BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA

IN THE MATTER OF THE APPLICATION BY PREVAILING WIND PARK, LLC FOR A PERMIT OF A WIND ENERGY FACILITY IN BON HOMME COUNTY, CHARLES MIX COUNTY AND HUTCHINSON COUNTY, SOUTH DAKOTA, FOR THE PREVAILING WIND	)))))))	**Sherman Fuerniss Exhibits EL18-026**

Sherman Fuerniss hereby submits the following exhibit list in the above - captioned docket:

1) Dr visit1

2) Dr visit 2

3) PV Map 4-2018 red on green 1

4) PV Map 4-2018 red on green 2

5) WHO-noise-2015-Open-Letter

6) NHMRC review

7) Low_frequency_noise-from-large-wind-turbines

8) Colin Hansen correspondence

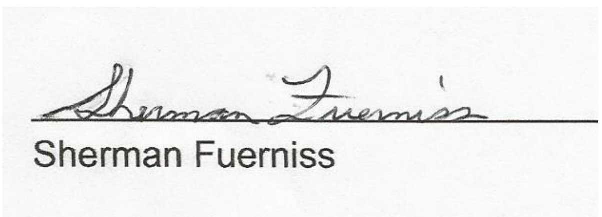
9) Vesta Operation Manual

10) B&McD Response to Noise Peer Review 7-3-2018

11) IMG_20181001_115514

Sherman Fuerniss serves the right to introduce additional exhibits necessary to rebut evidence presented by any other party in this docket.

Dated this first day of October 2018.



Sherman Fuerniss
Delmont, So. Dak. 57330
EL 18-026

Avera Medical Group

Patient: Sherman W Fuerniss
Appointment: 02/01/2018 at 11:00am with Richard W Honke for Vertigo at AVERA SB RHC - PARKSTON, 401 W GLYNN DRIVE, PARKSTON, SD 57366

Your Care Team
Avera St Benedict Clinic, Primary Care Provider
AVERA ST BENEDICT CLINIC
401 W GLYNN DR
PARKSTON, SD 57366
(605)928-7961

Thank You for Choosing Avera!
Below is a summary of the care you received during today's visit and instructions to follow at home.

Your Measurements and Vital Signs

Date	*Height*	*Weight*	*Body Mass Index*	*Temp*	*Blood Pressure*	*Pulse*
02/01/18					129/83	68
02/01/18	5'9.00"	228 lbs	33.7 kg/m2	97.2 F	135/92	67

Your Allergies
No Known Allergies

Medication Instructions
Below is an overview of your current and discontinued medications. Instructions on new prescriptions, refilled prescriptions and changed medications are outlined below. Please contact your nurse or provider for specific questions on taking your medications.

Keep all medications out of the reach of children. Medications can be abused. Keep your medication in a safe place to protect it from theft. Sharing, selling or giving away your medication to anyone else is dangerous and against the law.

Safely disposing of expired or unused medication is important in helping to protect your family and home and decrease the opportunity for your family, their friends or others to abuse your medication. Dispose of expired or unused medications through a safe drug disposal program. Ask your pharmacy for details in your community. If none is available to you, dispose of by mixing with waste such as coffee grounds or kitty litter and place in household trash. Unless otherwise directed by the medication's packaging, do not flush down the drain or toilet.

Your Medications

Start Taking	*Pick up at Parkston Drug: 112 W Main St, Parkston, SD, Phone: (605)928-3125* **Meclizine 25 Mg Tab** Take 1 tab oral three times a day; Quantity of 30; Refills: 3

Your Other Medications

Continue Taking	**Aspir 81 81 Mg Tablet.dr (Aspirin)** Take 1 Tab Oral daily

You Were Seen for the Following Reasons
- Vertigo
- Nausea
- Neck pain

Procedures or Tests Performed During Your Visit
Please contact your nurse or provider with any questions regarding tests or procedures performed during your visit.

Upcoming Tests or Procedures
Please contact your nurse or provider for instructions on future tests or procedures.

Injections Administered During Your Visit
Please contact your nurse or provider with any questions regarding injections administered during your visit.

We Have Made the Following Referrals
Please contact your nurse or provider with any questions regarding referrals made during your visit.

Your Immunization History

Immunization Series	*#*	*Date Given*	*Status*	*Next Due*
[redacted]			[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	

Immunizations	*Last Done*	*Next Due*
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	

Education Materials Provided During Your Visit
No education materials provided.

Upcoming Appointments
Below are dates and times of any future appointments within the next 30 days. Many clinics ask you to arrive 15-30 minutes prior to your scheduled visit to complete any paperwork or prepare for a procedure. Additionally, please bring all of your prescription bottles to any appointments.

Your Upcoming Appointments within the Next 30 Days
No appointments scheduled within the next 30 days.

Avera Medical Group

Patient: Sherman W Fuerniss
Appointment: 08/31/2018 at 9:10am with Mary K Schaefer, PA-C for Ear Pain at AVERA SB RHC - PARKSTON, 401 W GLYNN DRIVE, PARKSTON, SD 57366

Your Care Team
Avera St Benedict Clinic, Primary Care Provider
AVERA ST BENEDICT CLINIC
401 W GLYNN DR
PARKSTON, SD 57366
(605)928-7961

Thank You for Choosing Avera!
Below is a summary of the care you received during today's visit and instructions to follow at home.

Your Measurements and Vital Signs

Date	*Temp*	*Blood Pressure*	*Pulse*
08/31/18	96.9 F	135/88	63

Your Allergies
No Known Allergies

Medication Instructions
Below is an overview of your current and discontinued medications. Instructions on new prescriptions, refilled prescriptions and changed medications are outlined below. Please contact your nurse or provider for specific questions on taking your medications.

Keep all medications out of the reach of children. Medications can be abused. Keep your medication in a safe place to protect it from theft. Sharing, selling or giving away your medication to anyone else is dangerous and against the law.

Safely disposing of expired or unused medication is important in helping to protect your family and home and decrease the opportunity for your family, their friends or others to abuse your medication. Dispose of expired or unused medications through a safe drug disposal program. Ask your pharmacy for details in your community. If none is available to you, dispose of by mixing with waste such as coffee grounds or kitty litter and place in household trash. Unless otherwise directed by the medication's packaging, do not flush down the drain or toilet.

Your Medications

Start Taking	*Follow your Provider instructions for med changes.* **Aspirin EC 81 Mg Tablet.dr (Aspirin)** Take 1 tab oral daily; Quantity of 30; Refills: 3

Your Other Medications

Stop Taking	**Aspir 81 81 Mg Tablet.dr (Aspirin)** Reason: Prescription changed

You Were Seen for the Following Reasons
No reasons recorded.

Procedures or Tests Performed During Your Visit
Please contact your nurse or provider with any questions regarding tests or procedures performed during your visit.

Upcoming Tests or Procedures
Please contact your nurse or provider for instructions on future tests or procedures.

Injections Administered During Your Visit
Please contact your nurse or provider with any questions regarding injections administered during your visit.

We Have Made the Following Referrals
Please contact your nurse or provider with any questions regarding referrals made during your visit.

