63]. McCunney et al. [25] found an explanation for a lack of significant associations in the fact that sound levels from wind turbines do not reach levels which could cause such direct effects.

Results for quality of life (QoL) [64], measured using the WHO QoL index and including physical, environmental, social quality and satisfaction with health, showed no relation with sound levels (at levels up to 46 dB). This is in contrast with findings reported earlier by Shepherd et al. [47] and Nissenbaum et al. [48]. However, the results of these studies are hard to compare because the exposure levels are not the same and because different instruments were used to measure perceived quality of life.

Tonin et al. [74] studied 72 volunteers in a laboratory setting for a double-blind test similar to that of Crichton et al. [71] but used infrasound at a higher level (91 dB). Before the listening test, participants were influenced to a high expectancy of negative effects from infrasound with a video of a wind farm affected couple, or a low expectancy of negative effects with a video of an academic explaining why infrasound is not a problem. Then normal wind turbine sound was presented via a headset to all participants with the inclusion of the infrasound or no infrasound for a period of 23 min. The infrasound had no statistically significant effect on the symptoms reported by participants, but the concern they had about the effect of infrasound had a statistically significant influence on the symptoms reported.

A survey in Denmark [69] among 454 citizens living in rural areas at different distances to wind turbine farms with a varying numbers of wind turbines studied the effect on non-specific symptoms. The study included idiopathic symptoms (i.e. not related to a specific disease) as effects and distance to the wind farm and the number of turbines as a measure of exposure. The originally positive association of distance with fatigue, headaches and concentration problems all disappeared after adjustment for exposure to sound and odour from other sources.

Jalali et al. [76] report on a prospective cohort (i.e. before–after) study with 43 participants who completed a questionnaire in spring 2014 and again a year later. Exposure to a wind farm was only measured in terms of distance. Residents who were annoyed by the sound or sight of turbines, or who had a negative attitude towards them or were concerned about property devaluation, after 1 year experienced lower mental health and life quality and reported more symptoms than residents who were not annoyed and had positive attitudes towards turbines. The response rate for this study was

low (only 22%), and 12 people (of 43 that is approximately 25%) were not in the second round. Another weak point is the lack of a control group.

Against the background of the increasing number of wind farms in Germany, Krekel et al. [79] investigated the effect of the presence of wind turbines on residential well-being by combining household data from the German Socio-Economic Panel with a dataset on more than 20,000 wind turbines for the time period between 2000 and 2012. The key effect studied was life satisfaction. Results showed that the construction of one or more wind turbines in the neighbourhood of households had a significant negative effect on life satisfaction. This effect was limited in both distance and time.

More recent the first results were published of a new British study that was held near wind turbines in densely populated, suburban areas [43]. In this study part of the participants received a questionnaire that included explicit questions on the impacts of the local wind turbines on well-being, and the remaining part received a variant with no such questions. When including all participants, there was less annoyance from wind turbine sound in this study compared to what was found in earlier (Swedish, Dutch, Polish and Canadian) studies in rural areas. For the first group (with questions concerning local wind turbines), the sound levels were not significantly related to health problems and this group reported less health problems and better general health; this was opposite to the relationship found in the other, variant group.

3.2.4 Influence of Situational and Personal Factors

3.2.4.1 Visual Aspects

The paper of Voicescu et al. [65] on the Canadian data set (see Sect. 3.2) studied the effect of shadow flicker, expressed as the maximum duration in minutes per day, in combination with sound levels and distance, on annoyance and health complaints including dizziness. As shadow flicker exposure increased, the percentage of highly annoyed increased from 4% at short duration of shadow flicker (< 10 min) to 21% at 30 min of shadow flicker. Variables associated with the percentage highly annoyed due to shadow flicker included concern for physical safety and noise sensitivity. Reported dizziness was also found to be significantly associated with shadow flicker.

3.2.4.2 Economic Aspects

In the study of Michaud et al. [16] personal (economic) benefit was associated with less annoyance, in a significant but modest way, when excluding factors that were likely to be a reaction (such as annoyance) to the wind turbine operation. The association between personal benefit from a wind turbine was also found in the Netherlands [85]. In the Japanese study from Kageyama et al. [66,67], this relationship was

not found to be significant. However, it might not only be the benefit, but differences in attitude and perception as well as having more control over the placement of the turbines that might play a role [37].

3.2.4.3 Noise Sensitivity

Recent studies of Michaud et al. [36] and Kageyama et al. [66,67], both from 2016, confirm the independent role noise sensitivity has on reaction to wind turbines (see also Sect. 3.1.4.3). The influence of noise sensitivity on noise annoyance was reported earlier by many other researchers [42,59,86–88]. In all these studies, being highly noise sensitive was related to more annoyance. Similarly, the odds of reporting poor QoL and dissatisfaction with health were higher among those who were highly noise sensitive. However, after adjustment for current health status and work situation (unemployment) the influence of noise sensitivity became marginal. Fear and concern about the potential harm of wind turbines was an important predictor of annoyance as has been reported earlier for other noise sources [89–92].

In the Canadian study length of exposure seemed to be an important situational factor and led to up to 4 times higher levels of annoyance for people living more than 1 year in the vicinity of a wind turbine. This indicates sensitization to the sound rather than adaptation or habituation as is often assumed. The moderate effect of wind turbine sound level on annoyance and the range of (other) factors that predict the level of annoyance imply that efforts aimed at mitigating the community response to WTN will profit from considering other factors associated with annoyance. In the Japanese study [66,67] poor subjective health was not related to wind turbine sound levels, but again noise sensitivity and visual annoyance were significant predictors for the effects studied. Both noise sensitivity and visual annoyance seem, according to them, to be indicators of a certain vulnerability to environmental stimuli or changes in environmental factors.

Maffei et al. [75] studied 40 people subdivided in an experimental and control group (familiar for a long time with wind turbine sound versus not familiar). The study included a listening test to sound recorded at a wind farm of 34 wind turbines including background sound (wind in vegetation), or only background sound. Sound recordings of about 5-min duration were made at five distances (150, 200, 250, 300 and 1500 m) from the wind farm. For each distance 65 soundtracks were used. The aim was to detect wind turbine sound at varying distances. For both groups of participants, familiar and unfamiliar, there was no difference in recognition of wind turbine sound at distances of 300 m or less and detection was easiest at distances up to 250 m. At 1500 m those familiar with wind turbine sound could detect the sound better, but they also reported more often ‘false alarms’. Noise sensitivity was an important factor.

3.2.4.4 Social Aspects

According to Chapman et al. [93] and Crichton et al. [94], there is a strong psychogenic component in the relation between wind turbine sound and health complaints. This is not unique for wind turbine sound but has been documented for other sources as well, see e.g. [89,95,96]. In both studies [93,94] attention was given to expectations on the level of annoyance and the level of awareness ('notice') of the characteristics and prominent sounds of wind turbines [84]. The influence of these factors has been found in many studies regarding the effects of other sound sources [97]. In more recent years many researchers have investigated the social acceptance of wind projects in a number of countries by local communities and many stress the relevance of a fair planning process and local involvement [98–101]. The influence of injustice and fair planning process are confirmed in the most recent studies. Jalali [76] e.g. showed that concern about decreases in property values was associated with mental health problems.

Finally, Botterill and Cockfield [80] studied the discourse about wind turbines in submissions to public inquiries and in a small number of detailed interviews, and topics addressed in the discourse. Health and property values were found to be the most prominent topics discussed in the inquiries with regard to wind turbines in the submissions (and aesthetics/landscape arguments less often), but in the interviews these were never mentioned.

4 Health Effects of Low-Frequency Sound and Infrasound

In the non-scientific literature, which can be found on the internet, a range of health effects is attributed to the presence of wind turbines. Infrasound is described as an important cause of these effects, also when the infrasound levels must be very low or are unknown. In this section the question is whether infrasound or low-frequency sound deserves special consideration with respect to the effects of wind turbine sound. There is some discrepancy when comparing conclusions from the majority of scientific publications to conclusions in popular publications. Also, some scientific publications suggest possible impacts that are not generally supported. The findings regarding low-frequency sound and infrasound are not easy to interpret. It may be confusing that the frequency of the rhythmic changes in sound due to amplitude modulation is the same as the frequency of an infrasound component. Also, some authors conclude that low-frequency sound and infrasound play a role in the reactions to wind turbine sound that is different from the effects of 'normal' sound [16,102] which is contested by many others. In general, however, there is little definite evidence on specific health effects

of low-frequency sound when compared to health effects from 'normal' sound [103].

First, we will consider the audibility of infrasound and low-frequency sound and then possible health effects not involving audibility. Because we are, in the case of low-frequency sound and infrasound, dealing with other health effects, the paragraphs are structured different than was the case in the previous section.

4.1 Audibility of Infrasound and Low-Frequency Sound

Audible low-frequency sound is all around us, e.g. in road and air traffic. Audible infrasound is less ubiquitous, but can be heard from big machines and storms. In most publications on wind turbine sound, there is agreement that infrasound and low-frequency sound are both present in wind turbine sound. Generally, it is acknowledged that wind turbine infrasound is inaudible as infrasound levels are low with respect to human sensitivity [16,19,25,104,105].

Even close to a wind turbine, most authors argue that infrasound is not a problem with modern wind turbines. This can be shown from measurement results at 10 and 20 Hz. At the (infrasound) frequency of 10 Hz the A-weighted sound power level is typically 60 dB lower than the total sound level in dBA [15]. At a receiver with a total sound level of 45 dBA this means that the 10 Hz sound level is about minus 15 dBA or, in physical terms (not A-weighted), 55 dB. This is far below the hearing threshold at that frequency, which for normal-hearing persons is about 95 dB. A sound of 55 dB at 10 Hz would also be inaudible for the few persons that have been reported with a much lower hearing threshold (close to 80 dB). At 20 Hz, the upper frequency limit of infrasound, the result, again at a receiver total sound level of 45 dBA, would be a physical level of wind turbine sound of 50–55 dB which is much lower than the normal hearing threshold at that frequency of 80 dB [106].

As a part of a Japanese study on wind turbine low-frequency sound, persons in a laboratory were subjected to wind turbine sound where very low frequencies were filtered out over different frequency ranges [13]. When infrasound frequencies were filtered out, the study persons did not note different sensations. Above about 30 Hz they began to notice a difference between the filtered and original sound.

Leventhall [107] states that the human body produces infrasound internally (through blood flow, heartbeat and breathing, etc.) and this would mask infrasound from outside sources when this sound is below the hearing threshold.

In contrast to infrasound, there is general agreement that low-frequency sound is part of the audible sound of wind turbines and therefore contributes to the effects caused by wind turbine sound. The loudest part of the sound as radiated by a turbine is in the mid-frequency range (250–1600 Hz) [15,16]. This shifts to lower frequencies when the sound travels

through the atmosphere and enters a building because absorption by the atmosphere and a building facade reduces low frequencies less than higher frequencies. However, studying the effects of the low frequencies separately from the higher frequencies is not easy as both frequency ranges automatically go together: wind turbines all have very much the same sound composition. In a Canadian study on wind turbines, the sound levels at the facades of dwellings were calculated as both A- and C-weighted sound levels, but this proved not to be an advantage as the two were so closely linked that there was no added value in using both [82]. A limit in A-weighted decibels (where the A-weighting mimics human hearing at moderate sound levels) thus automatically limits the low-frequency part of the sound [105].

Bolin et al. [108] calculated and compared wind turbine and road traffic sound over a broad frequency range (0–2000 Hz) at sound levels considered acceptable in planning guidelines (40 dB L_{Aeq} for wind turbine sound and 55 dB L_{Aeq} for road traffic sound). Compared to road traffic sound, wind turbine sound had lower levels at low frequencies. Thus, at levels often found in urban residential areas, low-frequency sound from wind turbines is less loud than from road traffic sound. Recent measurements in dwellings and residential areas show that similar levels of infrasound occur, when comparing wind turbine sound with sound from traffic or household appliances [109].

4.2 Effect of Lower Frequencies

McCunney et al. [25] mention that both infrasound and low-frequency sound have been suggested to pose possibly unique health hazards associated with wind turbine operations. From their review of the literature, including results from field measurements of wind turbine-related sound and experimental studies in which people have been purposely exposed to infrasound, they conclude that there is no scientific evidence to support the hypothesis that wind turbine infrasound and low-frequency sound has effects that other sources of infra/low-frequency sound do not have.

4.3 Subaudible Effects

Several authors have linked infrasound and low-frequency sound from wind turbines to health effects experienced by residents, assuming that infrasound can have physiological effects at levels below the (normal) hearing threshold [110–112]. This was supported by Salt and Kaltenbach [113] who argued that normal hearing is the result of inner hair cells in the inner ear producing electric signals to the brain in response to sound received by the ear. However, infrasound and low-frequency sound (up to 100 Hz) can also lead to signals from the outer hair cells (OHC) and the threshold for this is lower than for the inner hair cells. This means that

inaudible levels of infrasound and low-frequency sound can still evoke a response [113]. The OHC threshold is 60 dB at 10 Hz and 48 dB at 20 Hz. Comparing this to actual sound levels (see Sect. 4.1) shows that infrasound levels from wind turbines could just exceed this OHC threshold when their total outdoor sound level is 45 dBA. It is unlikely that the OHC threshold can be exceeded indoors, where levels are lower, except at a high sound level that may occur very close to a wind turbine. Salt and Kaltenbach [113] conclude from this that it is ‘scientifically possible’ that infrasound from wind turbines thus could affect people living nearby. However, it is not clear to what reactions these signals would lead or if they could be detrimental when just exceeding the OHC threshold. If such inaudible sound could have effects, it is not clear why this has never been observed with everyday sources (other than wind turbines) that produce infrasound and low-frequency sound such as strong winds, road and air traffic, or with physiological sounds from heartbeat, blood flow, etc.

Farboud et al. [114] conclude that physiological effects from infrasound and low-frequency sound need to be better understood; it is impossible to state conclusively that exposure to wind turbine sound does not cause the symptoms described by authors such as Salt and Hullar or Pierpont.

Leventhall [107] argues that infrasound at low level is not known to have an effect. Normal pressure variations inside the body (from heart beat and breathing) cause infrasound levels in the inner ear that are greater than the levels from wind turbines. From exposure to high levels of infrasound, such as in rocket launches and associated laboratory studies or from natural infrasound sources, there is no evidence that infrasound at levels of 120–130 dB causes physical damage to humans, although the exposure may be unpleasant [107].

Stead et al. [115] come to a similar conclusion when considering the regular pressure changes at the ear when a person is walking at a steady pace. The up and down movement of the head implies a slight change in atmospheric pressure that corresponds to pressure ‘sound’ levels in the order of 75 dB. The pressure changes in the rhythm of the walking frequency are similar in frequency (close to 1 Hz), and level to the pressure changes from infrasound at rotation frequencies measured at houses near wind farms.

4.4 Vestibular Effects

According to Pierpont the (infra)sound of wind turbines can cause visceral vibratory vestibular disease (VVVD), affecting the vestibular system from which we derive our sense of balance. She characterized this new disease with the following symptoms: ‘a feeling of internal pulsation, quivering or jitteriness, and it is accompanied by nervousness, anxiety, fear, a compulsion to flee or check the environment for safety, nausea, chest tightness, and tachycardia’ [111], stat-

ing that infrasound and low-frequency sound were causing this ‘wind turbine syndrome’. Pierpont’s research was based on complaints from 38 people from 10 families who lived within 300–1500 m from one or more turbines in the USA or Great Britain, Italy, Ireland and Canada. In several publications (e.g. [22,25]), it was pointed out that Pierpont’s selection procedure was to find people who suffer the most, and it was not made clear that it was indeed the presence of the wind turbine(s) that caused these symptoms. Although the complaints may be genuine, it is possible that very sensitive people were selected and/or media coverage had led to physical symptoms attributed to environmental exposures as has been demonstrated for wind turbines [93] and other environmental exposures [116]. Van den Berg [44] noted that the symptoms of VVVD are mentioned in the Diagnostic and Statistical Manual of Mental Disorders (DSM) as stress symptoms in three disorders: an adjustment disorder, a panic disorder and a generalized anxiety disorder. The wind turbine syndrome may thus not be a new phenomenon, but an expression of stress that people have and which could have a relation to their concern or annoyance with respect to a (planned) wind farm.

In his examination of the wind turbine syndrome, Harrison [27] argued that at a level of 40–50 dBA no component of wind turbine sound approaches levels high enough to activate the vestibular system. The threshold for this is about 110 dB for people without hearing ailments. In people with a hearing ailment, particularly the ‘superior (semicircular) canal dehiscence syndrome’ (SCDS), this threshold is lower and can be 85 dB. Such levels are only reported very close to wind turbines. Reports show that 1–5% of the adult population may have (possibly undiagnosed) SCDS.

Schomer et al. [117] studied residents of three homes where residents generally did not hear the wind turbines in their area, but they did report symptoms comparable to motion sickness. Schomer et al. suggest that this could result from sound affecting the vestibular sensory cells and in their opinion wind turbine infrasound could generate a pressure that they compare with an acceleration exceeding the U.S. Navy’s criteria for motion sickness. This has been investigated by Nussbaum and Reinis much earlier [118]. They exposed 60 subjects to a tone of 8 Hz and 130 dB with high distortion (high-level harmonics at multiples of 8 Hz) or low distortion (harmonics at lower level). Dizziness and nausea were primarily associated with the low distortion exposure, i.e. a relatively high infrasound content. In contrast, headache and fatigue were primarily associated with the high distortion exposure, with a relatively low infrasound content. Nussbaum and Reinis [118] hypothesized that the effects of the purer infrasound could be explained as acoustically induced motion sickness. However, this was concluded from exposure levels (130 dB) much higher than wind turbines can cause.

4.5 Vibroacoustic Disease

According to Alves-Pereira and Castelo Branco [112], the infrasound and low-frequency sound of a wind turbine can cause vibroacoustic disease (VAD), an affliction identified by a thickening of the mitral valve (one of the valves in the heart) and the pericardium (a sac containing the heart). The most important data regarding VAD are derived from a study among aircraft technicians who were professionally exposed to high levels of low-frequency sound [119]. VAD is controversial as a syndrome or disease. Results of animal studies have only been obtained in studies using low-frequency sound levels which are found in industrial settings. No studies are known that use a properly selected control group. And finally, the way the disease was diagnosed has been criticized because of a lack of precision [120]

After investigating a family with two wind turbines at 322 and 642 m from their dwelling, Alves-Pereira and Castelo Branco [112] concluded that VAD occurred and was caused by low-frequency sound. The measured sound levels were substantially lower (20 dB or more) than levels at which VAD was thought to occur by Marciniak et al. [119] and the levels were below the normal hearing threshold for a considerable range of frequencies in this range. In their review of evidence on VAD Chapman et al. [93] concluded that in the scientific community VAD was only supported by the group who coined the term and there is no evidence that vibroacoustic disease is associated with or caused by wind turbines.

4.6 Effect of Vibrations

Vibrations from wind turbines can lead to ground vibrations and these can be measured with sensitive vibrations sensors. In several studies vibrations have been measured at large distances, but this was because these vibrations could affect the performance of seismic stations that detect nuclear tests. These vibrations are too weak to be detected or to affect humans, even for people living close to wind turbines [98].

In measurements at three dwellings, Cooper et al. [104] found surges in ground vibration near wind turbines that were associated with wind gusts, outside as well as inside one of the three houses. Vibration levels were weak (less than from people moving around), but measurable. According to Cooper, two residents were clearly more sensitive than the other four; the sensations experienced by the residents seemed to be more related to a reaction to the operation of the wind turbines than to the sound or vibration of the wind turbines. This echoes earlier findings from Kelley [121] who investigated complaints, from two residences, that were thought to be associated with strong low-frequency sound pulses from the experimental downwind MOD-1 wind turbine. The low-frequency sound pulses were generated when a turbine blade passed the wind wake behind the mast. The

residents perceived ‘audible and other sensations, including vibration and sensed pressure changes’. Although the wind turbine sound at frequencies below about 30 Hz was below the normal hearing threshold, this sound was believed to be causing the annoyance complaints. The sound levels were within a range of sound levels and frequencies cited in a report from Stephens et al. [122] for situations where (sub-audible) industrial sound within this range was believed to be the source of the complaints. This could be explained by the response of a building to the sound outside: the distribution of sound pressure in the building can be the result of structure-borne sound, standing waves and resonances due to the configuration of a room, closet and/or hallway. The rhythmic character of wind turbine sound could have an added effect because of the periodic pressure pulses; if these coincide with a structural resonance of the building the indoor level can be higher than expected from just reduction by the facade. These structural vibrations can lead to sound at higher frequencies which are audible. Several authors have pointed out that the rhythmic character itself (technically, amplitude modulation) is more relevant to human perception than low-frequency sound or infrasound (see *What makes wind turbine sound so annoying?* in Sect. 3.1.1). However, the appreciation of the sound may depend on a combination of the frequency and strength of the modulation and the balance of low- and higher-frequency components [123].

5 Discussion and Conclusions

5.1 Primary Findings

This review summarizes the findings of ten previous reviews on the effect of wind turbines on health and the role of personal, situational and physical factors other than sound. In addition, the results from 22 papers that were published later (after early 2015) were reviewed. The results will be presented here with an indication of a possible change over time when comparing evidence before and since 2015.