Your Immunization History

Immunization Series	*#*	*Date Given*	*Status*	*Next Due*
[redacted]			[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]		
[redacted]	[redacted]	[redacted]	[redacted]	

Immunizations	*Last Done*	*Next Due*
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	

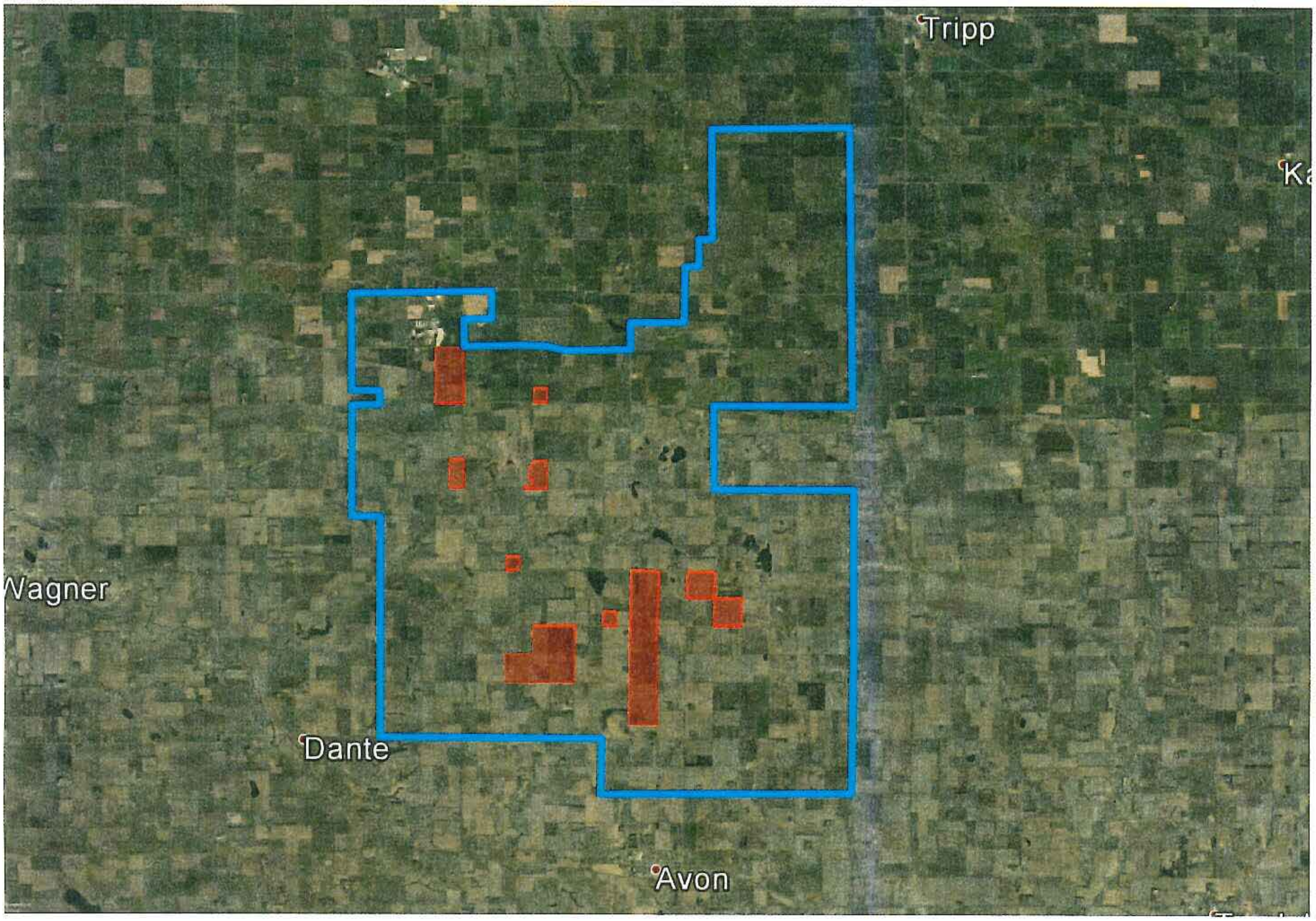
Education Materials Provided During Your Visit
No education materials provided.

Upcoming Appointments
Below are dates and times of any future appointments within the next 30 days. Many clinics ask you to arrive 15-30 minutes prior to your scheduled visit to complete any paperwork or prepare for a procedure. Additionally, please bring all of your prescription bottles to any appointments.

Your Upcoming Appointments within the Next 30 Days
No appointments scheduled within the next 30 days.

Get AveraChart Smart
AveraChart is a user-friendly patient portal that can be used to communicate with your care team and review your medical record - online!

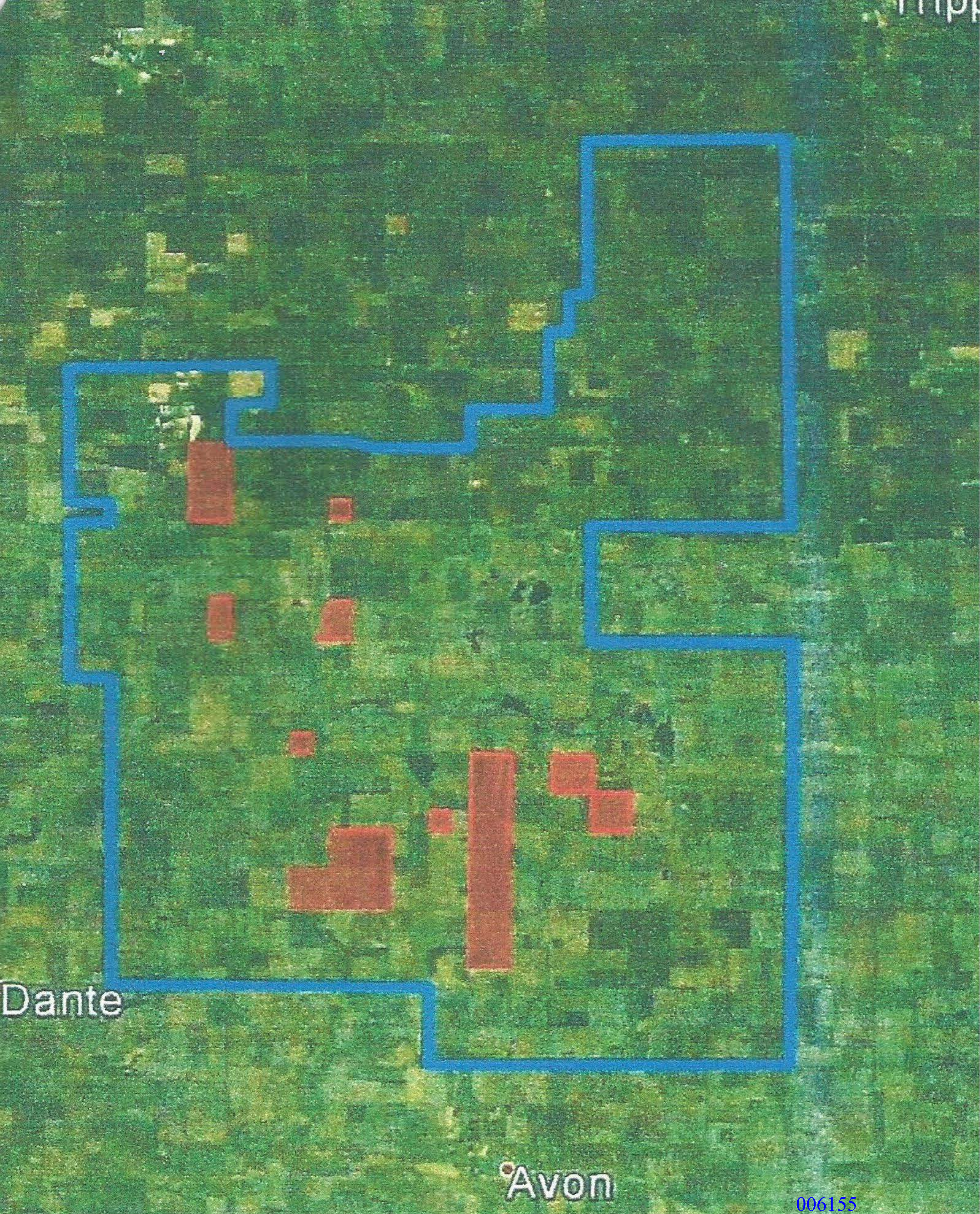
WELCOME!



Prevailing Wind Park

220 MW	Q4 2018	Q4 2019
Power Generation	Start of Construction	Commercial Operations

S·POWER
An AES and AIMCo Company


Dante
Avon

Open Letter to the members of the panel developing the WHO Environmental Noise Guidelines for the European Region.

Marie-Eve Héroux
Wolfgang Babisch.
Goran Belojevic.
Mark Brink.
Sabine Janssen.
Peter Lercher.
Jos Verbeek.
Marco Paviotti.
Göran Pershagen
Kerstin Persson Waye.
Anna Preis.
Stephen Stansfield.
Martin van den Berg.

Ladies and Gentlemen,

We understand that you are currently in the process of developing the WHO Environmental Noise Guidelines for the European Region as a regional update to the WHO Community Noise Guidelines. We also understand that:

1. The new Guidelines will be based upon a review of evidence on the health effects of environmental noise in the light of significant research carried out in the last few years.

2. The guidelines will review evidence on the health benefits of noise mitigation and interventions to decrease noise levels.

3. The evidence will be systematically reviewed to assess likely effects such as: sleep disturbance, annoyance, cognitive impairment, mental health and wellbeing, cardiovascular diseases, hearing impairment and tinnitus and adverse birth outcomes.

One of the sources of noise you are investigating is that from wind turbines which was not addressed in previous guidelines.

We welcome your review because, despite mounting anecdotal and academic evidence, for too long mitigation against adverse health effects following the construction of wind turbines has been absent from planning guidelines and **noise pollution regulations** in many European countries, especially **with respect to sound below 200 Hz.**

There is a pressing need for new guidelines to encourage governments better to safeguard the health of their citizens.

You will be aware that these problems are not confined to Europe. Neither are they confined to human beings.

We are hopeful that your deliberations will result in tough new European guidelines which in turn will prompt a serious worldwide examination of all aspects of this problem, including the widely-reported effects on animals.

Yours sincerely,

The undersigned:

Mrs. V.C.K. Metcalfe Community Councillor	Scotland	07.07.2016
Mauri Johansson, MD, MHH Specialist in Community and Occupational Medicine, including Environmental Medicine (retired)	Denmark/EU	07.07.2016
Susan Crosthwaite Community Councillor. Author of 'Request for Action' to Scottish Government	Scotland.	07.07.2016
Sarah Laurie Bachelor Medicine, Bachelor Surgery and CEO, Waubra Foundation	Australia	07.07.2016
Dr. Rachel Connor Bachelor Medicine, Bachelor Surgery, and Fellow of the Royal College of Radiologists. Chair of Moscow and Waterside Community Council	United Kingdom	07.07.2016
Virpi Poikolainen Physical therapist, Bachelor of Health Care. Community & County Councillor	Finland	07.07.2016
Alun Evans MD Professor Emeritus.Centre for Public Health. The Queen's University of Belfast.Institute of Clinical Science B	Northern Ireland	08.07.2016
Vojko Bernard, metallurgist, President of Alpe Adria International	Slovenia	08.07.2016
Angela Armstrong, M.B., Ch.B. retired General Medical Practitioner and Occupational Physician	Scotland	08.07.2016
Tomaž Ogrin, BSc, MSc Chemistry, researcher, scientist	Slovenia	08.07.2016
Dr. Katarina Dea Žetko, BA, MSc, PhD historical and germanic linguistics, Lecturer	Slovenia	08.07.2016
William K.G. Palmer P. Eng.	Ontario, Canada	08.07.2016
Jerry L. Punch, Ph.D. Professor Emeritus, Department of Communicative Sciences and Disorders, Michigan State University, East Lansing, Michigan	USA	08.07.2016
Curt Devlin, B.A., MA Software Architect, Health Sciences	USA	08.07.2016
Alec N. Salt, PhD. Professor of Otolaryngology, Washington University School of Medicine, St Louis	USA	08.07.2016

Gary Goland, Cert App Sci, (Medical Lab), Royal Melbourne Institute of Technology, Medical researcher, Adelaide	Australia	08.07.2016
Dominic Mette Friends Against Wind	France	08.07.2016
Sven Johannsen CEO & Erik Brunne, Cert. Acoustic Engineers & Infrasound Experts, GuSZ Gutachter u. Sachverständigen Zentrum für Umwelt-Messungen GmbH www.umweltmessung.com	Germany	08.07.2016
Johannes Mayer M.D. Family medicine, Osteopathic Medicine Clin. Ass. Prof. Osteopathic medicine Athens/Ohio/USA President Osteopathic physicians (BDOÄ)	Germany	08.07.2016
Greta Gallandy-Jakobsen author, retired teacher, editor of wind turbine victims' website vind-alarm-danmark.eu	Denmark	08.07.2016
Sherri Lange www.na-paw.org CEO North American Platform Against Wind Power.	USA & Canada.	08.07.2016
Wayne C. Spiggle, MD physician	USA	08.07.2016
John Harrison, PhD Expertise in wind turbine sound generation and propagation. Former member: Ontario Ministry of the Environment Focus Group on Wind Turbine Noise Regulation. Invited Speaker: 2008 World Wind Energy Conference	Canada	08.07.2016
Mark Duchamp President, Save the Eagles International www.SaveTheEaglesInternational.org Chairman, World Council for Nature, www.wcfn.org +34 693 643 736	Spain	08.07.2016
Maxwell Whisson, MB,BS FRCPath retired medical consultant and leader in Medical Research, primarily cancer & haematology	Australia	09.07. 2016
George Papadopoulos Pharmacist (B. Pharm), Yass, NSW	Australia	09.07.2016
Mary Morris Community based noise and health researcher and community advocate, (near) Waterloo, South Australia	Australia	09.07.2016
R.Y.McMurtry CM, MD, FRCS, FACS	Canada	09.07.2016
Arline L. Bronzaft, Ph.D Professor Emerita, City University of New York	USA	09.07.2016

Angela Kearns Retired Registered Nurse and Midwife	Australia	09.07.2016
Eric Rosenbloom President National Wind Watch, Inc. <https://www.wind-watch.org/	USA	09.07.2016
Mariana Alves-Pereira, PhD Researcher and Expert on the biological response to Infrasound and low-frequency noise exposure	Portugal	09.07.2016
Susan Smith Retired teacher. Founding member of Mothers Against Wind Turbines. Experiencing life within 900 metres of an industrial wind turbine	Canada	09.07.2016
George M Lindsay, B.Sc., PhD Engineer	United Kingdom	09.07.2016
Ove Björklund Engineer. Board member of the Association “Good Environment Hylte”	Sweden	09.07.2016
Madeleine Kura Co-founder of Cesme Sustainabilty Platform website http://www.cesmeplatformu.org/en/ Izmir	Turkey	09.07.2016
Sandy Reider, MD Lyndonville, Vermont	USA	09.07.2016
Per Fisker, MD retired Consulting Gynecologist and Obstetrician	Denmark	10.07.2016
Jutta Reichardt, Soz.Päd.(graduate degree) behavioral therapist Spokeswoman of sound victims on www.opfer.windwahn.de (Affected by infra, low frequency and structure born sound of technical facilities such as wind turbines, pumps etc.)	Germany	10.07.2016
Esen Fatma Kabaday Whiting Çeşme Municipality Councillor Biologist, Environmental Specialist (MS), Project Cycle Management Specialist	Turkey	10.07.2016
Bernd Stymer Oldest and largest resistance against wind madness in Sweden website http://www.helgaro-liv.se/	Sweden	10.07.2016
William G. Acker Consulting Engineer with Acker & Associates; Eight years of research work on Infrasound & Low Frequency Noise from Cooling Towers, Industrial Wind Turbines, Boilers and Automoblies. Green Bay, Wisconsin	USA	10.07.2016
James Vanden Boogart President, Brown County Citizens for Responsible Wind Energy. Brown County	USA	10.07.2016