Results confirm the earlier evidence that living in areas with wind turbines is associated with an increased percentage of highly annoyed residents. Earlier findings of a possible association with perceived and measured sleep disturbances are not confirmed in the latest studies, nor does recent evidence support the notion of a possibly decreased quality of life in relation to exposure to wind turbine sound. Also, the findings of recent studies do not support a relation between subjective and objective stress indicators and exposure to wind turbine sound. Earlier findings on personal, situational and contextual factors (such as visual aspects, attitude, benefits, perceived injustice and fair planning process) are confirmed in the most recent studies. Available scientific research does not provide a definite answer about the question

whether wind turbine sound can cause health effects which are different from those of other sound sources. However, wind turbines do stand out because of their rhythmic character, both visually and aurally. Several new laboratory studies have in particular addressed the role of amplitude modulation (AM). Results are inconclusive regarding the effect of amplitude modulation on annoyance. A common conclusion seems to be that AM appears to aggravate existing annoyance, but does not lead to annoyance in persons who benefit from or have a positive attitude towards wind turbines. Recent reviews of McCunney et al. [25] and Harrison [27] conclude that there is no scientific evidence to support the hypothesis that wind turbine infrasound and low-frequency sound have effects that other sources do not have. In general, evidence on specific health effects of low-frequency sound is limited. As the CCA [28] worded it: 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 recent studies largely support earlier scientific findings but have improved the state of the art with thorough research and adding objective measures to self-reported effects. Exposure characterization has been improved considerably by including local sound measurements in field studies, and the recent AM studies have improved the knowledge base considerably.

5.2 Discussion

5.2.1 Physical, Social and Personal Factors Add

There are many models or schemes that show how people react to sound. However, much of the public debate about wind turbines and sound is at the planning stage when wind turbines are not yet present. Michaud et al. [63] proposed a model that incorporates the influence of (media) information and expectations as well as actual wind turbine sound exposure. In Fig. 3 we present a simplified model based on the one from Michaud et al. [63]. It shows that plans for wind turbines or actual wind turbines can lead to disturbances and concern, but a number of factors can influence the effect of the (planned) turbines (see ‘Michaud model’ for these factors). Personal factors include attitude, expectations, noise sensitivity. Situational factors include other possible impacts such as visibility or shadow flicker, other sound sources, type of area. Contextual factors include participation, the decision-making process, the siting procedure, procedural justice.

The model illustrates that next to wind turbine sound itself, several other features are relevant for residents living in the vicinity of wind turbines. These include physical and personal aspects, and the particular circumstances around decision-making and siting of a wind farm as well as commu-

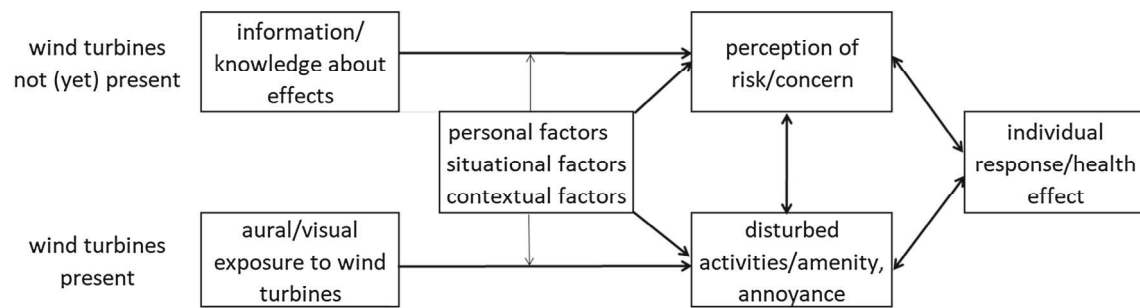


Fig. 3 A graphic summary model for the relationship between exposure to wind turbines and individual response (after Michaud et al. [63])

nication and the relation between different people involved in the process. There is consensus that visual aspects play a key role in reactions to wind turbines and this includes the (mis-)match with the landscape, shadow casting and blinking lights. Shadow casting from wind turbines is described as annoying for people and also the movement of the rotor blades themselves can be experienced as disturbing. Light reflection/flicker from the blades and vibrations play a minor role in modern turbines as far as the effect on residents is concerned. It has been shown that people who benefit from and/or have a positive attitude towards wind turbines in their environment in general report less annoyance. People who perceive wind turbines as intruding into their privacy and detrimental to the quality of their living environment in general report more annoyance. Perceived (procedural) injustice has been found to be related with the feeling of intrusion and lack of control/helplessness. Most studies confirm the role of noise sensitivity in the reaction to wind turbines, independent of the sound level or sound characteristics. Attitude and media coverage are just a few elements of the complex process of policy and decision-making for siting wind turbines. Most recent studies conclude that social acceptance of wind projects is highly dependent on a fair planning process and local involvement. The latest evidence seems to confirm the role of these factors described in earlier reviews and studies.

5.2.2 Evidence on Adverse Effects of Wind Turbine Sound

Noise annoyance is the main health effect associated with the exposure to sound from an operational wind turbine. At equal sound levels, sound from wind turbines is experienced as more annoying than that of traffic sources [19,29]. From epidemiological and laboratory studies, the typical character of wind turbine sound comes forward as one of the key issues. Particularly, the rhythmic character of the sound (technically, amplitude modulation or AM), described as a swishing or wooshing sound, is experienced as annoying. Residential wind turbine sound levels themselves are modest when compared to those from other sources such as road or industrial sound. However, recent laboratory studies [12,71,72]

are inconclusive regarding the effect of amplitude modulation on annoyance. One conclusion is that ‘there is a strong possibility that amplitude modulation is the main cause of the properties of wind turbine noise’, in which properties refer to sounds that are easily detectable and highly annoying at relatively low sound levels [12]. Another dismisses amplitude modulation as a negative factor per se because it is highly related to attitude [72]. A common factor is that AM appears to aggravate existing annoyance, but does not lead to annoyance for persons positive about or benefiting from wind turbines. The general exposure–effect relation for annoyance from wind turbine sound includes all aspects that influence annoyance and thus averages over all local situations and non-acoustic factors. The relation can therefore only form an indication of the annoyance levels to be expected in a local situation.

New evidence regarding the effect of night time wind turbine sound exposure on sleep suggests no direct effect, but remains inconclusive. The current results do not allow a definite conclusion regarding both subjective and objective sleep indicators [62]. However, studies do find a relationship between self-reported sleep disturbance and annoyance from wind turbines [41] and between self-reported sleep disturbance and perceived quality of life [47,48].

For other health effects, there is insufficient evidence for a direct relation with wind turbine sound levels.

Based on noise research in general, we can conclude that chronic annoyance from wind turbines and the feeling that the quality of the living environment has deteriorated or will do so in the future, and can have a negative impact on well-being and health in people living in the vicinity of wind turbines. This is similar to the effect of other stressors [19]. The moderate effect of the level of wind turbine sound on annoyance and considering the range of factors that influence the levels of annoyance implies that reducing the impact of wind turbine sound will profit from considering other factors associated with annoyance. The influence of these factors is not necessarily unique for wind turbines. The fact that residents can respond very differently to a sound shows that annoyance from a sound is not inextricably bound up with that sound.

5.2.3 Evidence on Adverse Effects of Low-Frequency Sound and Infrasound

There is substantial knowledge about the physical aspects of low-frequency sound. Low-frequency sound can be heard daily from road and air traffic and many other sources. Less is known about infrasound and certainly the perception of infrasound. Infrasound can sometimes be heard, e.g. from big machines and storms, but is not as common as low-frequency or ‘normal’ sound. However, with sensitive equipment infrasound, as well as vibrations, can be measured at large distances. Infrasound and low-frequency sound are present in wind turbine sound. Low-frequency sound is included in most studies as part of the normal sound range. In contrast, infrasound is in most studies considered as inaudible as the level of infrasound is low with respect to human sensitivity. Studies of the perception of wind turbine infrasound support this. Infrasound and low-frequency sound from wind turbines have been suggested to pose unique health hazards. There is little scientific evidence to support this. The levels of infrasound involved are comparable to the level of internal body sounds and pressure variations at the ear while walking. Infrasound from wind turbines is not loud enough to influence the sense of balance (i.e. activate the vestibular system), except perhaps for persons with a specific hearing condition (SCDS). Effects such as dizziness and nausea, or motion sickness, could be an effect of infrasound, but are expected at much higher levels than wind turbines produce in residential situations. Vibroacoustic disease and the wind turbine syndrome are controversial and scientifically not supported. At the present levels of wind turbine sound, the alleged occurrence of vibroacoustic disease (VAD) or the disease (VVVD) causing the wind turbine syndrome (WTS) is unproven and unlikely. However, the symptoms associated with WTS are symptoms found in relation to stress.

The rhythmic character of wind turbine sound is caused by a succession of sound pulses produced by the blade rotations. From early research it was concluded that this may lead to structural vibrations of a house and wind turbines thus may be perceived indirectly inside a house and hence lead to annoyance. This possibility needs further investigation.

5.3 Strengths and Limitations

The strengths of this review are the use of a robust search strategy to identify relevant studies, its broad approach in terms of both the range of outcomes and noise characteristics considered and the special consideration of the role of low-frequency sound and infrasound. We also tried to make the available knowledge accessible for a broader audience by avoiding technical terms as much as possible. We added to earlier reviews by reviewing the latest studies which are

of high quality and have shown how the state of knowledge developed over time. However, we recognize limitations as well. Although the literature search was performed systematically, the review is primarily a narrative one and in this sense will repeat in a less rigid manner the conclusions of previous reviews. Although the studies were systematically selected and structured, in our wording and interpretation we follow a ‘story line’ inherent to a narrative review. The text reflects our view, based on an extensive amount of knowledge of (reactions to) wind turbine sound and environmental sound in general.

5.4 Methodological Considerations and Implications for Future Research

Again, or we might say still, we can conclude that the earlier identified lack of methodological and statistical strength of wind turbine studies by CCA [28] still holds. With a few exceptions in general, the sample size of most studies is limited, and with regard to both the exposure and outcomes, there is room for improvement.

5.5 Final Conclusion

Systematic reviews published since 2009 including some recent and high quality ones, and new evidence not yet reviewed suggest that exposure to wind turbine sound is associated with higher odds for annoyance. The proximity of a wind turbine or wind farm has not conclusively been proven to negatively affect stress responses, quality of life, sleep quality (subjective and objective) nor other health complaints. A reason for this may be that individual traits and attitudes, visual aspects as well as the process of wind farm planning and decision-making are highly likely to influence the response to sound from wind turbines. Larger-scale studies at locations with varying circumstances and with a before after component (prospective cohort) are recommended for the future. Ideally measured sound levels over the whole frequency range and routinely collected registry health data should be used in conjunction with more subjective data.

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MEASUREMENT AND LEVEL OF INFRASOUND FROM WIND FARMS AND OTHER SOURCES

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Infrasound is generated by a range of natural and engineered sources. The measurement of infrasound at low levels requires a specific methodology, as it is readily affected by even light surface breezes on the microphone. Such a methodology, based on measurements below the ground surface in a test chamber, has been developed to measure infrasound at two Australian wind farms and also in the vicinity of a beach, a coastal cliff, the city of Adelaide and a power station. The measured levels have been compared between each source and against the infrasound audibility threshold of 85 dB(G). The measured level of infrasound within the wind farms is well below the audibility threshold and is similar to that of urban and coastal environments and near other engineered noise sources.

INTRODUCTION

Infrasound is generally considered to be sound at frequencies less than 20 Hz and is often described as inaudible. However, sound below 20 Hz remains audible provided that the sound level is sufficiently high [1]. Infrasound is generated by a range of natural sources, including waves on the coastline, waterfalls and wind. It is also generated by a wide range of engineered sources such as industrial processes, vehicles, air conditioning and wind farms. The thresholds of audibility for infrasound have been determined in a range of studies [2]. The G-weighting has been standardised to determine the human perception and annoyance due to noise that lies within the infrasound frequency range [3]. A common audibility threshold from the range of studies is an infrasound level of 85 dB(G) or greater. The audibility threshold limit of 85 dB(G) is consistent with other European standards and studies, including the UK Department for Environment, Food and Rural Affairs threshold developed in 2003 [2], the UK Department of Trade and Industry study [4], the German Standard DIN 45680 [5] and independent research conducted by Watanabe and Møller [6].

There have been concerns raised in the community regarding the generation of infrasound by Australian wind farms. The generation of infrasound was detected on early international turbine designs, which incorporated the blades 'downwind' of the tower structure [7]. The mechanism for the generation was the blade passing through the wake caused by the presence of the tower. Modern wind turbines now locate the blade 'upwind' of the tower.

Australian States presently assess the noise from wind farms under a range of Standards and Guidelines [8-12]. These Standards and Guidelines do not provide prescriptive requirements for infrasound from wind farms due to the absence of evidence that infrasound should be assessed.

A specific methodology was developed to reduce the influence that even light surface breezes can have on the infrasound results. The methodology is based on measurements being conducted below the ground surface in a test chamber that is approximately 500mm square and 500mm deep. Infrasound was measured using this below ground methodology at

two Australian wind farms, Pacific Hydro's Clements Gap Wind Farm which has been operating in the mid-North of South Australia since 2010 and comprises 27 Suzlon S88 wind turbines, each with a rated capacity of 2.1 MW, and at the coastal Cape Bridgewater Wind Farm which has been operating since 2008 in south-western Victoria, and comprises 29 REpower MM82 wind turbines, each with a rated capacity of 2.0 MW. Infrasound was also measured in the vicinity of a beach, a coastal cliff, the city of Adelaide and a power station using the below ground methodology. This paper reports on the study that:

- Develops a methodology to measure infrasound that minimises the influence of wind on the microphone;
- Measures the levels of infrasound at a range of distances from a wind turbine, for two wind farms;
- Compares the results against recognised audibility thresholds; and
- Compares the results with infrasound measurements taken near natural sources, such as beaches, and engineered sources, such as a power station and general activity within the city of Adelaide.

MEASUREMENT TECHNIQUE

Equipment

All measurements were conducted with a SVANTEK 957 Type 1 NATA calibrated sound and vibration analyser. The SVANTEK 957 Type 1 meter has a measured frequency response down to 0.5 Hz. A GRAS 40AZ ½" free field microphone with a frequency response of ± 1 dB to 1 Hz and ± 2 dB to 0.5 Hz was used with the SVANTEK meter. The meter and microphone arrangement is therefore suitable for measurement of noise levels in the infrasound range to the level of accuracy required for the assessment.

Microphone Mounting Method

A microphone mounting method is provided in IEC 61400-11 [13]. The method was developed to minimise the influence of wind on the microphone for the measurement of noise in frequencies higher than those associated with infrasound. This

is achieved by mounting the microphone at ground level on a reflecting surface and by protecting the microphone with two windshields constructed from open cell foam. The method was not developed specifically for the measurement of infrasound, and wind gusts can be clearly detected when measuring in the infrasound frequency range using the above method. Therefore, this study has developed an alternative method to reduce the influence of wind on the microphone that would otherwise mask the infrasound from a particular source. A below ground surface method was developed based on a similar methodology [14]. This method has been adapted for this study, and includes a dual windshield arrangement, with an open cell foam layer mounted over a test chamber and a 90mm diameter primary windshield used around the microphone. The microphone mounting arrangement is depicted in Figure 1.

Verification of Technique

The below ground technique was analysed at a remote site away from wind farms, transport corridors and other appreciable noise sources and in very still conditions. The aim of the analysis was to determine the level of transfer of infrasound from outside to inside the chamber. The following

procedure was used:

- A constant level of infrasound was generated using a tone signal generator and sub-woofer speaker (B&W Type ASW CDM), mounted 1m above the ground at a distance of 10m horizontally from the chamber. The lowest frequency that could be generated by the signal generator was 8 Hz and therefore the infrasound was generated at a number of discrete frequencies between 8 and 20 Hz.
- The infrasound was measured using the IEC 61400-11 above ground technique;
- The infrasound was measured using the below ground technique;
- The infrasound was measured without the tone signal generator operating to determine the ambient level of infrasound.

The measurement results are summarised in Table 1. The measured levels inside and outside of the chamber were consistent at all of the frequencies produced by the signal generator. The measurement of a constant source of infrasound in still conditions is the same above the ground as in the chamber using the technique described above.

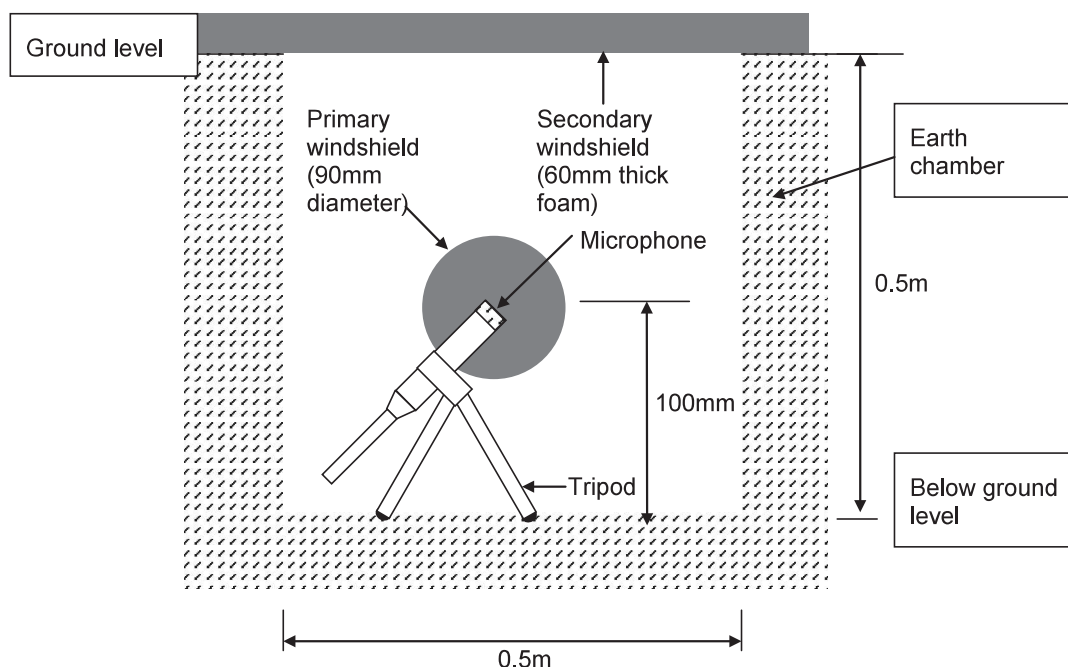


Figure 1. Schematic diagram of the microphone position (not to scale)

Table 1. Measurement at approximately 10m from the controlled source with no wind

Frequency (Hz)		8.00	10.0	12.5	16.0	20.0
Noise Level (dB)	Inside chamber	47	50	54	60	63
	Outside chamber	47	50	54	60	63
	Ambient level	39	38	39	39	37

RESULTS

Infrasound was measured at the Clements Gap Wind Farm and the Cape Bridgewater Wind Farm, using the below ground methodology. In addition, the level of infrasound was measured in the vicinity of a beach, a coastal cliff, a city and a power station using the same methodology. At Clements Gap Wind Farm, the infrasound was measured at distances of 85m, 185m and 360m from the base of a turbine in a downwind direction. The testing was conducted between approximately 7pm and 11pm on Tuesday 11 May 2010, under a clear night sky with a light breeze. Operational data indicates that the turbines were subject to hub height wind speeds of the order of 6 to 8m/s during the period of the testing. The wind speed at ground level was not measured.

At Cape Bridgewater Wind Farm, the infrasound was measured at distances of 100m and 200m from the base of a turbine in a downwind direction. The testing at the wind farm site was conducted between approximately 4am and 6am on Wednesday 2 June 2010, under a clear night sky with a light breeze. During the testing, the operational status of the turbines was constantly observed and confirmed. Measurements were conducted with both the turbines operational and with the turbine blades stationary.

To determine the level of infrasound from natural sources, measurements using the below ground method were made at Cape Bridgewater 25m from the high waterline of a beach, at approximately 250m inland from a coastal cliff face and at 8km inland from the coast. To determine the level of infrasound from other engineered noise sources, measurements using the below ground method were conducted at a distance of approximately 350m from a gas fired power station as well as within the city of Adelaide at least 70m from any major road. The measured levels of infrasound are summarised in Table 2 and are shown graphically in one third octave bands in Figures 2, 3, 4 and 5.

Table 2. Measured levels of infrasound

Noise Source	Measured Level (dB(G))
Clements Gap Wind Farm at 85m	72
Clements Gap Wind Farm at 185m	67
Clements Gap Wind Farm at 360m	61
Cape Bridgewater Wind Farm at 100m	66
Cape Bridgewater Wind Farm at 200m	63
Cape Bridgewater Wind Farm ambient	62
Beach at 25m from high water line	75
250m from coastal cliff face	69
8km inland from coast	57
Gas fired power station at 350m	74
Adelaide CBD at least 70m from any major road	76

DISCUSSION

At the Clements Gap Wind Farm, the level of attenuation with increasing distance from the turbine is consistent with the theoretical reduction of 6dB for each doubling of the distance due to “hemispherical spreading” of the sound wave. This observation confirms that the measured levels were predominantly produced by the turbine. At the Cape Bridgewater Wind Farm, higher ambient noise levels (without the turbines operating) were encountered than at the Clements Gap Wind Farm and therefore the same attenuation with increasing distance was not observed. This indicates that the measured levels included a significant contribution of infrasound from the turbine at 100m but at a distance of 200m, the infrasound from other sources was at least as significant. The levels of infrasound from waves at a beach (in light swell conditions) and in the vicinity of a coastal cliff were in the same order of magnitude as the infrasound measured close to the wind turbines.

At 8km from the coast, the level of infrasound was significantly lower than levels observed in close proximity to the beach and the coastal cliff. The levels of infrasound in the city of Adelaide and in the vicinity of a gas fired power station were greater than the levels observed close to the wind turbines. The measured levels of infrasound from the wind turbines and all other natural and engineered sources were well below the 85dB(G) threshold of audibility.