David Moriarty Falmouth, Mass	USA	10.07.2016
Marshall Rosenthal MA Cultural Anthropology, Syracuse University, BS Biology, City College of NY, former Health Officer, Child Development Group of Missisippi	USA	10.07.2016
Bruce Rapley, BSc, MPhil, PhD Consulting Scientist. Principal Consultant: Environmental Health, Acoustics and Human Cognition, Atkinson & Rapley Consulting Ltd. arg@paradise.net.nz	New Zealand	11.07.2016
Steven Cooper Acoustical Engineer, The Acoustic Group	Australia	11.07.2016
Janet Holtkamp practitioner of Chinese Medicine, Nieuw-Buinen	Netherlands	11.07.2016
Ipar Buğra Dilli Head of Karaburun City Council	Turkey	11.07.2016
Ghislaine Siguier Présidente, Victimes des Éoliennes (Victims of Wind Turbines), http://en.friends-against-wind.org/victims	France	11.07.2016
Dr Mireille Oud medical physicst, founder of Dutch LinkedIn Expertise Group on Low Frequency Noise, author of 'Explanation for suffering from low-frequency sound'	Netherlands	11.07.2016
Prof. Dr. Ümit Erdem EGE University, Agricultural Faculty, Dep. of Landscape Architecture, Izmir Emeritus Fellow Member of the European Ecological Federation http://www.europeanecology.org	Turkey	11.07.2016
Prof. Dr. Zuhal Okuyan (MD) Community Health specialist and Medical Ethics lecturer Dokuz Eylul University, Izmir	Turkey	11.07.2016
Mustafa Tanısık Bodrum Peninsula Environmental Protection Platform	Turkey	11.07.2016
Stephen E. Ambrose, ASA, INCE Brd.Cert. Acoustic Investigator	USA	11.07.2016
Jean Pierre Riou Président de l'association "Le Mont Champot" (lemontchampot.blogspot.fr)	France	11.07.2016
Robert W. Rand, ASA, INCE	USA	11.07.2016

Christine Lavanchy Research laboratory technician. Member of Paysage Libre Vaud committee, 1096 Cully	Switzerland	11.07.2016
Paul Housiaux Solicitor (retd.)	United Kingdom	11.07.2016
Simon & Brooke Yates Mt Torrens, South Australia	Australia	11.07.2016
Barbara Lebiedowska Professor emeritus, independent researcher http://www.kdepot.eu/ http://lebiedowska.blog.onet.pl/	Poland	11.07.2016
Marek Lebiedowski Professor emeritus, independent researcher http://www.kdepot.eu/	Poland	11.07.2016
Marcin Przychodzki Lawyer and editor-in-chief of stopwiatrakom.eu website	Poland	11.07.2016
Paweł Kotwica Political scientist, translator and community advocate	Poland	11.07.2016
Marek Jasudowicz Mayor, Municipality of Giżycko, Masurian Lake District	Poland	11.07.2016
Hal Wilson B.Ed ((Chemistry and Mathematics) retired, Staffordshire	England	11.07.2016
Rick James, INCE E-Coustic Solutions, LLC, Okemos, MI 48805	USA	11.07.2016
Prof. Dr. Ali Osman Karababa Faculty of Medicine, Department of Public Health, Ege University, Izmir	Turkey	11.07.2016
Annette Smith Executive Director, Vermonters for a Clean Environment	USA	11.07.2016
Dr Gary Hopkins Emergency physician	Australia	11.07.2016
Dr. Alan C Watts OAM; HDA; B.Sc; M.B., Ch.B; L.R.C.P; M.R.C.S. retired medical practitioner with an interest in the health effects of wind turbines	Australia	12.07.2016
Dr. Colleen J Watts OAM; B.Sc.Agr.(Hons); M.Phil; Ph.D. Environmental scientist	Australia	12.07.2016
Carl V Phillips, MPP PhD consumer health advocate; former professor of public health and evidence-based medicine	Australia	12.07.2016
Annie Gardner	Australia	12.07.2016

Patina Schneider Australian Industrial Wind Turbine Awareness Network	Australia	12.07.2016
Jean-Louis Butré President of EPAW.org. Also: President of the French Fédération Environnement Durable regrouping 1060 French local associations	France	12.07.2016
Witold Jaszczuk, D.Eng. Vice President, Central Board, Liga Walki z Hałasem (Anti-Noise League), http://www.lwzh.org.pl/	Poland	12.07.2016
Zbigniew Sienkiewicz Ecology, environment & human health, protection of citizens' rights	Poland	12.07.2016
Keith Stelling, MA, MNIMH, Dip Phyt Independent Researcher, Ontario	Canada	12.07.2016
David R. Lawrence, MD Board Certified Internal Medicine ABIM Member Connecticut State Medical Society. Member Litchfield County Medical Association, Executive Committee. Assistant Clinical Professor, Department of Medicine, University of Connecticut School of Medicine	USA	12.07.2016
Norma C. Schmidt, RN BScN Retired Professor of Nursing	Canada	12.07.2016
Peter R Mitchell, AM BchE Founding Chairman of the Waubra Foundation	Australia	13.07.2016
Catherine Mitchell Director, Mothers Against Wind Turbines, Ontario	Canada	13.07.2016
Linda Rogers, NP-PHC Nurse Practitioner Primary Health Care, Ontario	Canada	13.07.2016
John O'Sullivan CEO, Principia Scientific International, principia-scientific.org	United Kingdom	13.07.2016
Krzysztof Skotak Researcher, Environmental and Health expert, National Institute of Public Health	Poland	13.07.2016
Dr. Matthias Kleespies Environmental scientist and climate researcher	Germany	13.07.2016
Ross McLeod Environmental Health Officer(retired), Queensland	Australia	13.07.2016
Dr Timothy Ball (Climatologist), Professor (retired), University of Winnipeg	Canada	13.07.2016

Andrew Duncan B.S.c Property Studies. County Councillor Westmeath County Council. Spokesperson Lakelands Windfarm Information Group. (LWIG).	Eire	14.07.2016.
Malcolm Roberts, BE, Engineering University of Queensland, MBA, Business, University of Chicago. Project manager for The Galileo Movement (Aus).	Australia	14.07.2016
Lon Briet, Environmental Platform. Bodrum.	Turkey	14.07.2016
Michael Jankowski. Electronics Engineer.	Canada	14.07.2016
Nicholas Kouwen, PhD., P.Eng., FASCE. Distinguished Professor Emeritus and Adjunct Professor Department of Civil and Environmental Engineering University of Waterloo. Waterloo, ON. N0C 1E0	Canada	14.07.2016
Shellie Correia, Mothers Against Turbines TM	Canada	15.07.2016
Ferdinand Deželak. Head of laboratory for physical measurements Institute of Occupational Safety. Ljubljana. Vice president of the Slovenian Acoustic Society.	Slovenia	15.07.2016
Miha JANC, Dr.Vet.Med., Dr.Sci., Emeritus Professor of Microbiology., University of Ljubljana, Slovenia.	Slovenia	15.07.2016
Mads F. Hovmand, Senior Scientist Terrestrial Ecology,Department of Biology University of Copenhagen.DK-1353 Copenhagen K, MFH@bi.ku.dk	Denmark	15.07.2016
Gitte Nielsen Monnetvej 8	Denmark	15.07.2016
Jay J Tibbetts MD Vice Chair/Chair Brown County Board of Health Declared Shirley Wind IWTs a Human Health Hazard Oct, 2014 Green Bay, WI	USA	15.07.2016
Kalevi Nikula Legal and External Affairs Director (retired) M.Sc., Physiology/Biophysics/Biochemistry. Chairman, The Finnish Association of Citizens Against Industrial Wind Power Plants (TV-KY ry.) http://www.tvky.info	Finland	16.07.2016

Expert Review of the NHMRC Draft Information Paper, "Evidence on Wind farms and Human Health"

Emeritus Professor Colin H Hansen
University of Adelaide

April 10, 2014

Summary

The NHMRC Draft Information Paper: "Evidence on Wind Farms and Human Health", is a document that seems to be predisposed to the notion that noise from wind farms has no direct or indirect effects on the health of people living in their vicinity. This conclusion is reached on the basis that no evidence in the numerous studies published on the subject is of sufficient scientific merit to be considered reliable and thus taken into account. Based on the evidence or supposed lack thereof, it would be equally valid to conclude that there is **no evidence that wind farms do not have** a substantial impact on the health of some people who live in their vicinity. However, this notion is never mentioned in the paper, which could lead to the unfortunate conclusion that the paper is biased towards the interests of the wind farm industry.

Another unfortunate conclusion that one may reach on reading the Draft Information paper is that suggestions of associations between environmental noise and adverse health effects "*are based on limited evidence*." This is in direct contravention of what is stated in the 2009 WHO report titled, "Night Noise Guidelines for Europe", which states, "*While noise-induced sleep disturbance is viewed as a health problem in itself (environmental insomnia), it also leads to further consequences for health and wellbeing*" and "*For the primary prevention of subclinical adverse health effects related to night noise in the population, it is recommended that the population should not be exposed to night noise levels greater than 40 dB of $L_{night,outside}$ during the part of the night when most people are in bed*".

The Draft Information Paper contains a few errors of fact and also seems to not appreciate the current state of the art in noise surveys. This results in incorrect conclusions being made and these are outlined in some detail in the following discussion. The Draft Information Paper is based on the document, "Final Report: *Systematic review of the human health effects of wind farms*", which has excluded, on questionable grounds, many important studies that show a link between wind farms and health effects.

The discussion of the need for further research to properly evaluate the effect of wind farm noise on the health and well-being of people in surrounding communities is relegated to Appendix C. This is perhaps the most important outcome of the review and should occupy a more prominent place in the Draft Information Paper.

Introduction

In undertaking this review I note that the systematic review of the literature, Final Report: *Systematic review of the human health effects of wind farms*, which has been finalised, also underpins the Draft Information Paper. Therefore I begin my review with some brief comments on the systematic review document in so far as they are relevant to my "*evaluation of the appropriateness of the conclusions made in the Information Paper regarding the potential health effects of wind turbines*".

There seems to be a misunderstanding in the systematic review document regarding the current state of the art in noise surveys. The state of the art for community surveys of noise from sources other than wind farms has been well established by extensive peer review (see Schomer and Parmidighantam, 2013) and such studies do not necessarily meet the general criteria specified for inclusion in the systematic review. For example it is not generally possible to hide the purpose of a noise study; aircraft noise studies are invariably done in the vicinity of airports, traffic noise studies are invariably done where there is a significant amount of traffic and military noise studies are done near military bases, with little chance of hiding the purpose of the survey. In addition almost all noise studies are necessarily cross sectional studies as it is generally not possible to predict sufficiently far in advance when and where a particular noise source may arrive. Nevertheless, this is the state of the art of noise surveys and as such should be applied to selecting appropriate studies for the systematic review of wind farm noise.

It is also unfortunate that studies by medical researchers such a Pierpont (2009) were excluded on the basis that they were case reports and case series studies. It is difficult to justify such exclusions, especially in the case of Pierpont whose work involved comparison studies (before and after turbines were operating as well as before and after relocation of residents).

An important study by Moller and Pedersen (2011) clearly establishes that as wind turbine power generating capacity increases so too do the LFN emissions and therefore it is predicted that so too will their effects be increased on residents in their near vicinity. This study was not mentioned in the systematic review. However, it has great importance to the conclusions drawn in the Draft Information Paper, as many current wind farms contain turbines of much greater generating capacity than turbines that were the basis of many previous studies, and it is generally expected that future wind farms will include turbines of even higher generating capacity than is the current case, leading to even more serious health effects on surrounding communities.

The 7 studies that met the criteria listed in the systematic review were all rated by the document as "*D, The body of evidence is weak and findings cannot be trusted.*" This effectively implies that no studies that have ever been done on the health effects of wind farm noise provide any useful information. This is an extraordinary result considering the extensive peer review undergone by numerous articles not included in the above mentioned seven, which were rejected on the basis of not satisfying some very strict criteria, but which have been published in reputable international journals. Rejection of all of these peer reviewed papers is the main limitation of the systematic review and this has led to the Draft Information Paper reaching incorrect conclusions.

The following paragraphs document specific comments in response to the review request from NHMRC in which I was asked whether:

- the rationale applied in examining the evidence on the potential health effects of wind turbine noise is understandable and clearly explained;
- the evidence has been accurately translated into the messages in the draft Information Paper; and
- the conclusions in the documents align with my understanding of the latest evidence in my area of expertise (i.e. acoustics).

Rationale applied in examining the evidence on the potential health effects of wind turbine noise is understandable and clearly explained

Although the rationale applied to examine the evidence is understandable and has been explained reasonably clearly, this does not mean that the rationale is logical or acceptable. As explained above, the rejection of peer reviewed papers in reputable international journals, which clearly show a link between wind turbine noise and adverse health effects has not been sufficiently well justified. Also the rejection of case series studies has not been sufficiently well justified. In addition, the argument that any health effect claimed to be due to noise has to have a direct physiological link with noise in order to be considered, is also flawed, as there is no logical reason to exclude indirect effects such as adverse health effects due to stress and disturbed sleep, which in turn have been shown in many studies to be directly linked to excessive wind turbine noise.

The evidence has been accurately translated into the messages in the draft Information Paper

In **Sections 3.2 and 3.3**, of Draft Information Paper the selection of evidence and included studies are discussed. As mentioned above, the main limitation of the systematic review procedure is that it rejected peer reviewed papers in reputable international journals, which clearly demonstrated a link between wind turbine noise and health effects (e.g. Phillips, 2011) and this has led to the Draft Information Paper reaching some incorrect conclusions.

In **section 3.4**, under the heading, **study design**, the Draft Information Paper states, "*All seven studies that met the inclusion criteria for the systematic component of the independent review used a cross-sectional design. Cross-sectional studies examine the relationship between an exposure (in this case wind turbines) and specific health outcomes in a defined population at a single point in time. Because the health outcomes were assessed at a single point in time, none of the included studies were able to provide any indication of the order of events — that is, whether a health outcome first occurred before or after the exposure began. This might mean that a person's self-reported health outcomes were present prior to the person's exposure to wind turbines*."