CONCLUSIONS

A method for measuring infrasound from wind turbines has been successfully demonstrated. The method shows that wind turbines generate infrasound and that close to wind turbines, the level of infrasound is well below the audibility threshold of 85 dB(G). An attenuation rate of 6dB per doubling of distance from a single turbine was also demonstrated. Infrasound is prevalent in urban and coastal environments at similar levels to the level of infrasound measured close to a wind turbine.

ACKNOWLEDGEMENTS

Pacific Hydro commissioned Sonus to conduct a study with the aim of gaining a better understanding of the levels of infrasound from wind farms and more generally in the environment.

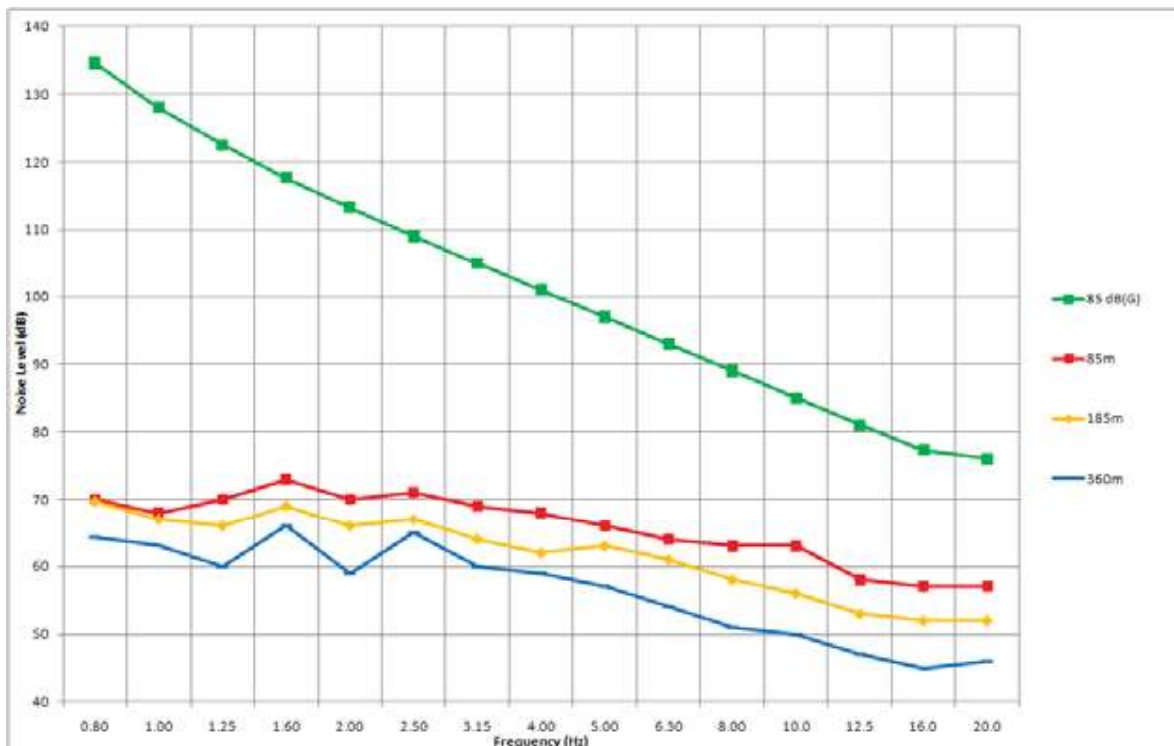


Figure 2. Measured levels of infrasound at Clements Gap Wind Farm

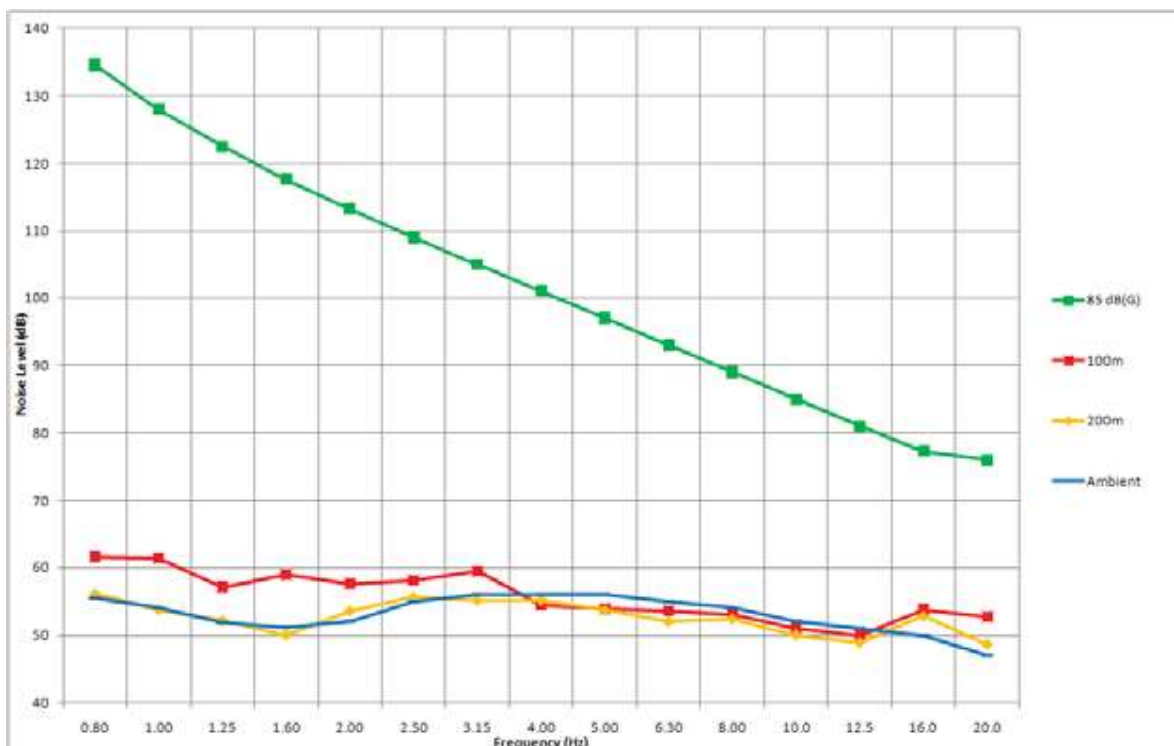


Figure 3. Measured levels of infrasound at Cape Bridgewater Wind Farm

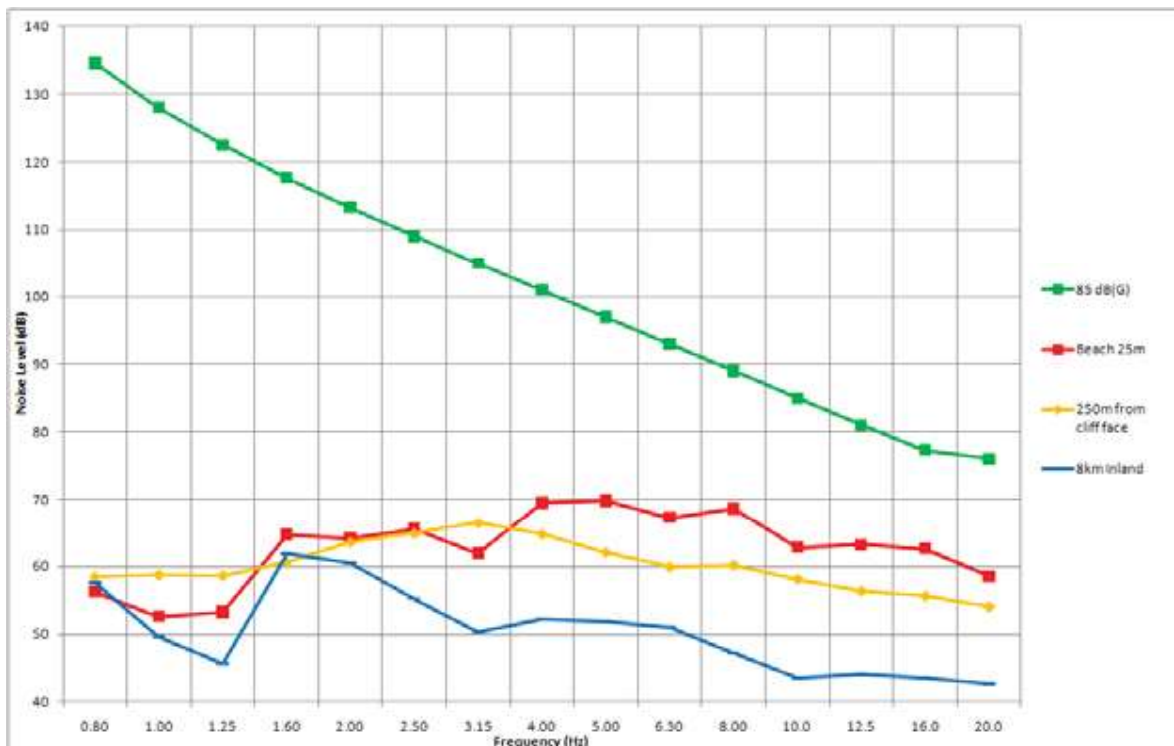


Figure 4. Measured levels of infrasound from natural sources

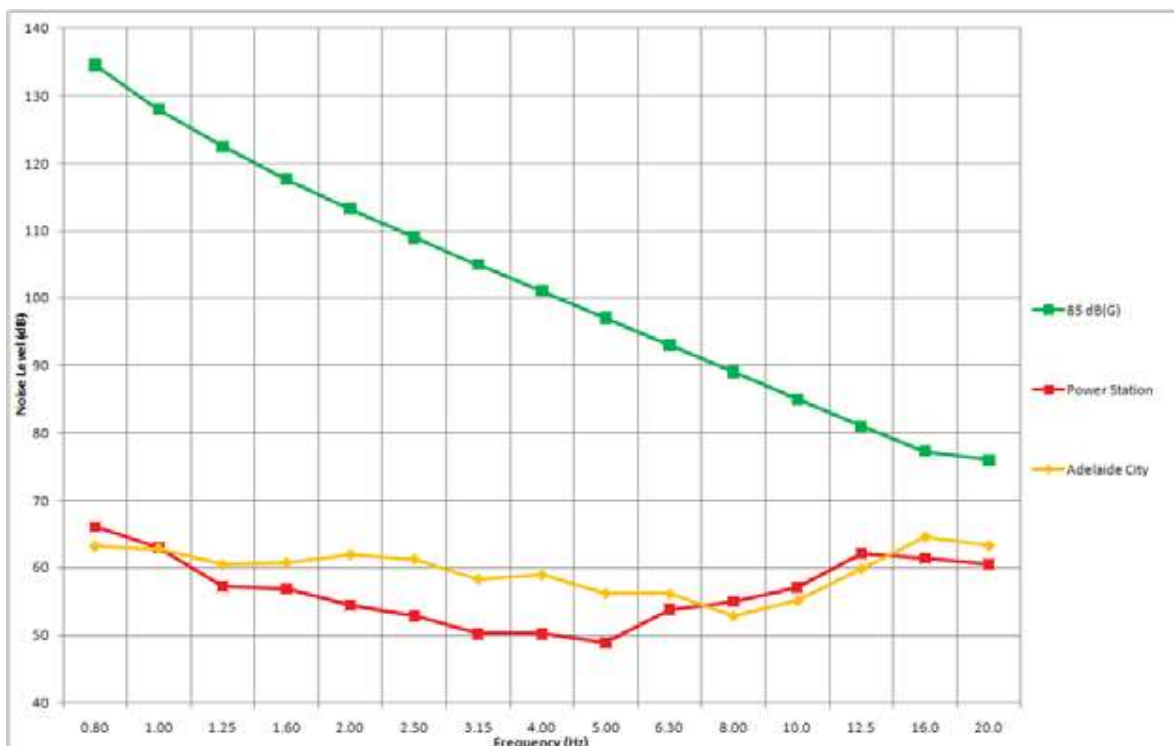


Figure 5. Measured levels of infrasound from engineered sources

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Low frequency noise and infrasound from wind turbines

Robert D. O'Neal^{a)}, Robert D. Hellweg Jr.^{b)} and Richard M. Lampeter^{b)}

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A common issue raised with wind energy developers and operators of utility-scale wind turbines is whether the operation of their wind turbines may create unacceptable levels of low frequency noise and infrasound. In order to answer this question, one of the major wind energy developers commissioned a scientific study of their wind turbine fleet. The study consisted of three parts: 1) a world-wide literature search to determine unbiased guidelines and standards used to evaluate low frequency sound and infrasound, 2) a field study to measure wind turbine noise outside and within nearby residences, and 3) a comparison of the field results to the guidelines and standards. Wind turbines from two different manufacturers were measured at an operating wind farm under controlled conditions with the results compared to established guidelines and standards. This paper presents the results of the low frequency noise and infrasound study. Since the purpose of this paper is to report on low frequency and infrasound emissions, potential annoyance from other aspects of wind turbine operation were not considered, and must be evaluated separately. © 2011 Institute of Noise Control Engineering.

Primary subject classification: 14.5.4; Secondary subject classification: 21.8.1

1 INTRODUCTION

Early down-wind wind turbines in the US created low frequency noise; however current up-wind wind turbines generate considerably less low frequency noise. Epsilon Associates, Inc. ("Epsilon") was retained by NextEra Energy Resources, LLC ("NextEra"), formerly FPL Energy, to investigate whether the operation of their wind turbines may create unacceptable levels of low frequency noise and infrasound. This question has often been posed to NextEra, and other wind energy developers and operators of utility-scale wind turbines. NextEra is one of the world's largest generators of wind power with approximately 7,600 net megawatts (MW) in operation as of July 2010.

The project was divided into three tasks: 1) literature search, 2) field measurement program, and 3) comparison to criteria. Epsilon conducted an extensive literature search of the technical and scientific literature on the effects of low-frequency noise and infrasound and existing criteria in order to evaluate low-frequency noise and infrasound from wind turbines. After

completion of the literature search and selection of criteria, a field measurement program was developed to measure wind turbine noise to compare to the selected criteria.

The frequency range 20–20,000 Hz is commonly described as the range of "audible" noise. The frequency range of low frequency sound is generally from 20 Hertz (Hz) to 200 Hz, and the range below 20 Hz is often described as "infrasound". However, audibility extends to frequencies below 20 Hz.

Low frequency sound has several definitions. American National Standards ANSI/ASA S12.2¹ and ANSI S12.9 Part 4² have provisions for evaluating low frequency noise, and these special treatments apply only to sounds in the octave bands with 16, 31.5, and 63-Hz mid-band frequencies. For these reasons, in this paper on wind turbine noise, we use the term "low frequency noise" to include 12.5 Hz–200 Hz with emphasis on the 16 Hz, 31 Hz and 63 Hz octave bands with a frequency range of 11 Hz to 89 Hz.

International Electrotechnical Commission (IEC) standard 60050-801:1994³ defines "infrasound" as "Acoustic oscillations whose frequency is below the low frequency limit of audible sound (about 16 Hz)." This definition is *incorrect* since sound remains audible at frequencies well below 16 Hz provided that the sound level is sufficiently high. In this paper we define infrasound to be below 20 Hz, which is the limit for the standardized threshold of hearing. Since there is no sharp

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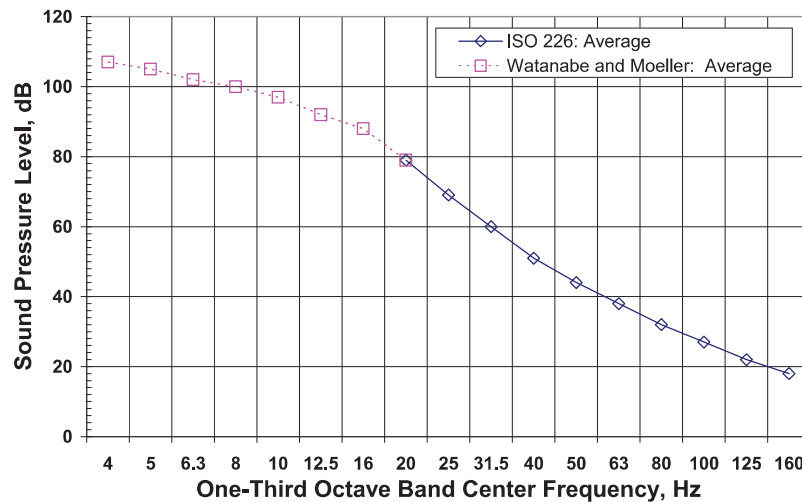


Fig. 1—Low frequency average threshold of hearing from ISO 226⁶ and Watanabe and Moeller⁷.

change in hearing at 20 Hz, the division into “low-frequency sound” and “infrasound” should only be considered “practical and conventional.”

2 EFFECTS AND CRITERIA OF LOW FREQUENCY SOUND AND INFRASOUND

We performed an extensive world-wide literature search of over 100 scientific papers, technical reports and summary reports on low frequency sound and infrasound—hearing, effects, measurement, and criteria. Leventhall⁴ presents an excellent and comprehensive study on low frequency noise from all sources and its effects. The Leventhall report also presents criteria in place at that time, which does not include some of the more recently developed ANSI/ASA standards on outdoor environmental noise and indoor sounds.

The United States government does not have specific criteria for low frequency noise. The US Environmental Protection Agency (EPA) has guidelines for the protection of public health with an adequate margin of safety in terms of annual average A-weighted day-night average sound level (L_{dn}), but there are no corrections or adjustments for low frequency noise. The US Department of Transportation (DOT) has A-weighted sound pressure level criteria for highway projects and airports, but these do not have adjustments for low frequency noise. The following sections describe the low frequency and infrasound criteria to which wind turbine sounds are compared in later sections.

2.1 Threshold of Hearing and Audibility

Moeller and Pedersen⁵ present an excellent summary on human perception of sound at frequencies below 200 Hz. The ear is the primary organ for sensing infrasound. Hearing becomes gradually less sensitive for

decreasing frequencies. But, humans with a normal hearing organ can perceive infrasound at least down to a few hertz if the sound level is sufficiently high.

The threshold of hearing is standardized for frequencies down to 20 Hz⁶. Based on extensive research and data, Moeller and Pedersen propose normal hearing thresholds for frequencies below 20 Hz; however, their proposed threshold is higher than that obtained by Watanabe and Moeller⁷. To be conservative, we have used the data from Watanabe and Moeller⁷ for the region below 20 Hz. (See Fig. 1.) Moeller and Pedersen⁵ suggest that the curve for low frequency thresholds for normal hearing is “probably correct within a few decibels, at least in most of the frequency range.”

The hearing thresholds show considerable variability from individual to individual with a standard deviation among subjects of about 5 dB independent of frequency between 3 Hz and 1000 Hz with a slight increase at 20–50 Hz. This implies that the audibility threshold for 97.5% of the population is greater than the values in Fig. 1 minus 10 dB and for 84% of the population is greater than the values in Fig. 1 minus 5 dB. Moeller and Pedersen suggest that the “pure-tone threshold can with a reasonable approximation be used as a guideline for the thresholds also for [low frequency] non-sinusoidal sounds”⁵; ISO 226 has thresholds for frequencies at and above 20 Hz and approximately equates the thresholds and equal loudness contours for non-sinusoidal sounds to those in the standard for sinusoidal sounds⁶.

As frequency decreases below 20 Hz, if the noise source is tonal, the tonal sensation ceases. Below 20 Hz tones are perceived as discontinuous. Below 10 Hz it is possible to perceive the single cycles of a tone, and the perception changes into a sensation of pressure at the ears.

Below 100 Hz, the dynamic range of the auditory system decreases with decreasing frequency, and the compressed dynamic range has an effect on equal loudness contours: a slight change in sound level can change the perceived loudness from barely audible to loud. This combined with the large variation in individual hearing may mean that a low frequency sound that is inaudible to some may be audible to others, and may be relatively loud to some of those for whom it is audible. Loudness for low frequency sounds grows considerably faster above threshold than for sounds at higher frequencies⁵.

Non-auditory perception of low frequency and infrasound occurs only at levels above the auditory threshold. In the frequency range of 4–25 Hz and at “*levels 20–25 dB above [auditory] threshold it is possible to feel vibrations in various parts of the body, e.g., the lumbar, buttock, thigh and calf regions. A feeling of pressure may occur in the upper part of the chest and the throat region*” [emphasis added]⁵.

2.2 ANSI S12.9-Parts 4 and 5—Evaluating Outdoor Environmental Sound

American National Standard ANSI/ASA S12.9-2007/Part 5⁸ has an informative annex which provides guidance for designation of land uses compatible with existing or predicted annual average adjusted day-night average outdoor sound level (DNL). Ranges of the DNL are outlined, within which a specific region of compatibility may be drawn. These ranges take into consideration the noise reduction in sound level from outside to inside buildings as commonly constructed in that locality and living habits there. There are adjustments to day-night average sound level to account for the presence of low frequency noise, and the adjustments are described in ANSI S12.9 Part 4, which use a sum of the sound pressure levels in octave bands with center frequencies of 16, 31 and 63 Hz.

ANSI S12.9/Part 4 identifies two thresholds: annoyance is minimal when the 16, 31.5 and 63 Hz octave band sound pressure levels are each less than 65 dB and there are no rapid fluctuations of the low frequency sounds. The second threshold is for increased annoyance which begins when rattles occur, which begins at L_{LF} 70–75 dB. L_{LF} is 10 times the logarithm of the ratio of time-mean square sound pressure in the 16, 31.5, and 63-Hz octave bands divided by the square of the reference sound pressure.