The above statement shows a lack of appreciation of the current state of the art in noise surveys. As discussed in Schomer and Parmidighantam (2013), where the lead author is an expert in such surveys, almost all noise surveys are cross-sectional studies, as it has not been possible to predict in advance where and when an annoying noise source would be located. Schomer and Parmidighantam (2013) write, "cross-sectional is the state-of-the-art in acoustics. There are hundreds of refereed papers on cross-sectional surveys in acoustics." They go on to point out that of the 43 international surveys undertaken for aircraft noise, 42 were cross-sectional studies, of the 37 international surveys for road traffic noise, 37 were cross-sectional studies and of the 11 international surveys of railroad noise, 11 were cross-sectional studies. If we use the same logic as the Draft Information Paper is applying to wind farm noise, then we would conclude that there is no valid scientific evidence that aircraft noise, traffic noise and railroad noise adversely affect the health of communities and that for all we know, any reported adverse health effects may have been there before the noise was. We could further conclude that all the militant communities around airports are making it up and further, that the curfew for many airports around the world should be lifted, as airport noise studies are not "scientifically sound". Of course these conclusions would be in direct contravention with the conclusions reached by international experts responsible for the 2009 WHO document, which states categorically that transportation noise is responsible for a range of serious adverse health effects.

Under the heading, **selection bias**, in **Section 3.4**, the Draft Information Paper states, "*There is a high risk of selection bias in a study with a low participation rate, as those who chose to participate in the study may have different exposure and health outcomes to those who did not participate*." One would have thought that the whole purpose of the review was to determine if wind farms caused adverse health effects so one would expect that those most exposed or affected would be those most likely to participate in studies. The logic for excluding such studies is flawed, as they provide excellent evidence that there are adverse health effects from wind farm noise.

Under the heading, **selection bias**, the Draft Information Paper states, "*In many of the studies, the purpose of the research was not masked (i.e. hidden) from participants. Where the studies did attempt to hide the intent of the study from participants, this may not have been effective. A lack of successful masking of a study's purpose can contribute to selection bias by making it more likely that a person who is concerned about wind farms will take part than a person who is not concerned about wind farms*." As pointed out by Schomer and Parmidighantam (2013), this is an argument that ignores the state-of-the-art in noise surveys for which it is virtually impossible to mask the intent of a survey. One may ask how well an aircraft noise survey is hidden in a survey near an airport for which the answer is invariably "not very well".

Under the heading, **information bias,** in **section 3.4**, there is a very unbalanced discussion attempting to explain why surveys may show that people living near wind farms suffer worse adverse health effects than those living further away, when in fact their health outcomes may be the same. The same argument could be used for any noise survey, including all the transportation noise surveys that have been used to shape government policy. Again this statement is in direct contravention to what is argued by other international experts and the World Health Organisation.

The same argument as above can be applied to the statements made under the heading, **confounding factors** in **Section 3.4**. It would be virtually impossible in practice to take account of every possible confounding factor and again this argument would null the results of almost every noise survey taken to date.

Under the heading, **consistency** in **Section 3.4**, the Draft Information Paper states, "*Among the seven studies reviewed, there was no consistency in finding an association between wind turbine exposure and self-reported physical or mental health outcomes. However there was some consistency in showing associations between wind farm exposure and annoyance, disturbed sleep and poorer quality of life*." Perhaps it would be helpful if the link between disturbed sleep / annoyance and adverse health effects were made at this point in the document, rather than waiting until Section 7. This would also be a good place to reference the 2009 WHO report on night noise levels.

Under the heading, **overall quality rating** in **Section 3.4**, the Draft Information Paper states, "*the body of evidence is weak and cannot be trusted), following NHMRC criteria for assessing the quality of evidence. This grading is largely due to the methodological weakness of the cross-sectional design used by all studies*." For reasons discussed above, cross-sectional studies are the state of the art in noise surveys. Almost all peer reviewed and published papers are cross-sectional as it is generally not possible to predict sufficiently far in advance the location and installation date of a future noise source.

The summary dismissal of all published evidence of sleep deprivation and health effects could indicate bias in favour of finding that wind farms do not adversely affect the health of neighbouring communities.

In **Section 4**, the Draft Information Paper states, "*In addition, it examined whether any health or health-related effects have been observed from these emissions when produced by sources other than wind farms (parallel evidence).*" It is not sufficient to just examine the level of a noise when comparing two different exposures. Also important are the frequency content, variability and impulsive nature, as well as the duration and time of day or night that it is experienced. It is unlikely that any studies of noise other than wind farm noise would be suitable for comparison with a wind noise study. Note also that the 2009 WHO document has already reported on the health effects of relatively low-level night-time environmental transportation noise.

In **Section 5**, the Draft Information Paper states, "*Deciding whether an association between wind farm exposure and a particular health outcome is causal — that is, wind farm exposure causes the health outcome — requires more evidence. First, it must be clear that the exposure (to wind turbines) preceded the outcome (the health or health-related effect).*" Although this is a desirable requirement, it may not be a very practical one. In cases where the adverse health effect is due to a wind farm, there will obviously be no evidence of such an effect prior to the wind farm being constructed. However, obtaining this evidence through medical records of participants may be problematic and so the proposed requirement in itself may not be achievable.

In **Section 5**, the Draft Information Paper states, "*Second, it must be possible to rule out alternative explanations for the association, including both: bias resulting from the design of the study or the way the study was conducted; and causation by one or more confounding factors associated with wind farm exposure.*" When one looks at all the possible confounding factors listed in the systematic review, one could easily conclude that it would not be possible to eliminate all of them simultaneously. It would be more helpful to examine the accepted state of the art for the numerous published surveys of other noise sources such as transportation noise and use those requirements and methods of analysis.

In **Section 5**, the Draft Information Paper states, "*Third, it should be shown: that the association is consistent with other evidence on the effects of the exposure (e.g. noise from some other source); and ideally, that there is a biological mechanism by which the exposure could cause the health outcome with which it is associated.*" It would be clearer if it was pointed out that "exposure" refers to the character of the noise (impulsiveness, frequency content etc.), and its duration in addition to its level. It is unlikely that one would find groups exposed to such noise, except in the vicinity of wind farms, so this requirement may be impractical to satisfy. Likely biological mechanisms have been suggested in the scientific literature (e.g. see Salt and Lichtenhan, 2014), even though the Draft Information Paper implies that no such mechanisms exist. More importantly, if a noise source leads to sleep disturbance on a prolonged basis, it is well known that adverse health effects are likely to result. This effect is discussed in some detail in the 2009 WHO report.

In **Section 5**, the Draft Information Paper states, "*NHMRC found no consistent direct evidence that exposure to wind farms was associated with any health outcome. The few associations reported by individual studies could have been due to chance. Therefore NHMRC concluded there is no reliable or consistent evidence that wind farms directly cause adverse health effects in humans*." This is written in a way that could indicate bias. A more balanced version would be "NHMRC found no consistent direct evidence that exposure to wind farms was **or was not** associated with any health outcome. The few associations reported by individual studies **may or may not** have been due to chance. Therefore NHMRC concluded there is no reliable or consistent evidence that wind farms directly **cause or do not cause** adverse health effects in humans."

In **Section 5**, the Draft Information Paper states, "*Therefore even though there was support for some of these associations in studies of effects of noise from other sources, NHMRC could not conclude that exposure to wind farm noise causes annoyance, sleep disturbance or poorer quality of life*." This statement is written in a way that could indicate bias. To make it more balanced, the following statement should be added. "On the other hand, NHMRC could not conclude that exposure to wind farm noise **does not cause** annoyance, sleep disturbance or poorer quality of life." Of course a result such as this only occurred because all of the evidence pointing to health effects was rejected during the systematic review.

The conclusions in the documents align with my understanding of the latest evidence in my area of expertise (i.e. acoustics)

Regarding Section 7.1, in the Draft Information Paper, it seems that the statements are written with a clear bias towards the belief that wind farm noise does not cause adverse health effects. The first dot point states that "*there is no reliable or consistent evidence that proximity to wind farms or wind farm noise directly causes health effects*." This statement could also be written as "there is no reliable or consistent evidence that proximity to wind farms or wind farm noise **does not cause** health effects." The two statements effectively state the same thing but with a different bias. To eliminate any unintended bias, the word "**cause**" in the original statement should be replaced with "**causes or does not cause**".

To remove bias in the second dot point which states, "*Finding an association between wind farms and these health-related effects does not mean that wind farms cause these effects*" the following words should be added at the end, "nor does it mean that wind farms do not cause these effects". The statement "*These associations could be due to selection or information bias or to confounding factors.*" Should be replaced with "These associations **may or may not** be due to selection or information bias or to confounding factors."

The fourth dot point which states, "*It is unlikely that substantial wind farm noise would be heard at distances of more than 500–1500 m from wind farms*" is incorrect. I have many measurements showing that wind farm noise can be heard at distances up to 8 km from a wind farm. There are many factors that contribute to how far away a wind farm can be heard, including wind farm layout and size (number of turbines), individual turbine size, terrain and atmospheric conditions. Regarding wind farm layout, it is well documented that some wind farms produce a low-frequency thumping noise that can disturb people several kilometres away and this is likely to be worse if turbines are located too close together so that some turbines are in the wake of upstream turbines in some wind directions.

The fifth dot point states, "*Noise from wind turbines, including its content of low-frequency noise and infrasound, is similar to noise from many other natural and human-made sources. There is no evidence that health or health-related effects from wind turbine noise would be any different to those from other noise sources at similar levels*." The first part of the statement may be true of some mining noise sources but is certainly not true of surface transportation noise which has been the subject of most of the health impact studies. The second sentence in the above statement ignores the completely different character of wind farm noise when compared with surface transportation noise and should be removed from the document. This is discussed in more detail earlier in this review.

The sixth dot point which states, "*People exposed to infrasound and low-frequency noise in a laboratory (at much higher levels than those to which people living near wind farms are exposed)* *experience few, if any, effects on body functioning*" is misleading. First, there is no quantitative definition of how much higher the words "much higher" mean. Second there is no distinction between acute and chronic exposure. As shown by Swinbanks (2012), the **length** of exposure to infrasound is important, with effects becoming more pronounced as the exposure duration increases. Typical laboratory exposures are of very short duration (less than 1 hour), whereas wind farm exposures prior to adverse effects can often (but not always) be measured in terms of weeks or months. Also, the above statement does not take into account the differences in character of wind farm infrasound and the character of the sound typically used in laboratory tests. As explained by Salt and Lichtenhan (2014), there are a number of physiological mechanisms whereby infrasound and low-frequency noise from wind farms can adversely affect human health. The fact that all people are not affected does not diminish the importance of recognising these mechanisms in people who are affected and who are physiologically more disposed to being affected.

Under the **Annoyance** heading in Section 7.2.1, the Draft Information Paper states, "*The five studies all reported an association between annoyance and higher estimated levels of wind farm noise or living closer to a wind farm.*" And then goes on to state, "*Factors other than the noise produced by wind farms, such as the participants' demographic, psychological and biological factors, their attitudes and perceived degree of control, and situational factors (including day and time, activity disturbance, type of area and features of the dwelling) may have contributed to the annoyance reported by participants.*" I find it puzzling that consistent results from five different studies can be so easily discarded. All those other factors mentioned should even out when looking at the effect of distance from a wind farm and clearly the **most likely** effect on annoyance is the wind farm, when it is shown that annoyance decreases with distance.

Under the **Sleep** heading in Section 7.2.1, the Draft Information Paper states, "*Six studies reported poorer sleep (mostly disturbed sleep and poor sleep quality) among people exposed to higher estimated levels of wind farm noise or living closer to wind farms.*" And then goes on to state "*The reported associations of wind turbine noise with sleep quality were generally weak*." Again, it is difficult to justify this statement given that six different studies all reported that people living closer to wind farms had poorer sleep. Under the same heading is the statement, "*The studies did not assess whether poorer sleep associated with wind farm noise might have had any effect on health*." One would have thought that the effect of poor sleep on health was well understood and did not need to be further considered in these studies, as this consideration would make the studies more complicated and expensive to undertake. So it would be better if this statement were removed or qualified. Another statement, "*participants who did not economically benefit from wind turbines reported more sleep interruption than others*" is made without any mention of the other differences between the groups which could represent equal or more important confounding factors (see page 61 of the referenced paper).

Under the **Quality of life** heading in Section 7.2.1, the Draft Information Paper points out that all 3 studies that assessed quality of life, found that it decreased following the construction of a nearby wind farm. The last sentence in this section attempts to explain away this association and is not at all helpful. It could be construed as significant bias in favour of the wind farm industry and should be deleted.

Under the **Noise in other environments** heading in Section 7.2.2, the Draft Information Paper states "*The World Health Organization reported a number of effects on sleep when night noise is in the range of 30–40 dBA (measured outside)*". This statement is correct. However, later statements, "*There is no evidence that health or health-related effects from wind turbine noise would be any different to those from other noise sources at similar levels. Based on the studies referred to above,* *wind turbines would be unlikely to cause any direct health effects at distances of more than 500 m. At 500-1500 m from a wind farm, wind turbine noise levels are generally in the range 30–45 dBA. At these distances, effects on sleep are likely to be modest, if any*," are incorrect on a number of levels (see below) and again indicate the possibility of bias by the writers of the document.

- If noise levels supposedly vary from 30 to 45 dBA at distances of 500—1500 m from a wind farm, then why is it stated that wind farms "*are unlikely to cause any direct health effects at distances of more than 500 m*" and that the effects on sleep will be modest, if any? One would assume that in the above statement, 30 to 45 dBA corresponds to the distance range of 500 to 1500 m, so one would expect 30 dBA at 1500 m and 45 dBA at 500 m so the statement should read, "*are unlikely to cause any direct health effects at distances of more than 1500 m*".
- I do not agree that wind farm noise will be below 30 dBA at 1500 m. Of course it depends on the size and layout of the wind farm, individual turbine size, terrain and atmospheric conditions as well as distance to the nearest turbine. I have data taken in high wind shear conditions, when background noise levels are low, that show noise levels above 40 dBA at distances over 2000 m. I also have seen noise predictions made by acoustical companies working for wind farm developers that show estimated noise levels of 37 dBA at 1670 m. So the estimated noise levels given in the Draft Information Paper are way too low.
- Wind turbine noise does not have the same character as transportation noise. By the time it reaches residents located more than 1 or 1.5 km away, it has a much higher dominance of low frequency noise and infrasound. The A-weighted noise level underestimates the importance of low-frequency noise and infrasound (Salt and Lichtenhan, 2014) and it is incorrect to state that "*there is no evidence that health or health-related effects from wind turbine noise would be any different to those from other noise sources at similar levels*". This is because the level referred to here is the dBA or A-weighted level and this is not a good measure of the effects of environmental noise on health as it does not adequately take into account the effect of infrasound and low-frequency noise, nor does it account for variability or amplitude modulation associated with the noise.

Under the **Noise in other environments** heading in Section 7.2.2, the Draft Information Paper states, "*the noise in the studies discussed above would have included infrasound, which is considered by some to be an important component of the noise from wind farms. The infrasound from these other noise sources would be at similar levels to that from wind turbines. Therefore the evidence summarised above applies as much to infrasound as it does other sound frequencies from wind farms*." The effect of wind farm infrasound and low-frequency noise on people is a far more complex phenomenon than implied by the Draft Information Paper (see Salt and Lichtenhan, 2014).