The adjustment procedure for low frequency noise to the average annual A-weighted sound pressure level in ANSI S12.9/Part 4 uses a different and more complicated metric and procedure (Equation D.1) than those used for evaluating low frequency noise in rooms contained in ANSI/ASA S12.2. (See Sec. 2.3). Since

we are evaluating low frequency noise and not A-weighted sound levels, we do not recommend using the procedure for adjusting A-weighted levels. Instead we recommend using the following two guidelines from ANSI S12.9/Part 4: a sound pressure level of 65 dB in each of the 16-, 31.5-, and 63 Hz octave bands as an indicator of minimal annoyance, and 70–75 dB for the summation of the sound pressure levels from these three bands as an indicator of possible increased annoyance from rattles.

2.3 ANSI/ASA S12.2—Evaluating Room Noise

ANSI/ASA S12.2-2008¹ discusses criteria for evaluating room noise, and has two separate provisions for evaluating low frequency noise: (1) the potential to cause perceptible vibration and rattles, and (2) meeting low frequency portions of room criteria curves. Since the ANSI S12.2 criteria are for indoor sounds, in order to determine equivalent outdoor criteria for comparison to outdoor measurements, data from Sutherland⁹ and Hubbard and Shephard¹⁰ were used to determine typical noise reductions from outdoor to indoor with windows open. (The Appendix of this paper describes the noise reductions used to determine equivalent outdoor criteria to indoor criteria.) Table A1 presents octave band noise reductions applied in this evaluation along with the average low frequency octave band noise reductions from outdoor to indoors from Refs. 9 and 10 for open and closed windows. Table A2 presents the one-third octave band noise reductions applied in the analysis that were determined in the same manner using data from the same references.

Vibration and Rattles: Outdoor low frequency sounds of sufficient amplitude can cause building walls to vibrate and windows to rattle. Homes have low values of transmission loss at low frequencies, and low frequency noise of sufficient amplitude may be audible within homes. Window rattles are not low frequency noise, but may be caused by low frequency noise. ANSI/ASA S12.2 presents limiting levels at low frequencies for assessing (a) the probability of *clearly* perceptible acoustically induced vibration and rattles in lightweight wall and ceiling constructions, and (b) the probability of *moderately* perceptible acoustically induced vibration in similar constructions. The limiting sound pressure levels in the octave bands with center frequencies of 16, 31.5 and 63 Hz are presented in Table 1.

Applying the outdoor to indoor attenuations for wind turbine sources with windows open given in the last row of Table A1 to the ANSI/ASA S12.2 indoor sound pressure levels in Table 1 yields the equivalent

Table A1—Average low frequency octave band home noise reductions from outdoor to indoors in dB (from Ref. 9 and 10).

Noise Source	Window condition	Octave Band Center Frequency			
		16 Hz	31.5 Hz	63 Hz	125 Hz
Average aircraft and traffic sources	Closed windows	16	15	18	20
Average aircraft and traffic sources	Open windows	(11)*	(10)*	12	11
Average Wind Turbine	Closed windows	8	11	14	18
Average Wind Turbine	Open windows	(3)*+	(6)*+	9+	9+

* No data are available for windows open below 63 Hz octave band. The values for 16 Hz and 31 Hz were obtained by subtracting the difference between the levels for 63 Hz closed and open conditions to the 16 and 31 Hz closed values.

+ Used in this paper to determine equivalent outdoor criteria from indoor criteria in Tables 2 and 4

outdoor sound pressure levels that are consistent with the indoor criteria and are presented in Table 2.

Room Criteria Curves: ANSI/ASA S12.2 has three primary methods for evaluating the suitability of noise within rooms: a survey method—A-weighted sound levels, an engineering method—noise criteria (NC) curves, and a method for evaluating low-frequency fluctuating noise using room noise criteria (RNC) curves. ANSI/ASA S12.2 states “The RNC method

should be used to determine noise ratings when the noise from HVAC systems at low frequencies is loud and is suspected of containing sizeable *fluctuations or surging*.” [emphasis added] The NC curves are appropriate to evaluate low frequency noise from wind turbines in homes since wind turbine noise does not have significant fluctuating low frequency noise sufficient to warrant using RNC curves and since A-weighted sound levels do not adequately determine

Table A2—Average low frequency one-third octave band noise reduction in dB for homes from outdoor to indoors.

Condition	One-Third Octave Band Center Frequency, Hz												
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Open Window*	2	2	3	4	4.5	5	7	8	9	9	9	9	9
Average Closed Window with wind turbines ¹⁰	8	7	8	8	8	11	13	14	15	12	18	18	18

* Used to determine equivalent outdoor levels as shown in Table 7.

** Used to determine equivalent outdoor levels as shown in Table 9.

Table 1—ANSI/ASA S12.2 measured interior sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures.¹

Condition	Octave-band center frequency (Hz)		
	16	31.5	63
Clearly perceptible vibration and rattles likely	75 dB	75 dB	80 dB
Moderately perceptible vibration and rattles likely	65 dB	65 dB	70 dB

Table 2—Equivalent outdoor sound pressure levels to the ANSI/ASA S12.2 indoor sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures for wind turbines.

Condition	Octave-band center frequency (Hz)		
	16	31.5	63
Clearly perceptible vibration and rattles likely	78 dB	81 dB	89 dB
Moderately perceptible vibration and rattles likely	68 dB	71 dB	79 dB

if there are low frequency problems. [ANSI/ASA S12.2, Sec. 5.3 gives procedures for determining if there are large fluctuations of low frequency noise.]

Annex C.2 of ANSI/ASA S12.2 contains recommended room criteria curves for bedrooms, which are the rooms in homes with the most stringent criteria: NC and RNC criteria curve between 25 and 30. The recommended NC and RNC criteria for schools and private rooms in hospitals are the same. The values of the sound pressure levels in the 16–125 Hz octave bands for NC curves 25 and 30 are shown in Table 3. Applying the outdoor to indoor attenuations for wind turbine sources with windows open given in the last row of Table A1 to the ANSI/ASA S12.2 indoor sound pressure levels for NC-25 and NC-30 in Table 3 yields the equivalent outdoor sound pressure levels that are consistent with the indoor criteria and are presented in Table 4.

ANSI/ASA S12.2 also presents a method to determine if the levels below 500 Hz octave band are too high in relation to the levels in the mid-frequencies which could create a condition of “spectrum imbalance”. The method for this evaluation is:

- Calculate the speech interference level (SIL) for the measured spectrum. [SIL is the arithmetic average of the sound pressure levels in the 500, 1000, 2000 and 4000 Hz octave bands.] Select the NC curve equal to the SIL value with a symbol NC(SIL).
- Plot the measured spectra and the NC curve equal to the SIL value on the same graph and

Table 3—ANSI/ASA S12.2 low frequency octave band sound pressure levels for noise criteria curves NC-25 and NC-30. [Table 1 from Ref. 1].

NC Criteria	Octave-band-center frequency, Hz			
	16	31.5	63	125
NC-25	80	65	54	44
NC-30	81	68	57	48

determine the differences between the two curves in the octave bands below 500 Hz.

- Estimate the likelihood that the excess low-frequency levels will annoy occupants of the space using Table 5.

2.4 Other Criteria

2.4.1 World Health Organization (WHO)

No specific low frequency noise criteria are proposed by the WHO. The Guidelines for Community Noise report¹¹ mentions that if the difference between

Table 4—Equivalent outdoor sound pressure levels to the ANSI/ASA S12.2 low frequency octave band sound pressure levels for noise criteria curves NC-25 and NC-30. [Table 1 from Ref. 1].

NC Criteria	Octave-band-center frequency, Hz			
	16	31.5	63	125
NC-25 equivalent outdoor	83	71	63	53
NC-30 equivalent outdoor	84	74	66	57

Table 5—Measured sound pressure level deviations from an NC (SIL) curve that may lead to serious complaints¹.

Octave-band frequency, Hz=>	Measured Spectrum—NC(SIL), dB			
	31.5	63	125	250
Possible serious dissatisfaction	*	6–9	6–9	6–9
Likely serious dissatisfaction	*	>9	>9	>9

* Insufficient data available to evaluate

Table 6—DEFRA proposed criteria¹³ for the assessment of low frequency noise disturbance: Indoor L_{eq} one-third sound pressure levels for non-steady and steady low frequency sounds.

Location	One-Third Octave Band Center Frequency, Hz												
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Non-Steady L_{eq} , dB	92	87	83	74	64	56	49	43	42	40	38	36	34
Steady L_{eq} , dB	97	92	88	79	69	61	54	48	47	45	43	41	39

the C-weighted sound level and A-weighted sound level is greater than 10 decibels, then a frequency analysis should be performed to determine if there is a low frequency issue. A document prepared for the World Health Organization states that “there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above detection threshold may cause perceptual effects but these are of the same character as for ‘normal’ sounds. Reactions caused by extremely intense levels of infrasound can resemble those of mild stress reaction and may include bizarre auditory sensations, describable as pulsation and flutter”¹².

2.4.2 The UK Department for Environment, Food, and Rural Affairs (DEFRA)

The report prepared by the University of Salford for the UK Department for Environment, Food, and Rural Affairs (DEFRA) on low frequency noise proposed one-third octave band sound pressure level L_{eq} criteria and procedures for assessing low frequency noise¹³. The guidelines are based on complaints of disturbance from low frequency sounds and are intended to be used by Environmental Health Officers.

Existing low frequency noise criteria from several countries were reviewed and experiences with low frequencies complaints were considered in developing the proposed guidelines. The criteria are “based on

5 dB below the ISO 226 average threshold of audibility for steady [low frequency] sounds.” However, the DEFRA criteria are at 5 dB lower than ISO 226 only at 20–31.5 Hz; at higher frequencies the criteria are equal to the Swedish criteria which are higher levels than ISO 226 less 5 dB. For frequencies lower than 20 Hz, DEFRA uses the thresholds from Ref. 7 less 5 dB.

The DEFRA criteria are based on measurements in an unoccupied room, and it was noted by a practicing consultant that measurements should be made with windows closed¹⁴. However, we conservatively used windows open conditions for our assessment to determine equivalent outdoor criteria since the DEFRA measurement procedure does not explicitly state measurements are with windows closed. If the low frequency sound is “steady” then the criteria may be relaxed by 5 dB. A low frequency noise is considered steady if either $L_{10}-L_{90} < 5$ dB or the rate of change of sound pressure level (Fast time weighting) is less than 10 dB per second in the third octave band which exceeds the criteria by the greatest margin.

Applying indoor to outdoor one-third octave band transfer functions for open windows (as presented in Table A2 from analysis of data in Refs. 9 and 10) yields equivalent one-third octave band sound pressure level proposed DEFRA criteria for outdoor sound levels. Table 6 presents the indoor DEFRA proposed criteria for non-steady and steady low-frequency sounds. Table

Table 7—Equivalent outdoor L_{eq} one-third sound pressure levels for non-steady and steady sounds to the DEFRA indoor criteria¹³ for the assessment of low frequency noise disturbance.

Location	One-Third Octave Band Center Frequency, Hz												
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Non-Steady Equivalent outdoor * L_{eq} , dB	94	89	86	78	68.5	61	56	51	51	49	47	45	43
Steady Equivalent Outdoor* L_{eq}	99	94	91	83	73.5	66	61	56	56	54	52	50	48

* With windows open

Table 8—Japan Ministry of Environment Guidance for evaluating complaints of low frequency noise: Reference one-third octave band sound pressure level values for complaints of rattling.

Location	One-Third Octave Band Center Frequency, Hz										
	5	6.3	8	10	12.5	16	20	25	31.5	40	50
Outdoor L_{eq} , dB	70*	71*	72*	73	75	77	80	83	87	93	99

* The reference values are several dB lower than the supporting data contained in Ref. 15. At 5 Hz, window rattles started at about 74 dB in one study and 79 dB in another; at 6.3 Hz, rattles started at 74 dB in the first study and at 78 dB in the second; and at 8 Hz, window rattle started at 74 dB in the first study and 77 dB in the second study.

7 presents the DEFRA equivalent outdoor criteria for non-steady and steady low frequency sounds.

2.4.3 Japan Ministry of Environment

The Japan Ministry of Environment has published a handbook to deal with low frequency noise problems and has established reference values for guidance in dealing with complaints of rattling windows and doors and complaints of “mental and physical discomfort”¹⁵. It was noted that traditional Japanese houses have relatively light-weight and sensitive windows and partitions¹⁶.

Table 8 presents the Japanese reference outdoor one-third octave band sound pressure level values for guidance in dealing with complaints of rattling from environmental sounds from 5 Hz to 50 Hz. From 10 Hz to 50 Hz the guidance levels are equal to the observed threshold of rattles from two studies with a total of 78 samples. However, for the bands centered at 5, 6.3 and 8 Hz, the reference values are several dB lower than the supporting data contained in these two studies¹⁵. At 5 Hz, the lowest observed window rattle was at 74 dB in one study and 79 dB in another; at 6.3 Hz, rattles started at 74 dB in the first study and at 78 dB in the second; and at 8 Hz, window rattle started at 74 dB in the first study and 77 dB in the second study. Thus the reference values at 5, 6.3 and 8 Hz in Table 8 are conservative in comparison to the other values by 4, 3, and 2 dB respectively.

Table 9 presents the Japanese reference one-third octave band sound pressure level values for guidance in dealing with complaints of mental and physical discomfort from environmental sounds when evaluated indoors. Evaluation measurements are to be performed with windows closed to the outside. The values in Table 9 are less stringent than the DEFRA values in Table 6 for non-steady sounds but more stringent than the DEFRA values for steady sounds in some one-third octave bands. In order to obtain equivalent outdoor sound levels, the average noise reduction from wind turbine noise with windows closed from Ref. 10 was applied to the Japan reference values. Table 9 presents the Japanese indoor reference values, the noise reduc-

tions for windows closed¹⁰ and the equivalent outdoor reference values. These equivalent outdoor values are less stringent than the equivalent outdoor DEFRA values in Table 7 for both non-steady sounds and steady sounds except for the 80 Hz band in which the Japanese level is 1 dB more stringent than the DEFRA level for steady sounds.

2.4.4 C-weighted minus A-weighted ($L_{pC}-L_{pA}$)

Leventhall⁴ and others indicate that the difference in C-weighted and A-weighted sound pressure levels can be a predictor of annoyance. Leventhall states that if ($L_{pC}-L_{pA}$) is greater than 20 dB there is “a potential for a low frequency noise problem.” He further states that ($L_{pC}-L_{pA}$) cannot be a predictor of annoyance but is a simple indicator that further analysis may be needed. This is due in part to the fact that the low frequency noise may be inaudible even if ($L_{pC}-L_{pA}$) is greater than 20 dB.

3 LITERATURE REVIEW

The authors performed an extensive literature search of over 100 scientific papers, technical reports and summary reports on low frequency sound and infrasound—hearing, effects, measurement, and criteria. The following paragraphs briefly summarize the findings from some of these papers and reports.

3.1 Leventhall

Leventhall⁴ presents an excellent study on low frequency noise from all sources and its effects. The report presents criteria in place at that time and includes data relating cause and effects. Leventhall¹⁷ reviewed data and allegations on alleged problems from low frequency noise and infrasound from wind turbines, and concluded the following: “It has been shown that there is insignificant infrasound from wind turbines and that there is normally little low frequency noise.” “Turbulent air inflow conditions cause enhanced levels of low frequency noise, which may be disturbing, but the overriding noise from wind turbines is the fluctuating audible swish, mistakenly referred to

Table 9—Japan Ministry of Environment Guidance for evaluating complaints of low frequency noise: Reference one-third octave band sound pressure level values for complaints of mental and physical discomfort.

Location	One-Third Octave Band Center Frequency, Hz									
	10	12.5	16	20	25	31.5	40	50	63	80
Indoor L_{eq} , dB	92	88	83	76	70	64	57	52	47	41
Noise Reduction *, dB	8	7	8	8	8	11	13	14	15	12
Equivalent Outdoor L_{eq} , dB	100	95	91	84	78	75	70	66	62	53

* from Hubbard¹⁰ windows closed condition

as “infrasound” or “low frequency noise”. “Infrasound from wind turbines is below the audible threshold and of no consequence”. Other studies have shown that wind turbine generated infrasound levels are below threshold of perception and threshold of feeling and body reaction.

3.2 DELTA

The Danish Energy Authority project on “low frequency noise from large wind turbines” comprises a series of investigations in the effort to give increased knowledge on low frequency noise from wind turbines¹⁸. One of the conclusions of the study is that wind turbines do not emit audible infrasound, with levels that are “far below the hearing threshold.” Audible low frequency sound may occur both indoors and outdoors, “but the levels in general are close to the hearing and/or masking level.” “In general the noise in the critical band up to 100 Hz is below both thresholds”. The final report notes that for road traffic noise (in the vicinity of roads) the low frequency noise levels are higher [than wind turbine] both indoors and outdoors.

3.3 Hayes McKenzie Partnership

Hayes McKenzie Partnership Ltd performed a study for the UK Department of Trade & Industry (DTI) to investigate complaints of low frequency noise that came from three of the five farms with complaints out of 126 wind farms in the UK¹⁴. The study concluded that:

- Infrasound associated with modern wind turbines is not a source which will result in noise levels that are audible or which may be injurious to the health of a wind farm neighbor.
- Low frequency noise was measureable on a few occasions, but below DEFRA criteria. Wind turbine noise may result in indoor noise levels

within a home that is just above the threshold of audibility; however, it was lower than that of local road traffic noise.

- The common cause of the complaints was not associated with low frequency noise but the occasional audible modulation of aerodynamic noise, especially at night.
- The UK Department of Trade and Industry, which is now the UK Department for Business Enterprise and Regulatory Reform (BERR), summarized the Hayes McKenzie report: “The report concluded that there is no evidence of health effects arising from infrasound or low frequency noise generated by wind turbines.”¹⁹.

3.4 Howe

Howe performed extensive studies on wind turbines and infrasound and concluded that infrasound was not an issue for modern wind turbine installations—“while infrasound can be generated by wind turbines, it is concluded that infrasound is not of concern to the health of residences located nearby.”²⁰. Since then Gastmeier and Howe²¹ investigated an additional situation involving the alleged “perception of infrasound by individual.” In this additional case, the measured indoor infrasound was at least 30 dB below the audibility threshold given by Ref. 7 as presented in Fig. 1.

3.5 Branco

Branco and other Portuguese researchers have studied possible physiological affects associated with high amplitude low frequency noise and have labeled these alleged effects as “Vibroacoustic Disease” (VAD)²². “Vibroacoustic disease (VAD) is a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices, and caused by excessive exposure to low frequency noise.”

Hayes^{23,24} concluded that levels from wind farms are not likely to cause VAD after comparing noise levels from alleged VAD cases to noise levels from wind turbines in homes of complainers. Noise levels in aircraft in which VAD has been hypothesized are considerably higher than wind turbine noise levels. Hayes also concluded that it is “unlikely that symptoms will result through induced internal vibration from incident wind farm noise.”²³ Other studies have found no VAD indicators in environmental sound that have been alleged by VAD proponents²⁵.

3.6 French National Academy of Medicine

In 2006, the French National Academy of Medicine recommended²⁶ “as a precaution construction should be suspended for wind turbines with a capacity exceeding 2.5 MW located within 1500 m of homes.” [emphasis added] However, this precaution is not because of definitive health issues but because:

- Sound levels one km from some wind turbine installations “occasionally exceed allowable limits” for France (note that the allowable limits are long term averages).
- French prediction tools for assessment did not take into account sound levels created with wind speeds greater than 5 m/s.
- Wind turbine noise has been compared to aircraft noise (even though the sound levels of wind turbine noise are significantly lower), and exposure to high level aircraft noise “involves neurobiological reactions associated with an increased frequency of hypertension and cardiovascular illness. Unfortunately, no such study has been done near wind turbines.”²⁷

In March 2008, the French Agency for Environmental and Occupational Health Safety (AFSSET) published a report on “the health impacts of noise generated by wind turbines”, commissioned by the Ministries of Health and Environment in June 2006 following the report of the French National Academy of Medicine in March 2006²⁸. The AFSSET study recommends that one does not define a fixed minimum distance between wind farms and homes, but rather to model the acoustic impact of the project on a case-by-case basis. One of the conclusions of the AFSSET report is: “The analysis of available data shows: The absence of identified direct health consequences concerning the auditory effects or specific effects usually associated with exposure to low frequencies at high level.” (“L’analyse des données disponibles met en évidence: L’absence de conséquences sanitaires directes recensées en ce qui concerne les effets auditifs, ou les effets spécifiques généralement attachés à l’exposition à des basses fréquences à niveau élevé.”).

4 FIELD PROGRAM

Two types of utility-scale wind turbines were studied for this field program. These two turbines are among the most commonly used in the NextEra fleet: General Electric (GE) 1.5sle (1.5 MW), and Siemens SWT-2.3-93 (2.3 MW).

Sound levels for these wind turbine generators (WTGs) vary as a function of wind speed from cut-in wind speed to maximum sound level. Cut-in wind speed for the GE 1.5sle wind turbine is 3.5 m/s while the Siemens wind turbine has a cut-in wind speed of 4 m/s. Maximum reference sound power levels for the GE 1.5sle and Siemens 2.3-93 are approximately 104 dB and 105 dB respectively as provided by the manufacturer. These sound power levels are reached at electrical output levels of approximately 924 kW and 1767 kW for the GE and Siemens units, respectively. Under higher wind speeds, the sound levels from the wind turbines do not increase although electrical power output does continue to increase up to the rated power of each wind turbine (1500 kW and 2300 kW respectively).

Each wind turbine manufacturer has an uncertainty factor “K” of 2 dB to guarantee the turbine’s sound power level. (K accounts for both measurement variations and production variation²⁹.) The results presented later in this paper include sound power values which have added the manufacturer’s K value to the reference values, that is, 2 dB above the expected reference levels for the measured wind conditions and power output.

Real-world data were collected from operating wind turbines to compare to the low frequency noise guidelines and criteria discussed previously in Sec. 2. These data sets consisted of outdoor measurements at various reference distances, and concurrent indoor/outdoor measurements at residences within the wind farm.

NextEra provided access to the Horse Hollow Wind Farm in Taylor and Nolan Counties, Texas in November 2008 to collect data on the GE 1.5sle and Siemens SWT-2.3-93 wind turbines. The portion of the wind farm used for testing is relatively flat with no significant terrain. The land around the wind turbines is rural and primarily used for agriculture and cattle grazing. The siting of the sound level measurement locations was chosen to minimize local noise sources except the wind turbines and the wind itself. Hub height for these wind turbines is 80 meters above ground level (AGL).

Two of the authors collected sound level and wind speed data over the course of one week under a variety of operational conditions. Weather conditions were dry the entire week with ground level winds ranging from calm to 12.5 m/s (28 mph) over a 1-minute average. In order to minimize confounding factors, the data collection tried to focus on periods of maximum sound levels from

the wind turbines (moderate to high hub height winds) and light to moderate ground level winds.

Ground level (2 meters AGL) wind speed and direction were measured continuously at one representative location. Wind speeds near hub height were also measured continuously using the permanent meteorological towers maintained by the wind farm.

A series of simultaneous interior and exterior sound level measurements were made at four houses owned by participating landowners within the wind farm. Two sets were made of the GE WTGs, and two sets were made of the Siemens WTGs. Data were collected with both windows open and windows closed. Due to the necessity of coordinating with the homeowners in advance, and reasonable restrictions on time of day to enter their homes, the interior/exterior measurement data sets do not always represent ideal conditions. However, enough data were collected to compare to the criteria and draw conclusions on low frequency noise.

Sound level measurements were also made simultaneously at two reference distances from a string of wind turbines under a variety of wind conditions. Using the manufacturer's sound power level data, calculations of the sound pressure levels as a function of distance in flat terrain were made to aid in deciding where to collect data in the field. Based on this analysis, two distances from the nearest wind turbine were selected—305 meters (1,000 feet) and 457 meters (1,500 feet)—and were then used where possible during the field program. Distances much larger than 457 meters (1,500 feet) were not practical since an adjacent turbine string could then be closer and affect the measurements, or would put the measurements beyond the boundaries of the wind farm property owners. Brief background sound level measurements were conducted several times during the program whereby the Horse Hollow Wind Farm operators were able to shutdown the nearby WTGs for a brief (20 minutes) period. This was done in real time using cell phone communication.

All the sound level measurements described above were attended. One series of unattended overnight measurements was made at two locations for approximately 15 hours to capture a larger data set. One measurement was set up approximately 305 meters (1,000 feet) from a GE 1.5sle WTG and the other was set up approximately 305 meters (1,000 feet) from a Siemens WTG. The location was chosen based on the current wind direction forecast so that the sound level equipment would be downwind for the majority of the monitoring period. By doing this, the program was able to capture periods of strong hub-height winds and moderate to low ground-level winds.

All sound levels were measured using two Norsonic Model Nor140 precision sound analyzers, equipped

with a Norsonic-1209 Type 1 Preamplifier, a Norsonic-1225 half-inch microphone and a 7-inch Aco-Pacific untreated foam windscreen Model WS7. The instrumentation meets the "Type 1—Precision" requirements set forth in American National Standards Institute (ANSI) S1.4 for acoustical measuring devices³⁰. The microphone was tripod-mounted at a height of 1.5 meters (five feet) above ground. The measurements included simultaneous collection of broadband (A-weighted) and one-third-octave band data (3.15 hertz to 20,000 hertz bands). Sound level data were primarily logged in 10-minute intervals to be consistent with the wind farm's Supervisory Control And Data Acquisition (SCADA) system which provides electrical power output (kW) in 10-minute increments. A few sound level measurements were logged using 20-minute intervals for use in determining home transmission loss values. The meters were calibrated and certified as accurate to standards set by the National Institute of Standards and Technology. These calibrations were conducted by an independent laboratory within the past 12 months. Ground level wind speed and direction were measured with a HOBO H21-002 micro weather station (Onset Computer Corporation). The wind data were sampled every three seconds and logged every one minute.

5 RESULTS AND COMPARISON TO CRITERIA

Results from the field program are organized by wind turbine type. For each wind turbine type, results are presented per location type (outdoor or indoor) with respect to applicable criteria. Results are presented for 305 meters (1,000) feet from the nearest wind turbine. Data were also collected at 457 meters (1,500 feet) from the nearest wind turbine which showed lower sound levels. Therefore, wind turbines that met the criteria at 305 meters also met it at 457 meters. Data were collected under both high turbine output and moderate turbine output conditions (defined as sound power levels 2 or 3 dB less than the maximum sound power levels), and low ground-level wind speeds. The sound level data under the moderate conditions were equivalent to or lower than the high turbine output scenarios, thus confirming the conclusions from the high output cases. None of the operational sound level data were corrected for background noise. A-weighted sound power levels presented in this section (used to describe turbine operation) were estimated from the actual measured power output (kW) of the wind turbines and the sound power levels as a function of wind speed plus an uncertainty factor K of 2 dB.

Outdoor measurements are compared to criteria for audibility, for UK DEFRA disturbance using equivalent outdoor levels, for rattle and annoyance criteria as

Table 10—Summary of operational parameters—
Siemens SWT-2.3-93 (Outdoor).

Parameter	Sample #34	Sample #39
Distance to nearest WTG	305 meters	305 meters
Time of day	22:00-22:10	22:50-23:00
WTG power output	1,847 kW	1,608 kW
A-weighted sound power level*	107 dB	106.8 dB
Measured wind speed @ 2 m	3.3 m/s	3.4 m/s
L_{Aeq}	49.4 dB	49.6 dB
L_{A90}	48.4 dB	48.6 dB
L_{Ceq}	63.5 dB	63.2 dB

* Includes K, uncertainty factor of 2 dB

contained in ANSI S12.9/Part 4, for evaluating complaints of rattling using Japan Ministry of Environment guidance, and for perceptible vibration using equivalent outdoor levels from ANSI/ASA S12.2. Indoor measurements are compared to criteria for audibility, for UK DEFRA disturbance, for evaluating complaints of mental and physical discomfort using Japan Ministry of Environment guidance, and for suitability of bedrooms, hospitals and schools and perceptible vibration from ANSI/ASA S12.2.

5.1 Siemens SWT-2.3-93

5.1.1 Outdoor measurements—Siemens SWT-2.3-93

Sound levels during six 10-minute periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 305 meters (1,000 feet) from the closest Siemens WTG. This site was actually part of a string of 15 WTGs, four of which were within 610 meters

(2,000 feet) of the monitoring location. Representative sound level data from two 10-minute periods are presented herein and include contributions from all wind turbines as measured by the recording equipment. One data set is representative of time periods with low frequency sound level values near the maximum measured and the other data set is representative of the mean. The standard deviations for the low frequency one-third octave band levels for the six measurement periods were between 0.2–0.7 dB. The key operational and meteorological parameters during these two measurement periods are listed in Table 10.

Figure 2 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 305 meters (1,000 feet) from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound above 40 Hz may be audible depending on background sound levels.

Figure 3 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was “steady” according to DEFRA procedures, and the results show that all outdoor equivalent DEFRA disturbance criteria are met.

Figure 4 compares the one-third octave band sound levels (L_{eq}) for both samples of high output conditions to the Japan Ministry of Environment levels for evaluating complaints on rattle. The rattle criteria is met at all frequencies except at 5 Hz where the mean value is 1 dB (standard deviation of 0.4 dB) higher than the Japanese evaluation value. When one considers that the 5 Hz sound level is 3 dB lower than the observed threshold of rattle, one concludes that the Japanese criteria are met.

The measured outdoor sound levels also meet the outdoor equivalent Japan Ministry of Environment

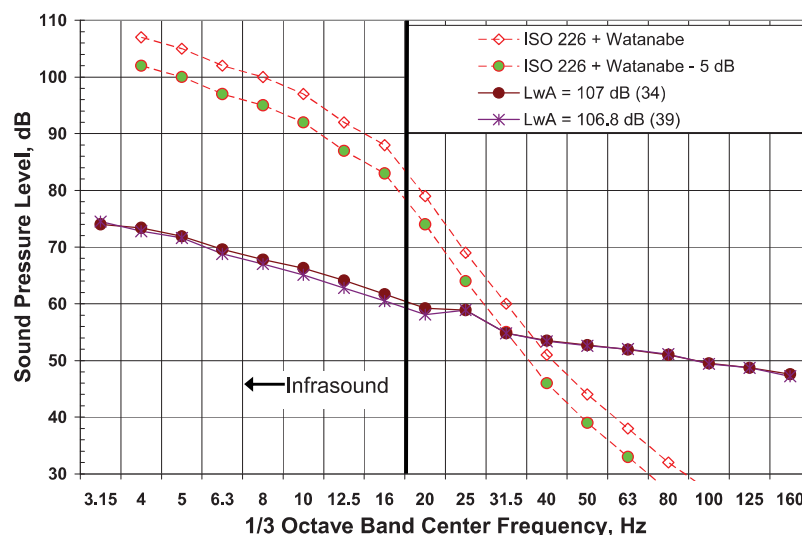


Fig. 2—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to audibility criteria.

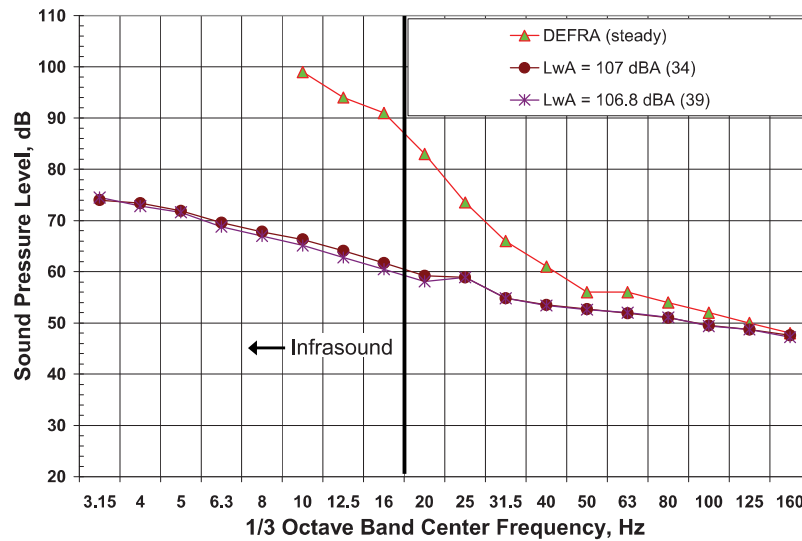


Fig. 3—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to outdoor equivalent DEFRA criteria.

criteria for evaluating complaints of mental and physical discomfort. This comparison is not presented in a figure since these criteria are generally less stringent than the DEFRA criteria.

Figure 5 plots the 16, 31.5, 63, and 125 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. In addition, the results show that all outdoor equivalent ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for bedrooms are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB). The 31.5 and 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4,

and the 16 Hz sound level is within 1.5 dB of this level, which is an insignificant increase since the levels were not rapidly fluctuating.

5.1.2 Indoor measurements—Siemens SWT-2.3-93

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from Siemens WTGs. In each house a 10-minute measurement was made in a room facing the wind turbines with a window both open and closed. Results from the testing at one of the homes are not presented due to the very high ground level winds

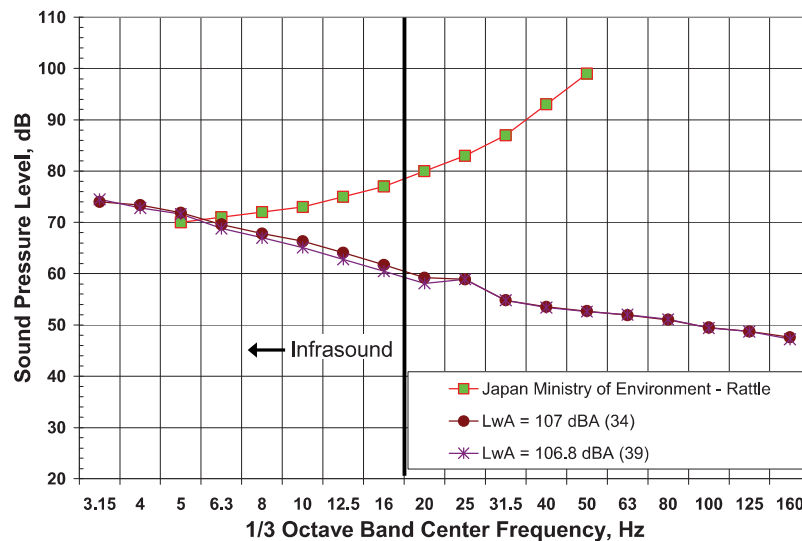


Fig. 4—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to Japan Ministry of Environment rattle criteria.

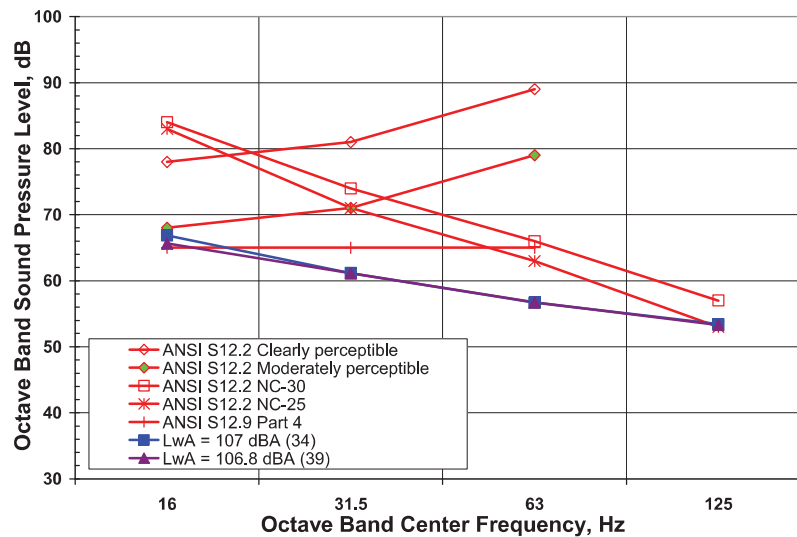


Fig. 5—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to ANSI criteria.

(~9 m/s) which dominated the sound environment. The remaining residence is designated Home “A” and was approximately 323 meters (1,060 feet) from the closest Siemens WTG. The home was near a string of multiple WTGs, four of which were within 610 meters (2,000 feet) of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 11.

The room in Home “A” where interior measurements were made had the following characteristics: approximately 3.6 meters wide (12 feet) by 4.9 meters long (16 feet), no furniture, carpeted flooring, two relatively new double-hung windows (no storm windows), sheetrock interior walls, and clapboard exterior walls. The sound level meter was located in the center of the room.

Figure 6 plots the indoor one-third octave band sound levels (L_{eq}) for Home “A”. The results show that infrasound is inaudible to even the most sensitive people approximately 1,000 feet from these wind turbines with

the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at or above 50 Hz may be audible depending on background sound levels.

Figure 7 plots the indoor one-third octave band sound levels (L_{eq}) for Home “A”. The low frequency sound was “steady” according to DEFRA procedures under the window open condition, and the results show that all indoor DEFRA disturbance criteria are met.

Although not shown in Fig. 7, the one-third octave band levels meet the Japan Ministry of Environment criteria for evaluating complaints of mental and physical discomfort since in the frequency range of the Japan criteria both samples meet the more stringent DEFRA criteria for “non-steady” sounds, which is more stringent than the Japan criteria.

Figure 8 plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home “A”. The results show the ANSI/ASA S12.2 low frequency criteria for perceptible vibration were easily met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for bedrooms, classrooms and hospitals were met, the spectrum was balanced, and the criteria for moderately perceptible vibrations in lightweight walls and ceilings were also met.

Table 11—Summary of operational parameters—Siemens SWT-2.3-93 (Indoor).

Parameter	Home “A” (closed/open)
Distance to nearest WTG	323 meters
Time of day	07:39-07:49/07:51-08:01
WTG power output	1,884 kW/1564 kW
A-weighted sound power level*	107 dB/106.7 dB
Measured wind speed @ 2 m	3.2 m/s/3.7 m/s
L_{Aeq}	33.8 dB/38.1 dB
L_{A90}	28.1 dB/36.8 dB
L_{Ceq}	54.7 dB/57.1 dB

* Includes K, uncertainty factor of 2 dB

5.2 GE 1.5sle

5.2.1 Outdoor measurements—GE 1.5sle

Sound level data during twelve 10-minute periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 305 meters (1,000 feet) from the closest GE 1.5sle WTG. This site was actually part of a string of more than 30 WTGs, four of which were within 610 meters (2,000 feet) of the

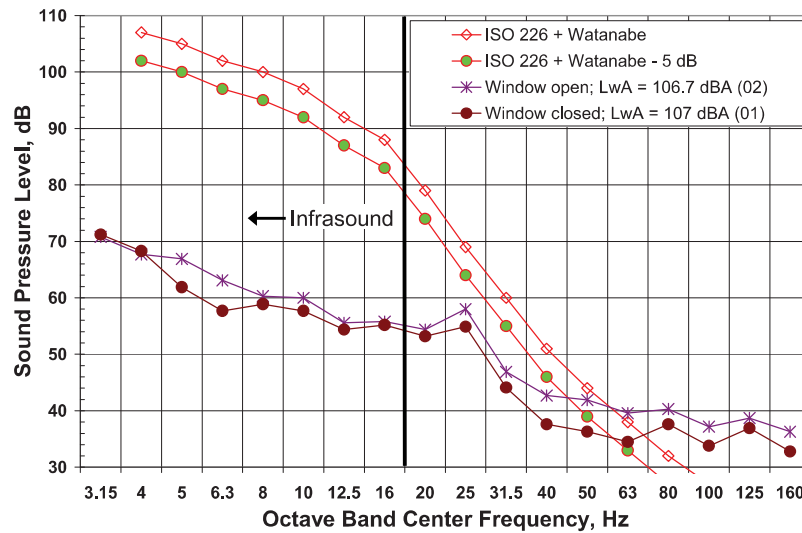


Fig. 6—Siemens SWT-2.3-93 wind turbine indoor sound levels at 323 meters compared to audibility criteria (Home “A”).

monitoring location. Representative sound level data from two 10-minute periods are presented herein and include contributions from all wind turbines as measured by the recording equipment. One data set is representative of time periods with low frequency sound level values near the maximum and the other data set is representative of the mean. The standard deviations for the low frequency one-third octave band levels for the twelve measurement periods were between 0.3–1.9 dB with the largest variation in the 10–16 Hz bands and the lowest at 160 Hz. The key operational and meteorological parameters for these two measurement periods are listed in Table 12.

Figure 9 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most

sensitive people 305 meters (1,000 feet) from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 31.5–40 Hz may be audible depending on background sound levels.

Figure 10 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was “steady” according to DEFRA procedures, and the results show the low frequency sound meet or are within 1 dB of outdoor equivalent DEFRA disturbance criteria.

Figure 11 compares the one-third octave band sound levels (L_{eq}) for both samples of high output conditions to the Japan Ministry of Environment levels for evaluating complaints on rattle. The rattle criteria is met at all

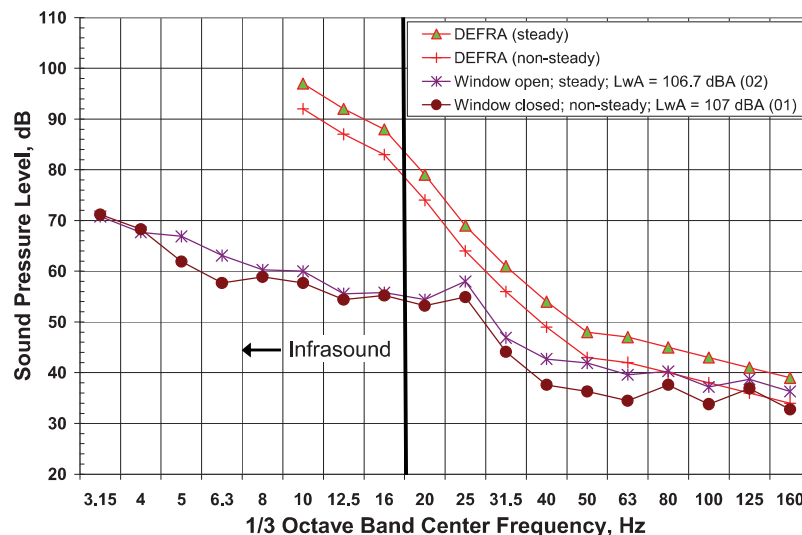


Fig. 7—Siemens SWT-2.3-93 wind turbine indoor sound levels at 323 meters compared to DEFRA criteria (Home “A”).

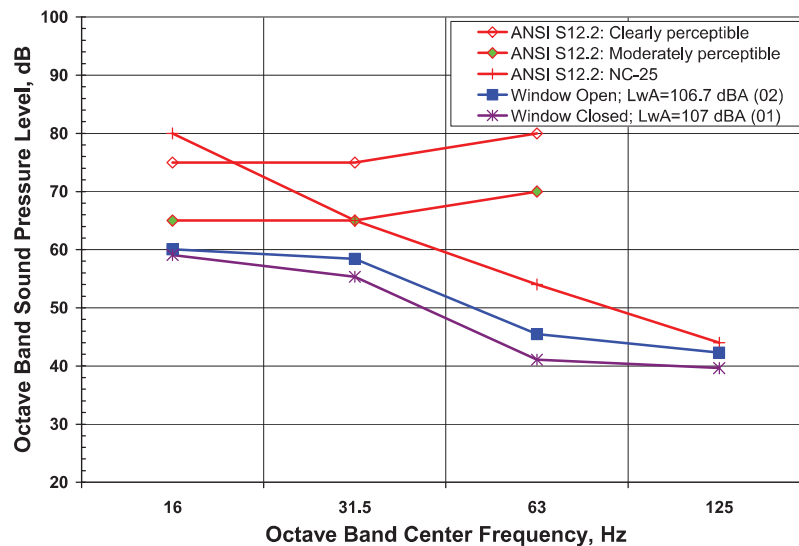


Fig. 8—Siemens SWT-2.3-93 wind turbine indoor sound levels at 323 meters compared to ANSI 12.2 criteria for perceptible vibrations and NC-25 (Home “A”).

frequencies; at 5 Hz the mean value is 70 dB (standard deviation=0.9 dB), while the two presented measure-

Table 12—Summary of operational parameters—GE 1.5sle (Outdoor).

Parameter	Sample #46	Sample #51
Distance to nearest WTG	305 meters	305 meters
Time of day	23:10-23:20	00:00-00:10
WTG power output	1,293 kW	1,109 kW
A-weighted sound power level*	106 dB	106 dB
Measured wind speed @ 2 m	4.1 m/s	3.3 m/s
L_{Aeq}	50.2 dB	50.7 dB
L_{A90}	49.2 dB	49.7 dB
L_{Ceq}	62.5 dB	62.8 dB

* Includes K, uncertainty factor of 2 dB

ments are approximately 1 dB higher, an insignificant increase. When one considers that the 5 Hz sound level is 3 dB lower than the observed threshold of rattle, one concludes that the Japanese criteria are met.

The measured outdoor sound levels also meet the outdoor equivalent Japan Ministry of Environment criteria for evaluating complaints of mental and physical discomfort. This comparison is not presented in a figure since these criteria are generally less stringent than the DEFRA criteria.

Figure 12 plots the 16, 31.5, 63 and 125 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. The results show that all outdoor equivalent ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for

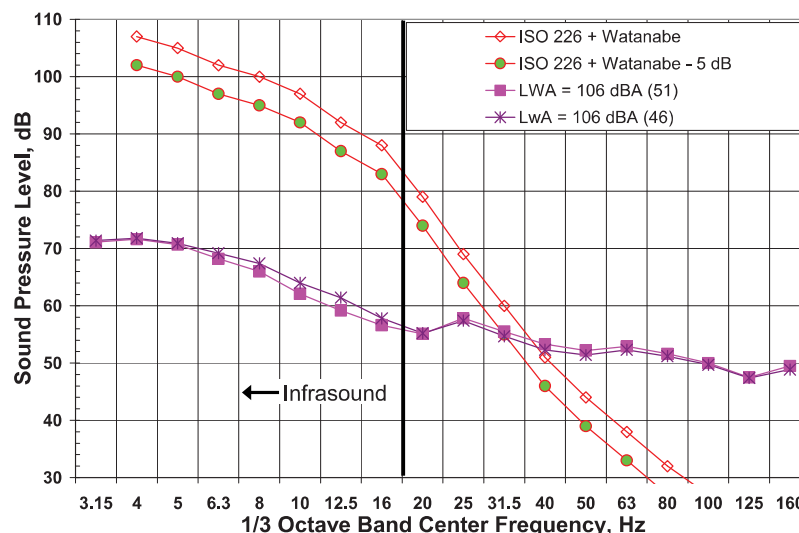


Fig. 9—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to audibility criteria.

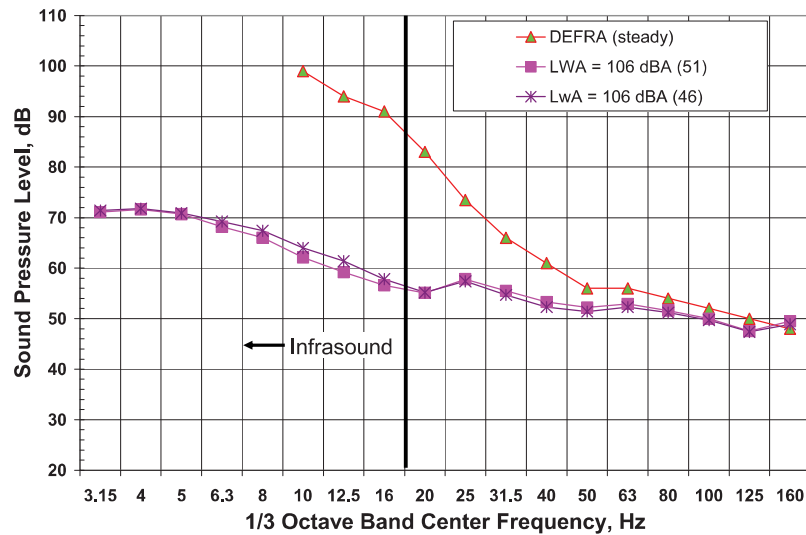


Fig. 10—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to outdoor equivalent DEFRA criteria.

bedrooms are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB). The 16, 31.5, 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4.

5.2.2 Indoor measurements—GE 1.5sle

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from GE 1.5sle WTGs. In each house, measurements were made in a room facing the wind turbines, and were made with a window both open and closed. These residences are designated Homes “B” and “C” and were approximately

305 meters (1,000 feet) from the closest GE WTG. Operational conditions were maximum turbine noise and high ground winds at Home “B”, and within 1.5 dB of maximum turbine noise and high ground level winds at Home “C”. Home “B” was near a string of multiple WTGs, four of which were within 610 meters (2,000 feet) of the house, while Home “C” was at the end of a string of WTGs, two of which were within 610 meters of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 13.

The room in Home “B” where interior measurements were made had the following characteristics:

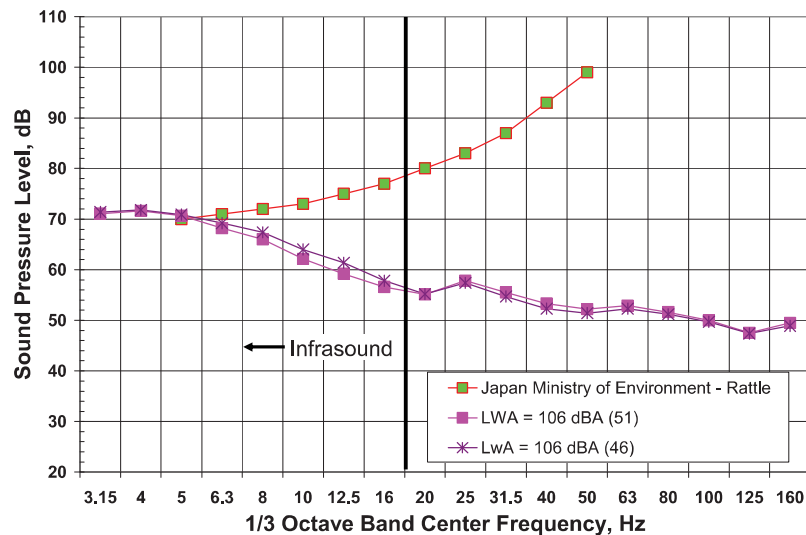


Fig. 11—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to Japan Ministry of Environment rattle criteria.

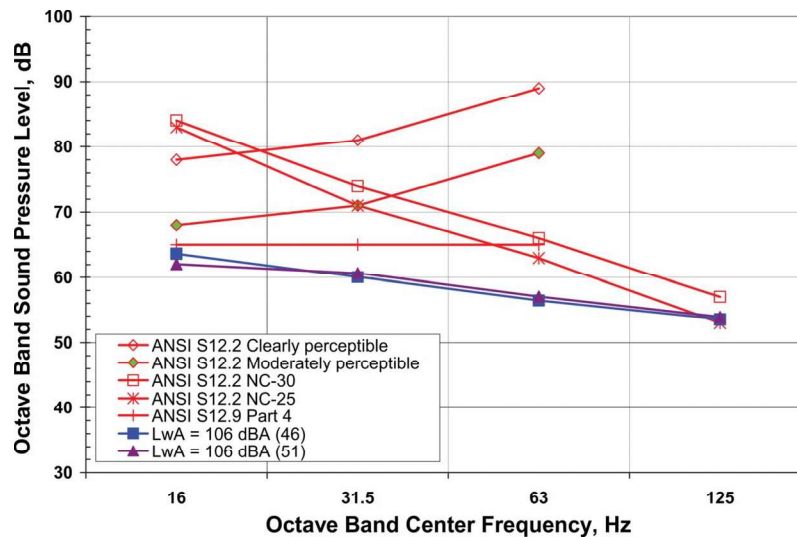


Fig. 12—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to ANSI criteria.

approximately 3.0 meters wide (10 feet) by 3.6 meters long (12 feet), bedroom furniture, carpeted flooring, two relatively new double-hung windows (no storm windows), paneling on the interior walls, and bricked exterior walls. The sound level meter was located just off-center in the room. The room in Home “C” where interior measurements were made had the following characteristics: approximately 2.4 meters wide (8 feet) by 3.6 meters long (12 feet), bathroom fixtures, linoleum flooring, one old casement window (no storm window), paneling on the interior walls, and wooden exterior walls. The sound level meter was located in the center of the room.

Figure 13 plots the indoor one-third octave band sound levels (L_{eq}) for Home “B”, and Fig. 14 plots the indoor one-third octave band sound levels for Home “C”. The results show that infrasound is inaudible to even the most sensitive people at around 305 meters (1,000 feet) from these wind turbines with the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 63 Hz may be audible depending on background sound levels.

Figure 15 plots the indoor one-third octave band sound levels (L_{eq}) for Home “B”, and Fig. 16 plots the indoor one-third octave band sound levels (L_{eq}) for Home “C”. The results show the DEFRA disturbance criteria were met for steady and non-steady low frequency sounds.

Although not shown in Figs. 15 and 16, the one-third octave band levels meet the Japan Ministry of Environment criteria for evaluating complaints of mental and physical discomfort since both samples meet the more stringent DEFRA criteria for “non-steady” sounds, which is more stringent than the Japan criteria.

Figure 17 plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home “B”, and Fig. 18 plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home “C”. The results show the ANSI/ASA S12.2 low frequency criteria for perceptible vibration were met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for bedrooms, classrooms and hospitals were met,

Table 13—Summary of operational parameters—GE 1.5sle (Indoor).

Parameter	Home “B” (closed/open)	Home “C” (closed/open)
Distance to nearest WTG	290 meters	312 meters
Time of day	09:29-09:39/09:40-09:50	11:49-11:59/12:00-12:10
WTG power output	1,017 kW/896 kW	651 kW/632 kW
A-weighted sound power level	106 dB/105.8 dB	104.7 dB/104.6 dB
Measured wind speed @ 2 m	6.2 m/s/6.8 m/s	6.4 m/s/5.9 m/s
L_{Aeq}	27.1 dB/36.0 dB	33.6 dB/39.8 dB
L_{A90}	23.5 dB/33.7 dB	27.6 dB/34.2 dB
L_{Ceq}	47.1 dB/54.4 dB	50.6 dB/55.1 dB

* Includes K, uncertainty factor of 2 dB

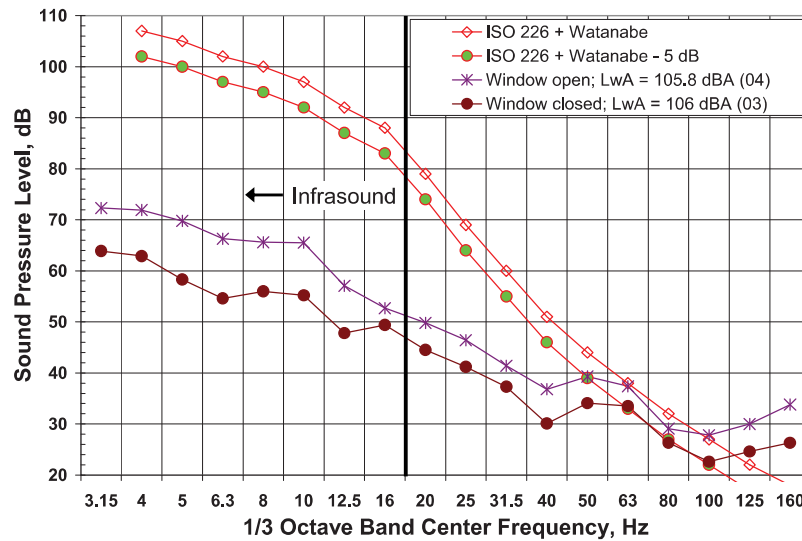


Fig. 13—GE 1.5sle wind turbine indoor sound levels at 290 meters compared to audibility criteria (Home “B”).

the spectrum was balanced, and the criteria for moderately perceptible vibrations in light-weight walls and ceilings were also met.

5.3 Noise Reduction from Outdoor to Indoor

Simultaneous outdoor and indoor measurements made at the three residences within the Horse Hollow Wind Farm discussed above, were used to determine noise reductions of the homes for comparison to that used in the determination of equivalent outdoor criteria for indoor criteria, such as ANSI/ASA S12.2 and DEFRA. Indoor measurements were made with windows open and closed. Tables 11 and 13 list the conditions of measurement for these houses.

Figures 19 and 20 present the measured one-third octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in these same figures are the one-third octave noise reductions discussed in the Appendix of this paper to obtain equivalent outdoor criteria for the indoor DEFRA criteria as well as the equivalent outdoor criteria for the Japanese mental and physical discomfort indoor criteria. It can be seen that for the window closed condition in Fig. 19, the measured noise reductions for all houses were greater than that used in our analysis for determining the equivalent outdoor criteria for the Japanese mental and physical discomfort indoor criteria. For the open window case in Fig. 20, which

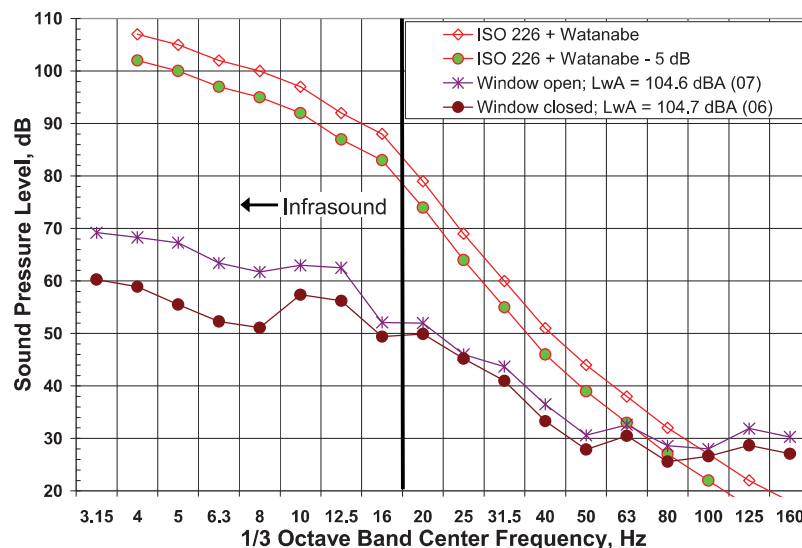


Fig. 14—GE 1.5sle wind turbine indoor sound levels at 312 meters compared to audibility criteria (Home “C”).

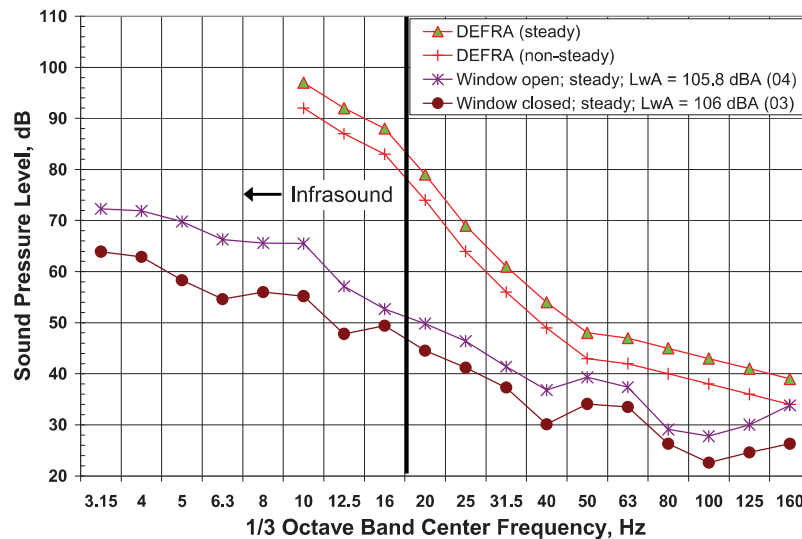


Fig. 15—GE 1.5sle wind turbine indoor sound levels at 290 meters compared to DEFRA criteria (Home “B”).

was used in our analysis for obtaining the equivalent outdoor DEFRA criteria, the average of the three homes has a greater noise reduction than assumed in the Appendix and all houses at all frequencies have higher values with one minor exception. Only Home “A” at 25 Hz had a lower noise reduction (3 dB), and this difference is not critical since the measured indoor sounds at 25 Hz at each of these home was significantly lower than the indoor DEFRA criteria and the indoor Japanese criteria. Furthermore, the outdoor measurements for both Siemens and GE wind turbines at 305 meters (1,000 feet) under high output/high noise levels met the equivalent outdoor DEFRA criteria at 25 Hz.

Table 14 presents the measured octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in Table 14 are the

octave band noise reductions used in Table 2 of this paper to obtain equivalent outdoor criteria for the indoor ANSI/ASA S12.2 criteria for perceptible vibration and for NC-25 and NC-30. It can be seen that for the window closed condition, the measured noise reductions for all houses were greater than that used in our analysis. For the open window case, the average of the three homes has a greater noise reduction than the values from Table A1, and all houses at all frequencies have higher values with one minor exception. Only Home “A” at 31 Hz (which contains the 25 Hz one-third octave band) had a lower noise reduction (3 dB), and this difference is not critical since the measured indoor sounds at 31 Hz at each of these homes was significantly lower than the indoor ANSI/ASA S12.2 criteria. Furthermore, the outdoor measurements for both Siemens and GE wind

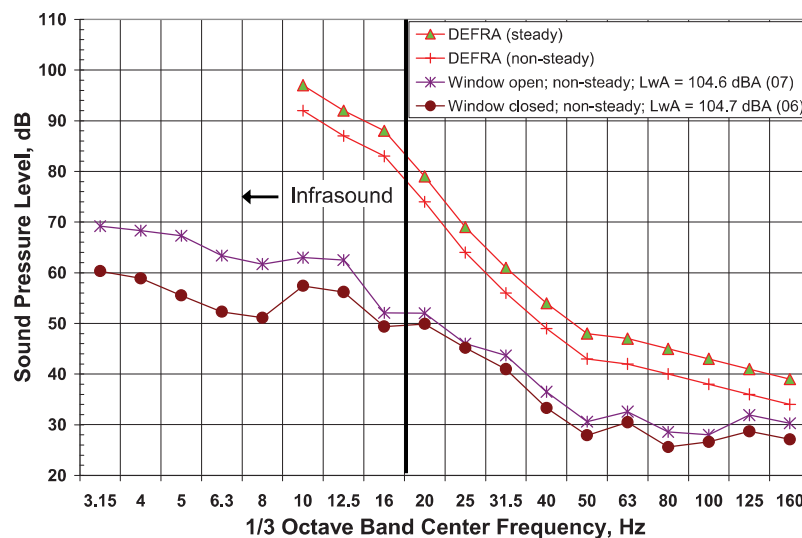


Fig. 16—GE 1.5sle wind turbine indoor sound levels at 312 meters compared to DEFRA criteria (Home “C”).

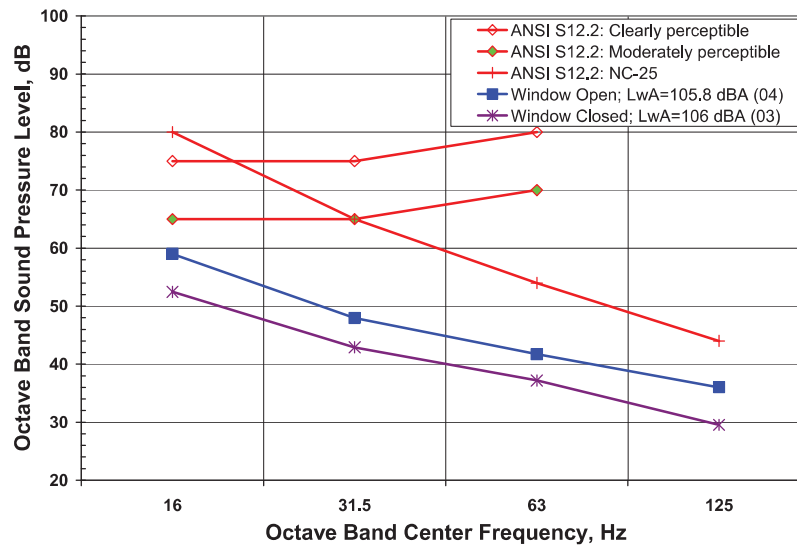


Fig. 17—GE 1.5sle wind turbine indoor sound levels at 290 meters compared to ANSI 12.2 criteria for perceptible vibrations and NC-25 (Home “B”).

turbines at 305 meters (1,000 feet) under high output/high noise levels met the equivalent outdoor ANSI/ASA S12.2 criteria at 31 Hz.

6 CONCLUSION

Sound levels from Siemens SWT 2.93-93 and GE 1.5sle wind turbines under maximum noise conditions at a distance more than 305 meters (1,000 feet) from the nearest residence meet the low frequency and infra-sound standards and criteria published by several independent agencies and organizations. At this distance the wind farms:

- meet ANSI/ASA S12.2 indoor levels for low frequency sound for bedrooms, classrooms and hospitals;
- meet ANSI/ASA S12.2 indoor levels for moderately perceptible vibrations in light-weight walls and ceilings;
- meet ANSI/ASA S12.2 criteria for balanced spectrum from low frequency sounds;
- meet ANSI S12.9/Part 4 thresholds for annoyance from low frequency sound and beginning of rattles;
- meet UK DEFRA disturbance based guidelines for low frequency sound;
- meet Japan Ministry of Environment Guidance for evaluating complaints of rattling from low frequency noise;
- meet Japan Ministry of Environment Guidance for evaluating complaints of mental and physi-

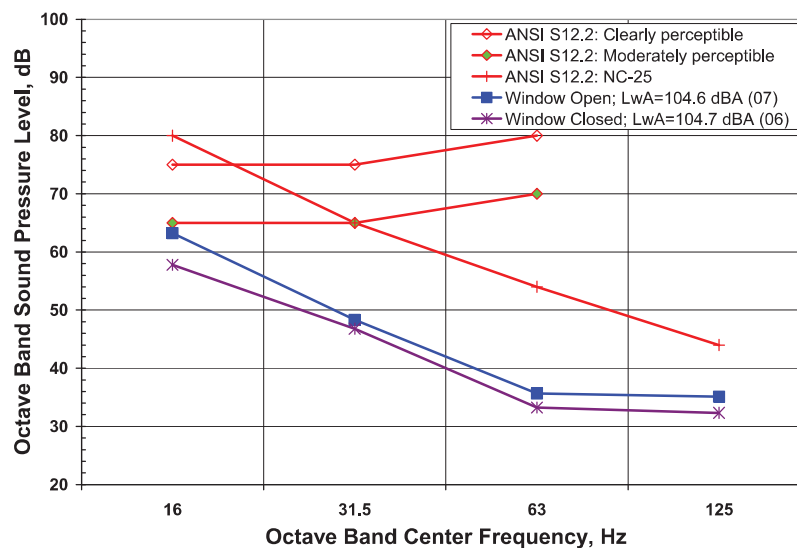


Fig. 18—GE 1.5sle wind turbine indoor sound levels at 312 meters compared to ANSI 12.2 criteria for perceptible vibrations and NC-25 (Home “C”).

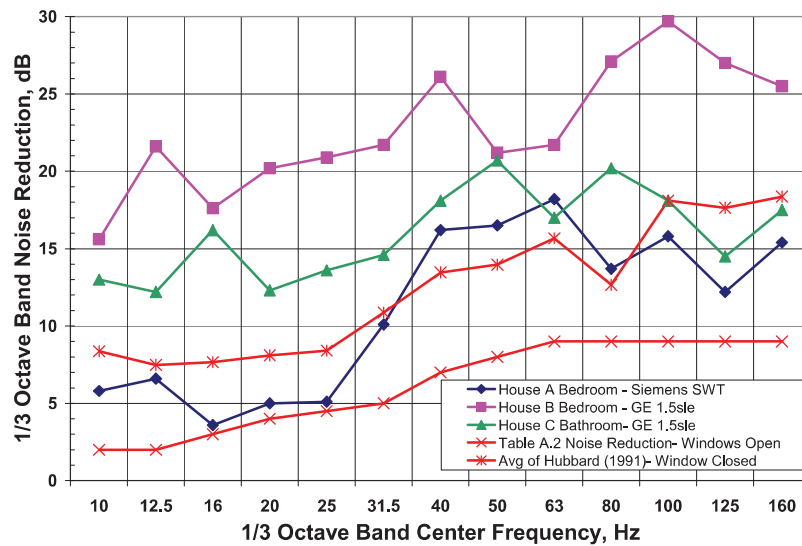


Fig. 19—One-third octave band interior noise reduction—Windows closed.

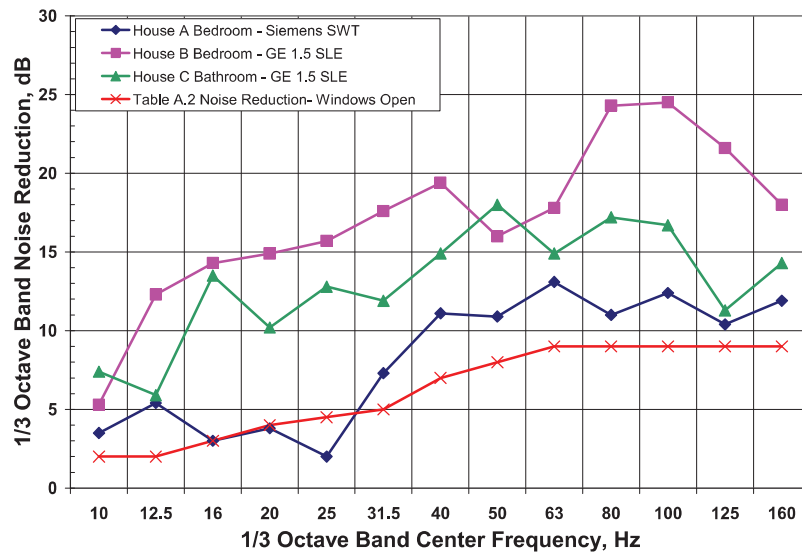


Fig. 20—One-third octave band interior noise reduction—Windows open.

- cal discomfort from low frequency noise;
- have no audible infrasound to the most sensitive listeners; and
- might have slightly audible low frequency noise at frequencies at 50 Hz and above depending on

other sources of low frequency noises in homes, such as refrigerators or external traffic or airplanes.

In accordance with the above findings, and in conjunction with our extensive literature search of

Table 14—Summary of octave band noise reduction—Interior measurements.

Home	Wind Turbine	Windows	16 Hz	31.5 Hz	63 Hz	125 Hz
A	Siemens SWT-2-3-93	Closed	5	6	16	14
A	Siemens SWT-2-3-93	Open	4	3	12	12
B	GE 1.5sle	Closed	20	22	22	27
B	GE 1.5sle	Open	13	17	18	21
C	GE 1.5sle	Closed	13	14	19	17
C	GE 1.5sle	Open	8	13	17	14
Table A1 Noise Reduction		Open	3	6	9	9

scientific papers and reports, there should be no adverse public health effects from infrasound or low frequency noise at distances greater than 305 meters (1,000 feet) from the wind turbine types measured: GE 1.5sle and Siemens SWT 2.3-93.

7 ACKNOWLEDGMENTS

Acknowledgement is made to NextEra Energy Resources, LLC ("NextEra"), formerly FPL Energy, for providing financial support for the study, allowing access to the wind farm, and supplying critical operational data. Epsilon determined all means, methods, and the testing protocol without interference or direction from NextEra. No limitations were placed on Epsilon by NextEra with respect to the testing protocol or upon the analysis methods; the conclusions are those of the authors.

8 APPENDIX: HOME NOISE REDUCTION USED TO DETERMINE EQUIVALENT OUTDOOR SOUND PRESSURE LEVEL CRITERIA BASED ON INDOOR CRITERIA

Since indoor measurements are not always possible, for comparison to outdoor sound levels the indoor criteria from ANSI/ASA S12.2 should be adjusted. Outdoor to indoor low frequency noise reductions have been reported by Sutherland for aircraft and highway noise for open and closed windows⁹ and by Hubbard and Shepherd for aircraft and wind turbine noise for closed windows¹⁰. Table A1 presents the average low frequency octave band noise reductions from outdoor to indoors from these two papers for open and closed windows. Sutherland only reported values down to 63 Hz; whereas Hubbard and Shepherd presented values to less than 10 Hz. The closed window conditions of Ref. 10 were used to estimate noise reductions less than 63 Hz by applying the difference between values for open and closed windows from Ref. 9 data at 63 Hz. It should be noted that the attenuation for wind turbines in Ref. 10 is based on only three homes at two different wind farms, whereas the traffic and aircraft data are for many homes. The wind turbine open window values were determined from the wind turbine closed window values by subtracting the difference in values between windows closed and open obtained by Ref. 9.

To be conservative, we use the open window case instead of closed windows except for the adjustments to the Japanese guideline which specifically called for closed windows. To be further conservative, we use the wind turbine noise reduction data in Ref. 10 (adjusted to open windows). However, it should be noted that it is

possible for some homes to have some slight amplification at low frequencies with windows open due to possible room resonances.

The average one-third octave band noise reductions used to determine equivalent outdoor one-third octave band criteria were determined in a similar manner. The first row of Table A2 and Fig. 20 present the average one-third octave band noise reductions values for *windows open* that were used to determine the equivalent outdoor one-third octave band criteria levels in Table 7 from the indoor criteria. The second row of Table A2 and Fig. 19 presents the one-third octave band noise reductions for windows closed determined by Ref. 10 for homes exposed to wind turbine sounds—these higher closed window noise reduction values were only used to determine equivalent outdoor levels for determining the equivalent Japanese guidance one-third octave band sound pressure level values for dealing with complaints of mental and physical discomfort from environmental sounds.

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FULL-LENGTH ORIGINAL RESEARCH

Potential of wind turbines to elicit seizures under various meteorological conditions

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SUMMARY

Purpose: To determine the potential risk of epileptic seizures from wind turbine shadow flicker under various meteorologic conditions.

Methods: We extend a previous model to include attenuation of sunlight by the atmosphere using the libradtran radiative transfer code.

Results: Under conditions in which observers look toward the horizon with their eyes open we find that there is risk when the observer is closer than 1.2 times the total turbine height when on land, and 2.8 times the total turbine height in marine environments, the risk limited by the size of the image of the sun's disc on the retina. When looking at the ground, where the shadow of the blade is cast,

observers are at risk only when at a distance <36 times the blade width, the risk limited by image contrast. If the observer views the horizon and closes their eyes, however, the stimulus size and contrast ratio are epileptogenic for solar elevation angles down to approximately 5° .

Discussion: Large turbines rotate at a rate below that at which the flicker is likely to present a risk, although there is a risk from smaller turbines that interrupt sunlight more than three times per second. For the scenarios considered, we find the risk is negligible at a distance more than about nine times the maximum height reached by the turbine blade, a distance similar to that in guidance from the United Kingdom planning authorities.

KEY WORDS: Photosensitive epilepsy, Flicker, Wind turbines, Atmospheric scattering of light.

The shadow from the blades of certain wind turbines can result in changes in retinal illumination at a rate >3 Hz. Flicker at such frequencies is known to cause epileptic seizures in susceptible people (Binnie et al., 2002). The risk is known to depend upon (1) the flicker frequency; (2) whether one or both eyes are stimulated; (3) the area of the retina receiving stimulation; (4) whether the central or peripheral retina is stimulated; (5) the amount of the change in light intensity (modulation depth); (6) the nature of its variation over time (mark/space fraction); and (7) the spectral composition of the light. A simple model that takes into account these parameters has been published (Harding et al., 2008), but the model fails to consider the atmospheric effects that reduce the shadow contrast. In the following article, we extend the earlier model of Harding et al. to include estimation of the effects of atmospheric scattering. The current view used by United Kingdom planning authorities is simply that “Flicker effects have been proven to occur only within ten rotor diameters of a turbine” (Office of the

Deputy Prime Minister, 2004). Therefore, if the turbine has 80-m diameter blades, the potential shadow flicker effect could be felt up to 800 m from a turbine.

The depth or darkness of the shadow of a turbine blade will depend on how much of the light comes directly from the sun and how much comes from elsewhere in the sky as a result of diffuse radiation. This in turn depends on the solar elevation (itself a function of latitude, time of day, and season), and on the amount of aerosols and optically thin clouds in the atmosphere. If the optical depth of cloud is sufficient to completely block the direct beam, then there is no shadow. The greatest contrast will be found when the atmosphere is clean and cloud free, when the scattering that leads to diffuse radiation is strongly wavelength dependent.

Although there is a little evidence that long wavelengths may be more epileptogenic (Parra et al., 2007), the basis for this is currently uncertain, and insufficient to suggest an action spectrum different from that for photopic vision. The variation in photopic luminance (V_λ) will, therefore, be considered.

METHOD

To determine the risk of seizures from wind turbines in persons with photosensitive epilepsy we have modeled the light–dark contrasts of turbine shadows for worst case

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conditions, that is, for a completely cloud-free atmosphere with the turbine blades rotating in a vertical plane and directly facing the observer on a line between the observer and the position of the sun in the sky. The observer is assumed to be looking straight ahead, so that we consider the radiation falling on a vertical plane at the location of the observer's eye (Fig. 1). We consider the mark/space fraction of the flicker to be within the epileptogenic range for reasons outlined by Harding et al. (2008).

For each meteorologic case, a determination of the diffuse radiance distribution in the sky, the intensity of the direct beam, together with the surface reflectivity (albedo) is required. To this end the libradtran radiative transfer code has been used (Mayer & Kylling, 2005). The model has been developed over several years and verified in a variety of measurement campaigns and, therefore, can be considered robust and reliable.

In the first instance we model the solar radiation for four possible atmospheric and ground conditions: a marine aerosol with a visibility of 30 km over a water surface, a rural aerosol also with a visibility of 30 km, an urban aerosol with a visibility of 10 km, and haze with a visibility of only 5 km. For all the nonmarine model runs, a grass surface was assumed. Although many of the larger turbines are located in open areas, the smaller turbines that have a higher and more epileptogenic flicker frequency are often located on roof tops. Roof surfaces exhibit a range of albedos; for simplicity we take the combined effect to be broadly similar to that of grass. The aerosol characteristics were taken from Shettle (1989) and the albedo for grass from Feister and Grewe (1995). The equivalent value for water, however,

was simply set at 0.035, due to the complications inherent in assigning a single Lambertian value for the range of sea states that could occur.

In many environments, especially urban areas, the presence of buildings, trees, and other obstructions close to the observer, as well as clouds close to the horizon, prevents the sun being viewed close to the horizon. Therefore, the lowest solar elevation angle modeled was chosen as 2° . Similarly for an observer looking directly ahead, once the sun is out of their field of view, the primary stimulus no longer has any potential to cause epileptic seizures; consequently, the upper limit is chosen as 40° . The model has been run at intervals between these two limits.

The output radiance distributions, calculated for wavelengths of 380–760 nm at 10 nm intervals, have been weighted with the CIE 1924 photopic action spectrum (Wyszecki & Stiles, 1982) to represent the sunlight as detected by the human eye. These values have then been converted to irradiances incident on a vertical surface, representing the observer's eye.

To incorporate the effect of a turbine blade upon these received irradiances, we make the assumption that the radiance in the vicinity of the solar disc is rotationally symmetric; this simplifies subsequent analysis, as only the angular width of the blade need be considered, with the relative position of the turbine axis with respect to the sun being removed. The contrast function then results from the blade obscuring the sky and occasionally the sun behind it.

Still considering the observer to be looking toward the horizon with the turbine in the foreground, we also include the cortical magnification factor (Drasdo, 1977)—an expression of the relative density of neurons on the visual cortex and hence the relative contributions of each part of the stimulus—to determine the perceived relative intensities of the direct and diffuse contributions (see Harding et al., 2008).

Then to find the contrast ratio, that is, the extremum value of the time varying contrast function, we additionally consider the area of the sun's disc that is obscured by a blade. As the observer becomes more distant from the turbine blade, the blade will obscure a smaller fraction of the direct beam/sun's disc. At a certain distance the fraction of the direct beam obscured as each blade passes in front of the sun will decrease to the point that the contrast is insufficient to induce seizures. The threshold Michelson contrast has been estimated as 5–10%, depending on the dataset used (Harding & Fylan, 1999; or Wilkins et al., 1980), which equates to a Weber contrast of 10–18%. In this case we define contrast in terms of the Weber fraction, as appropriate when the mark/space ratio is low, and we choose the more risk-averse figure of 10%. This contrast threshold distance is defined by the area of the sun obscured by the blade (the threshold obscuration area) and is, therefore, a function of the relative contributions of the diffuse and direct components and, in turn, the state of the atmosphere and the solar elevation.

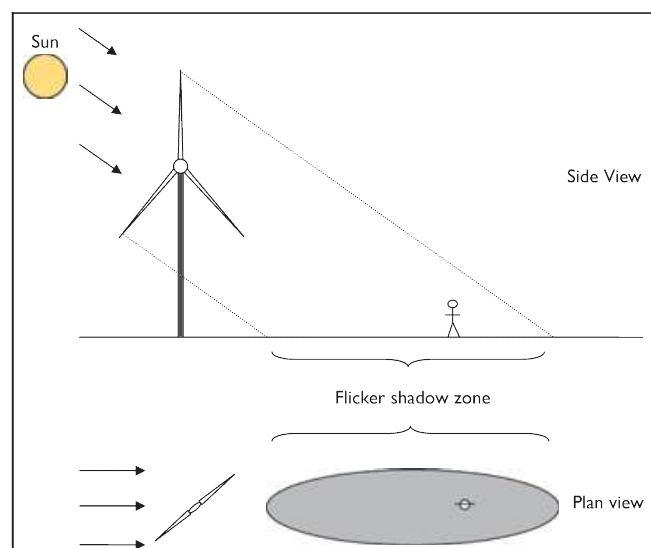
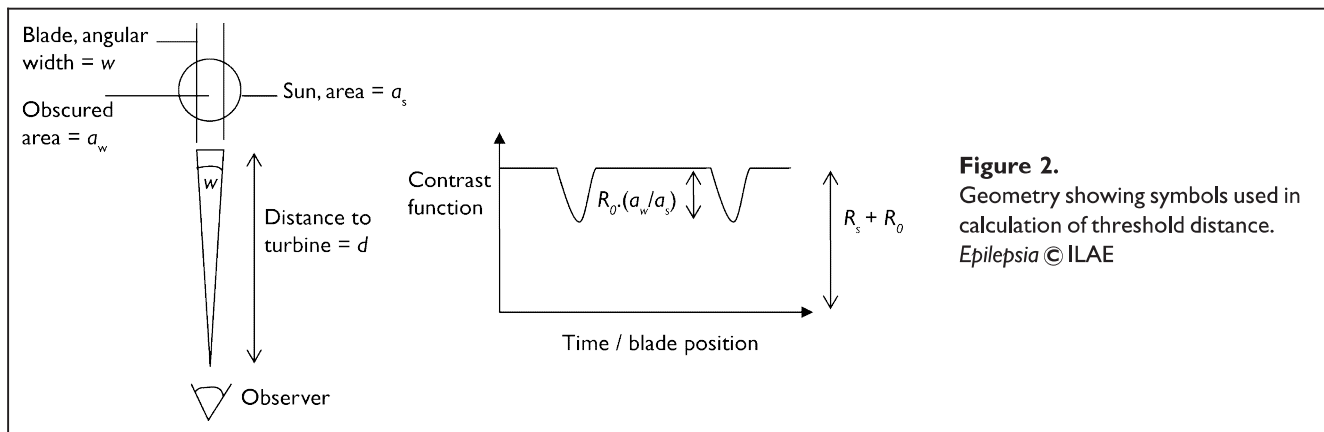


Figure 1.

Generalized geometry for turbine flicker, showing an observer in the shadow area. Note the main analysis assumes the observer and turbine blades are directly facing each other.

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To calculate the threshold obscuration area, we set the reduction in direct beam intensity due to blade obscuration equal to the maximum intensity multiplied by the epileptogenic contrast threshold (see Fig. 2 for geometry). The maximum intensity occurs when the sun is unobscured, and is given by the sum of the direct and sky contributions. The intensity is reduced most when the blade lies symmetrically over the sun, obscuring a fraction a_w/a_s of the direct beam, where a_w is the threshold obscuration area and a_s is the area of the solar disc. Rearranging, the threshold area can then be expressed as follows:

$$a_w = \frac{a_s(R_s + R_0)C_w}{R_0}$$

Here C_w is the epileptogenic contrast threshold, R_s is the relative contribution from the sky, and R_0 is the relative contribution of the sun's direct beam.

The blade is assumed to be delimited by parallel edges in the region of interest and lying symmetrically over the sun's disc at the time of minimum contrast ratio. Simple geometry then enables the threshold area to be expressed as an angular blade width.

Finally, the threshold width in each meteorologic situation can be converted to find the threshold distance in units of blade width—this is the distance beyond which the flicker from the turbine blade is no longer epileptogenic to an observer because the contrast ratio would fall below 10%. It is, as follows:

$$d = 0.5 \cot(w/2),$$

where w is the threshold angular blade width.

RESULTS AND DISCUSSION

As the aerosol loading of the atmosphere and the solar elevation angle change, the relative contributions of the diffuse and direct components will alter. In turn, as turbine blades pass in front of the sun, the fraction of the solar disc that results in a threshold contrast ratio will vary. When

applying the analysis in the preceding section to the cases modeled, we obtain the distances at which this threshold is reached. These are shown in Fig. 3.

It is clear that as the amount of aerosol in the atmosphere decreases, the direct beam contribution rises and so the threshold distance increases. Furthermore, when the sun approaches the horizon for the high visibility (low aerosol) cases the threshold distance increases to over 1,000 times the blade width. From atmospheric radiative considerations alone for each level of aerosol loading, it would be expected that as the solar elevation angle increases, a corresponding increase in the threshold distance would also be seen. However, the direct beam contribution in fact decreases with increasing solar elevation angle due to the cortical magnification factor. It is competition between these two aspects that results in a peak at 15–20° for the two highest aerosol cases and at 5° for the low aerosol cases: At lower solar elevation angles the direct beam is reduced by aerosol interactions, and at higher elevations its contribution falls due to the decreasing cortical magnification factor. Furthermore, it can be seen that the differing albedos of grass and

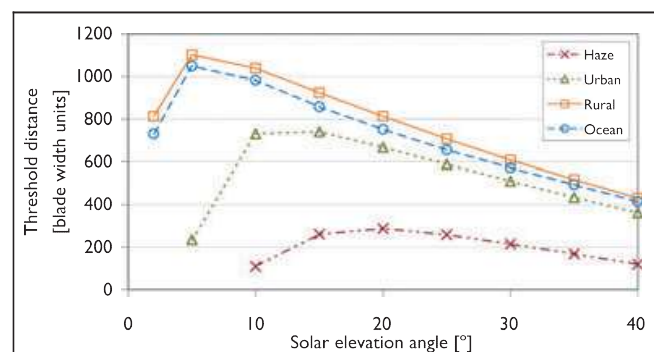


Figure 3.

Threshold distances corresponding to a threshold contrast ratio of 10%, as a function of solar elevation angle for sample aerosol loadings, as described in the text.

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water and the different aerosol properties in the two cases, increase the observed diffuse radiation component for marine environments, and in turn the threshold distances. It will also be noted that there is a lower limit reached for high aerosols—where even when the blade obscures the entire sun the contrast threshold is not achieved.

Taking the maximum threshold distance allows two example turbines to be considered. Wind turbines are commonly either for large-scale power generation as stand-alone structures, or for microgeneration, being sited on or close to the structure requiring electricity. A typical large 2MW turbine has a blade width of approximately 2 m (although very close to the rotation axis it may be more than this, and will taper toward the point). The contrast ratio threshold distance for a clear, low aerosol day would then be ~2 km. For a small turbine the equivalent distance is an order of magnitude less at 200 m, assuming a blade width of 20 cm.

It should be noted, however, that this does not imply that there is a risk of seizures wherever the turbine can be seen. For there to be a risk, the observer still must be within the shadow zone. For the 2MW turbine example (total height of 120 m), the furthest part of the shadow falls 1,380 m from the turbine when the sun is 5° above the horizon—less than the threshold distance in the previous paragraph. Therefore, in this example the locations on the ground that present a risk of seizures are determined by the extent of the shadow and not the contrast ratio threshold. This point suggests that there are a number of other factors that ought to be considered. We will discuss these below.

The most pertinent is a direct consideration of the cortical magnification factor. From Drasdo (1977) and Binnie et al. (2002), the proportion of patients at risk from a stimulus subtending a half-angle ϕ can be given as follows:

$$p = -0.184 + 2.1(1 - \exp(-0.0574\phi))$$

Solving for $p = 0$, shows that when the stimulus subtends a half-angle $<1.6^\circ$, no patients are at risk. In our case the dominant stimulus is the solar disc, which subtends a total angle of 0.53° , implying that although the contrast ratio would appear to be sufficient to cause seizures, the size of the solar disc stimulus prevents the flicker from being epileptogenic.

Yet the analysis thus far only includes radiative transfer in the atmosphere. A further consideration is scattering of the external stimulus within the eye, before the image reaches the retina. Following Vos et al. (1976), the intensity profile of an external point source falling on the fovea can be expressed as a power law for angles $>1'$. In general 50% of the source intensity falls within $2'$ and $3'$, and 90% within 1° .

We take the edge of the sun's image to be the radius at which the solar entoptic stray light is 10% of the steady diffuse background, the same limit used by de Wit and Coppens (2003). (Entoptic scatter of the circumsolar

radiation itself has not been included, although it is noted it would increase the calculated values slightly—the direct beam contribution will always be much larger.) To determine this radius, the ratio of the direct beam irradiance to the circumsolar value was calculated and multiplied by 0.1. The apparent radius of the solar disc was then found from the tables provided in Vos et al. (1976). This is plotted in Fig. 4, alongside the epileptogenic threshold radius of 1.6° . It is clear that for most combinations of solar elevation angle and aerosol loading, the minimum epileptogenic stimulus size is not reached. Moreover, even with the lowest aerosol loadings this threshold is not reached when the sun is $<20^\circ$ above the horizon. For land-based turbines the equivalent solar elevation angle is 40° —the upper limit of our analysis. The implications of this result are as follows: considering the contrast ratio threshold alone would lead to the conclusion that wind turbines can cause seizures up to 2 km distant; including the apparent stimulus size limits the solar elevation angle to 40° on land, and hence the maximum “at risk” distance is reduced to 1.2 times ($\cot 40^\circ$) the total turbine height (hub height plus blade length). For marine environments the “at risk” distance is 2.8 ($\cot 20^\circ$) times the total turbine height. In each case the total turbine height includes the height of any structure that the turbine might be situated on, for example, a building.

The weather conditions modeled so far have neglected the presence of clouds or other nonhorizontally homogeneous components. The minimum stimulus size required for patients to be “at risk,” however, allows us to consider a more general meteorologic situation with a bright patch in the sky of angular width 1.6° . Assuming the other epileptogenic conditions are met, this defines an angular blade width that would be required to cover and uncover the stimulus. The threshold distance in this case is equal to 35.8 multiples

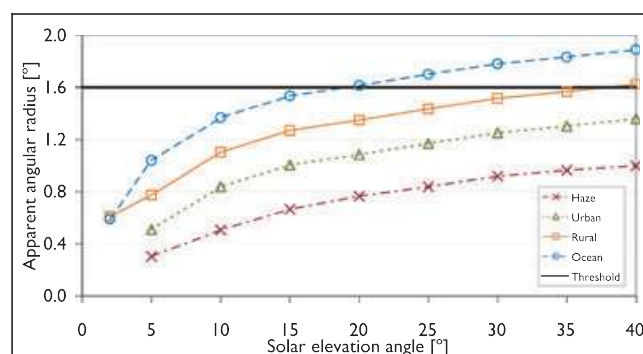


Figure 4.

Apparent solar angular radius due to entoptic (intraocular) scattering. The perceived edge is defined as the radius from the center of the retinal image of the sun at which intraocular scattering has reduced the sun's image intensity to 10% of the diffuse background intensity.

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of the blade width. For the large turbine example this would be approximately 70 m from the blades, and for a small turbine, approximately 7 m.

Up until this point we have assumed that the observer is directly facing the turbine looking toward the horizon. This would seem to be a reasonable first assumption; it also simplified calculations and caused the sun to be within the observer's field of view. That said, except during high aerosol loadings of the atmosphere, it is the body's natural response to look away from the sun, or to partially close the eyelids (Slaney, 2005). Indeed it is widely recommended not to view the sun directly because of the risk of retinal damage. Without the solar disc in the observer's field of view though, the analysis described in the preceding text does not hold.

There are some other possible scenarios in which turbine flicker of the direct solar beam could be epileptogenic. First where the observer stands in the shadow zone, but views the ground, and second, an observer viewing the turbine blades against the sky. The analysis was similar to that for the main case, but the threshold distances were found to be about two orders of magnitude smaller, with a maximum of 36 times the blade diameter for the marine case. The rural, urban, and haze aerosols all had lower threshold distances. This corresponds to a distance at which the general public would normally be excluded on other safety grounds, and may be less than the distance from the blades to the ground.

If rather than looking down, an observer chooses to close their eyes, but remains with their gaze directed ahead, the threshold distance is as in Fig. 5. The effect of the eyelids is to reduce the transmission of the incoming radiation (in the present study this is assumed to be wavelength independent), and to scatter radiation from all directions equally. The diffuse contribution is, therefore, the mean irradiance within a 40° field of view, and does not include any weighting by the cortical magnification factor because the entire

retina is then equally stimulated. From Fig. 5 we see that the contrast ratio threshold distance now increases with increasing solar elevation angle. For the lowest aerosol loadings this is from <600 at 5° to almost 1,100 at 40°. As discussed earlier for the main “eyes open” case, the limiting factor for marine and rural aerosols for these solar elevations is then the distance from the turbine that a shadow falls, rather than the contrast ratio threshold distance. For the 2MW turbine example with solar elevations of 5° and lower, we find that the contrast ratio threshold distance is the limiting factor. For example a 120 m total tower height, with blades 2 m wide, the contrast ratio threshold distance at 5° is 1,070 m on land—approximately nine times the total turbine height. The shadow, however, would extend to 1,370 m. As the sun drops lower, the contrast ratio threshold will fall and the blades' shadow will be cast outside this limit, therefore, not creating a risk of seizure. This worst case scenario is in line with the rule of thumb used by United Kingdom planning authorities to determine the “at risk” region—10 times the total turbine height (Harding et al., 2008).

The final contributing aspect to epileptogenic flicker is its frequency. Modern turbines are designed to have a constant tip speed ratio:

$$\lambda = \frac{4\pi}{n},$$

where n is the number of blades. The most efficient three-bladed turbines may have tip speed ratios of 6–7. The frequency at which the blades pass in front of a point on the sky can then be expressed as:

$$v = \lambda u \cdot \frac{n}{2\pi l} = \frac{2u}{l},$$

where u is the wind speed, and l is the blade length. This is in accordance with the fact that microgeneration turbines rotate faster than their larger counterparts. However, for the 2MW example, with 40 m blades, a wind speed of 20 m/s is required before the flicker frequency reaches 1 Hz, which is close to the typical storm protection shutdown speed of 25 m/s (BWEA 2005). Turbines of this size, therefore, rotate slower than 3 Hz, the lower frequency threshold at which seizures are a potential risk. For smaller turbines the flicker frequency is expected to be a factor of 10 or more higher, and, therefore, would have the potential to affect a larger proportion of people with epilepsy. For typical mean wind speeds of 5 m/s and a blade length of 2 m, the flicker frequency would be 5 Hz, although helical designs rotate at higher speeds and have shadows that move against one another, increasing the rate of shadow flicker.

CONCLUSIONS

This study has used a robust and accurate radiative transfer model to predict the radiance distribution and direct solar beam intensity for a range of clear sky atmospheric

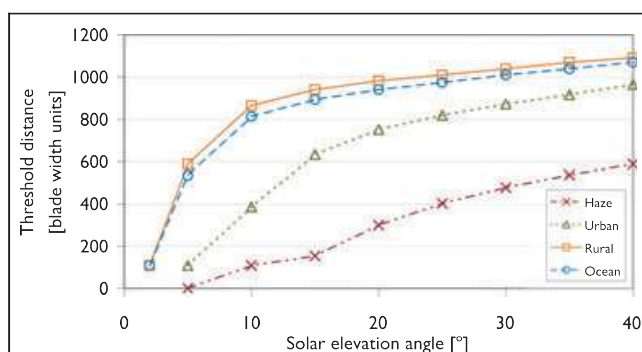


Figure 5.

Threshold distances as a function of solar elevation angle for sample aerosol loadings and an observer with closed eyelids.

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conditions. It is found that for a low aerosol loading of the atmosphere the epileptogenic contrast threshold of 10% is met for all locations where the turbine blade shadow would be reasonably expected to fall. However, with the eyes open, the apparent angular radius of the stimulus falls below the limit where any patients would be at risk (1.6°) for solar elevation angles of 40° or less (on land) and 20° or less (marine environments). Therefore, we envisage no epileptogenic risk to observers looking toward the horizon except when standing closer than 1.2 times the total turbine height on land, or situated closer than 2.8 times the total turbine height in marine environments.

Furthermore, considering the tendency of patients to look away from the sun as a natural reaction, but for those who find themselves in the shadow zone, we find that for an observer viewing the ground the contrast is almost always insufficient to be epileptogenic. If, alternatively, the observer maintains their gaze, but closes their eyes, then both the contrast ratio threshold distance and stimulus size conditions are sufficient down to a solar elevation angle of 5° , for the example discussed. In other words, when solar elevation is greater than 5° , there is epileptogenic potential where the blade's shadow falls. Below this angle the contrast ratio threshold limits the "at risk" region to <535 times the blade width on land. For the large turbine example used this corresponds to nine times the total tower height. It is noted that eye closure is a natural immediate protective action when exposed to flicker, and so has the unfortunate consequence of exacerbating its adverse effect in this context. A more effective strategy would be to cover one eye with the palm of a hand as monocular stimulation is known to be generally far less epileptogenic (Harding & Jeavons, 1995), or for the observer to simply avert their gaze toward the ground.

Finally we find that if flicker of sufficient contrast and stimulus size were produced by turbines, the larger turbines are unlikely to rotate fast enough to induce seizures. However, the rotation frequency increases inversely with the blade length, making small microgeneration turbines more likely to induce seizures, should the combined intensity and stimulus size conditions be met.

ACKNOWLEDGMENTS

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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Photic- and Pattern-induced Seizures: Expert Consensus of the Epilepsy Foundation of America Working Group

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Summary: *Purpose:* In August, 2004, the Epilepsy Foundation of America convened a workshop to begin to develop an expert consensus on photosensitive seizures.

Methods: Literature and data were reviewed, and consensus was derived from discussion.

Results: A flash is a potential hazard if it has luminance ≥ 20 cd/m², occurs at a frequency of ≥ 3 Hz, and occupies a solid visual angle of ≥ 0.006 steradians ($\sim 10\%$ of the central visual field or 25% of screen area at typical viewing distances). A transition to or from saturated red also is considered a risk. A pattern with the potential for provoking seizures contains clearly discernible stripes, numbering more than five light–dark pairs of stripes in any orientation. When the light–dark stripes of any pattern collectively subtend at the eye from the minimal-expected viewing

distance a solid angle of >0.006 steradians, the luminance of the lightest stripe is >50 cd/m², and the pattern is presented for ≥ 0.5 s, then the pattern should display no more than five light–dark pairs of stripes, if the stripes change direction, oscillate, flash, or reverse in contrast; if the pattern is unchanging or smoothly drifting in one direction, no more than eight stripes. These principles are easier to apply in the case of fixed media, for example, a prerecorded TV show, which can be analyzed frame-by-frame, as compared with interactive media.

Conclusions: A consensus view of stimuli likely to provoke visually evoked seizures can be developed. **Key**

Words: Seizures—Epilepsy—Photosensitivity—Reflex seizures—Expert consensus.

Seizures can be induced by visual stimuli, usually flicker (photic stimulation), or spatially periodic patterns, such as stripes (pattern stimulation). The seizures have implications not only for the individuals who have them, but also for Public Health agencies; the TV, motion picture, and video-game industries; and those who produce live events comprising intense visual stimuli [for review, see accompanying article (1)].

Public presentation and private use of material with intense visual stimuli has induced seizures in susceptible individuals over the years. A few such incidents in the UK in the early 1990s led the British Independent Television Commission (ITC) to develop guidelines designed to reduce the chances that transmitted material would induce a seizure in someone watching the broadcast. In December 1997, a Pokemon cartoon in Japan led to almost 700 admissions to hospital, mostly because of seizures. The Japanese television community immediately developed their own

guidelines, similar to those of the ITC, to address the problem. The ITC guidelines restrict use of bright flashes at frequencies $>3/s$ over $>25\%$ of the screen. Additional restrictions are placed on patterns of repeated light–dark stripes. International organizations, including the International Telecommunications Union and the International Standards Organization, have begun consideration of international guidelines for photic and pattern stimulation in public media to protect individuals with photosensitivity.

At present, with the exception of flashing fire alarms, no recommendations, guidelines, standards, regulations, or rules in the United States specifically address the issue of photosensitivity. Therefore in August 2004, the Epilepsy Foundation convened a workshop in Alexandria, Virginia, to begin to develop an expert consensus on the pertinent information. A working group was formed from interested physicians, scientists, representatives of the Federal Communications Commission, U.S. Access Board, U.S. Consumer Products Safety Commission, the Consumer Electronics Association, attorneys working on the issue, a representative from the video-game industry, and a consumer with epilepsy. The following is a working

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draft from the expert consensus. An accompanying article (1) presents a summary of literature presented to the participants. Although the statements were modified from the ITC guidelines in the UK, they are here offered as a consensus rather than guidelines as such. They have been extended to situations more general than those involving the viewing of video screens, but future work will be required to adapt this consensus to video games, movies, videotape-derived images, DVDs, and public displays of light. Future opinions will evolve in response to new scientific information and future international standards.

DRAFT CONSENSUS

Individuals who are photosensitive are at risk of seizures from flickering or intermittent images and certain types of regular patterns. These images may be encountered in television, video games, computer screens, motion pictures, advertising displays, rock concerts, theater, opera, dance halls, and architectural features. Leading medical opinion and experience of broadcast organizations around the world have led to the formulation of the following recommendations, aimed at reducing the risk of provoking a seizure in susceptible individuals.

To reduce the risk, the following recommendations on visual content are applicable when flashing images or regular patterns are clearly discernible. A flash considered to be a significant hazard for a photosensitive individual occurs when a pair of opposing changes in luminance exists (i.e., an increase in luminance followed by a decrease, or a decrease followed by an increase) of ≥ 20 cd/m². Irrespective of luminance, a transition to or from a saturated red also is considered a risk. Single, double, or triple flashes in 1 s are acceptable, but a sequence of flashes is not recommended when both of the following occur:

1. More than three flashes within any 1-s period.
2. From the minimal expected viewing distance, the total area of concurrent flashes subtends at the eye a solid angle of >0.006 steradians. This solid angle equates to one fourth of the area of the central 10 degrees of the visual field. For practical purposes, the area can be taken as applying to an area $>25\%$ of the area of a television screen, assuming standard viewing distances of ≥ 2 m (~ 9 feet).

Rapidly changing image sequences are provocative if they result in flashes in the central visual field, in which case, the same constraints apply as for flashes. A pattern with the potential for provoking seizures in pattern-sensitive individuals is one that contains clearly discernible stripes, numbering more than five light–dark pairs of stripes in any orientation. The stripes of concern can be parallel or radial, curved or straight, or formed by rows of repetitive elements, such as polka dots. If the stripes change direction, oscillate, flash, or reverse in contrast,

they are more likely to provoke seizures than if they are stationary. If the patterns obviously flow smoothly across, into, or out of the visual field in one direction, then they are less likely to provoke seizures.

When the light–dark stripes of any pattern collectively subtend at the eye, from the minimal expected viewing distance, a solid angle of >0.006 steradians, and the luminance of the lightest stripe is >50 cd/m², and the pattern is presented for ≥ 0.5 s, then the pattern should display no more than

1. Five light–dark pairs of stripes, if the stripes change direction, oscillate, flash or reverse in contrast.
2. Eight light–dark pairs of stripes, if the pattern is unchanging or continuously and smoothly drifting in one direction.

For practical purposes, these limits on the luminance, duration, and number of stripes may be taken as applying to patterns with a total area $>25\%$ of the area of a television screen, assuming standard viewing distances.

These principles are easier to apply in the case of fixed media (for example, a prerecorded TV show), which can be analyzed frame-by-frame. Interactive media, such as video games, may afford essentially limitless pathways through the game, depending on user actions. Therefore the working group recognizes that in the case of video games, the consensus recommendations apply to typical pathways of play but cannot cover every eventuality of play.

RATIONALE FOR THE RECOMMENDATIONS

The determination of the upper acceptable limit of flash rate (three flashes/s) originates in the studies of Jeavons and Harding (2). In a study of 170 patients, they demonstrated that only 3% of patients would be at risk with flashes at a rate of three per second or fewer. Above that flash rate, the probability of producing a photoparoxysmal response increased rapidly, reaching 65% at 10 flashes/s. Based on these and other studies, a maximum flash rate of three per second was selected by U.K. authorities to represent an acceptably small risk. The determination of the parameters of flash luminance and contrast (the difference between the opposing changes in luminance) was based on studies by Harding and Fylan (3) and Wilkins et al. (4). On the basis of their results, it was possible to estimate the proportion of patients affected as a function of the difference between screen luminance and luminance of the flash (5). Although flashes from stroboscopes in EEG laboratories have high intensities and short durations, they have seizure-provoking effects similar to those of other forms of visual stimulation. Stroboscopic stimuli also can be found in discotheques and in the theater. In the U.K., these are controlled by the “Health and Safety Executive Advice” on strobe lights.

The specification of the critical area was based on the knowledge that each of the visual cortices is independently sensitive, so that stimulation of the left or right half of the visual field results in equal sensitivity when compared with the whole field (6). It was therefore possible to determine that one fourth of the central 10 degrees of the visual field (0.006 steradians subtended at the eye) would provide protection for ~60% of the population at risk. The detailed justification for this specification can be found in Binnie et al. (5). Once 10 degrees of the visual field is affected by flickering or patterned stimuli, further increases in area of the affected visual field has little significance for the photosensitive response (7).

Binnie et al. (5) provide a description of the guidelines adopted in the U.K. with respect to regular patterns. However, more recent considerations (7) suggest that a simpler and more protective specification of pattern limits can be deduced. Based on the data obtained from Wilkins et al. (4,8) and Harding and Fylan (3), it was possible to determine the proportion of patients who would produce photoparoxysmal responses from a large pattern of bright stripes. Both the luminance of the dark stripe and the contrast between the bright and darker stripes could be used to deduce the risk for a variety of luminance differences. In addition, the previous data referred to allowed the production of guidance with regard to pattern area. All these considerations determined that if the luminance of the lightest stripe was $>50 \text{ cd/m}^2$, and the pattern was presented for periods $>0.5 \text{ s}$, and the pattern occupied the central 10 degrees of visual field, then the patterns could be a hazard. If the direction of the stripes changed or oscillated, only five pairs of stripes should be present. If the stripes were unchanging, eight stripes gave an equivalent theoretic level of risk because constant patterns are in general less provocative. In the context of television, experience indicates that drifting patterns have risks similar to those that are stationary. The determination of the period of 0.5 s was based on experiences of both Wilkins and Harding that paroxysmal discharges very rarely occurred in response to patterns with $<0.5\text{-s}$ duration. Although color

is an additional important factor in determining response to photic stimuli (9), its role is not yet sufficiently quantified to include recommendations on color in the consensus statement.

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