The **laboratory studies** referred to in Section 7.2.2 of the Draft Information Paper are not relevant to wind farm noise. The studies involved higher level and much shorter exposure durations and neither the wind farm noise spectrum nor crest factors (ratio of peak to rms levels) were duplicated.

Comments on Section 6 of the Draft Information Paper

I have the following comments regarding section 6 on noise in the Draft Information Paper, which is directly in my area of expertise.

In **Section 6.1**, it is implied that the A-weighting scale adequately takes into account the lower sensitivity of the ear at low frequencies. However, the A-weighting scale is a very inaccurate estimate of the loudness of a noise at low levels and low frequencies. It is an even more inaccurate estimate of the annoyance of low-frequency sound. It is well known that low-frequency noise is more annoying than noise characterised by a balanced frequency spectrum with the same overall A-weighted level. Although the generation of wind farm noise may be characterised by a relatively well-balanced spectrum, by the time it propagates the 2 kilometres or so to a residence and then passes through walls and windows to reach the inside, it becomes dominated by low frequencies below 200 Hz, which are much less attenuated by ground, atmospheric and building transmission effects. Thus, wind farm noise is more annoying than one may expect from the A-weighted level, especially in quiet rural environments where noise from other sources is very low, and especially late at night and in the early hours of the morning when people are trying to sleep.

In **Section 6.1**, the Draft Information Paper states, "*Wind turbines produce mechanical sound at a frequency of 20–30 Hertz (for a 1500 kilowatt turbine) and a "whooshing" aerodynamic sound in the range of 200–1000 Hertz. Noise from wind farms is mostly aerodynamic*." This is an over-simplification and not quite right. Noise from modern wind turbines (which are now all 3 MW in size or greater for recent and proposed wind farms in Australia) is mainly aerodynamic in nature and covers the frequency range from below 1 Hz to 500 Hz. Although aerodynamic sound is also produced at higher frequencies, these higher frequencies do not propagate sufficiently well for this higher frequency sound to be detectable at residences located 2 or more kilometres away. Low frequency aerodynamic sound is mostly a result of in-flow turbulence and possibly stall (see Laratro et al. 2014). It has been suggested that stall noise becomes more significant when there are high levels of wind shear, such as in the early hours of the morning. It has been further suggested that this type of noise is what appears as a "thumping" noise (Oerlemans, 2013), which can be very annoying when one is trying to sleep. However, more research is needed to properly demonstrate the link between blade stall and thumping noise. Aerodynamic noise generated by in-flow turbulence is worse when turbines are located in hilly terrain and also when they are placed in the wake of other turbines. This latter situation occurs more often in wind farms where turbines are placed closer together than recommended by the manufacturer. In addition, it is not definitively known how much the aerodynamically generated vibration of the tower and blades contribute to the noise levels experienced at residential locations.

In **Section 6.1**, the Draft Information Paper states, "*It is difficult to estimate the level of noise from wind farms in the presence of background noise.*" This is true but it is not impossible if the wind farm operator cooperates by shutting the wind farm down at various times so background noise levels can be established.

In **Section 6.1**, the Draft Information Paper states, "*As the sound level decreases with distance, it is unlikely that substantial noise would be heard at distances of more than 500–1500 m from wind farms*." This is not correct. See the first two dot points on the previous page.

In **Section 6.1** the Draft Information Paper states, "*Infrasound is considered by some to be an important component of the noise from wind farms. Evidence suggests that levels of infrasound are no higher in environments near wind turbines than in a range of other environments. For example, a South Australian study observed similar levels of infrasound at rural locations close to wind turbines, rural locations away from wind turbines, and at a number of urban locations*." Wind turbine infrasound has very specific characteristics. Its frequency content is the blade pass frequency and its harmonics (usually around 0.8 to 1 Hz and multiples thereof, respectively). In addition it varies in intensity over a turbine blade revolution and also over longer time frames. The periodic nature of the noise means that it could possibly have a different effect on people than noise that is random in nature, such as other environmental infrasound. There are experts in this area (e.g. Salt and Lichtenhan, 2014) who have demonstrated that one does not need to be able to "hear" infrasound or low-frequency sound for it to have a physiological effect on some people, causing them to have similar symptoms to motion sickness. There is still much to be understood about the effects of low-level infrasound and low-level, low-frequency noise on people, as well as the effects of the infrasound frequency content and peak to average levels. There is a well-founded suggestion that increasing the exposure duration can also affect the response of a subject (Salt and Lichtenhan, 2014), as can the presence or absence of noise in the audio frequency range (Swinbanks, 2012). It is also possible that low-frequency sound can have similar effects to those attributed to infrasound (Salt and Lichtenhan, 2014). Much more work needs to be done on the effects of infrasound and low-frequency sound on people before any definitive statement can be made.

Considerations that Appendix B suggests I should have been asked to provide

In Appendix B, the Draft Information Paper states, "*Expert reviewers have been asked to consider a number of factors, including: the comprehensiveness of the literature reviewed; the validity of conclusions drawn from the evidence and any alternative conclusions that could be drawn*". This does not seem to agree with the review request that I received. To be consistent with what I was asked to comment on, the word "validity" in the above statement should be changed to "appropriateness". The request that I received did not ask if I could draw any alternative conclusions as mentioned in the above statement. I was also not asked to comment on the comprehensiveness of the literature reviewed. Assuming that I should have been asked to consider the factors outlined in Appendix B, I have the following comments.

- I do not consider that the literature reviewed was sufficiently comprehensive as it stopped before the end of 2012 and did not include references to many surveys of transportation noise which would have informed the current state of the art for noise surveys. In addition, a number of relevant papers have been published since November 2012 and these should be included in the review prior to it being finalised. The references listed in the papers under the heading "References" below should be reviewed. Also, no reason has been given for omitting series case studies from the review. There are a number of this sort of study that show a definite link between wind farm noise and health effects and if included in the review, may have resulted in the NHMRC arriving at a more balanced conclusion such as, "There is some evidence that wind farms can cause adverse health effects in nearby residents. However, more research is needed to properly quantify these effects."
- I believe that the conclusions drawn are written in a very unbalanced way that could suggest bias in favour of the wind farm industry. The conclusions are written in a way that implies that the NHMRC is already predisposed to believing that wind farms pose no threat of adverse health effects, even though the statements in Appendix C call for more research to be done in order to be able to provide a definitive answer. I have made many suggestions in the preceding paragraphs regarding how the conclusions could be written in a more balanced way.

Other General Comments

I could find no evidence of any effort in the systematic review to determine whether there was any source of bias by the authors of any of the seven studies that were deemed to have met the criteria. In cases where such studies are funded by the wind industry, it would not be surprising to find outcomes that suggest no adverse health effects, in a similar way that many early medical studies on the effects of smoking that were funded by the tobacco industry found no adverse health effects for smokers. Thus any studies funded by the wind farm industry should have been excluded due to the potential for bias.

In appendix C, there is the statement, "*Given the lack of objective health measurements in these studies, information bias cannot be excluded as an explanation for any apparent association*." This sort of statement in itself is unhelpful and insulting to all of the researchers who have undertaken these studies and found a link (either direct or indirect) between wind farms and health. The statement should be removed or at the very least changed to "*Given the lack of objective health measurements in these studies, information bias, **however unlikely it may be**, cannot be excluded as an explanation for any apparent association*."

Much is made of the need for longitudinal studies. Given the difficulty in undertaking such studies, it is surprising that nothing is mentioned about giving people with reported health problems 2 weeks holiday far away from any wind farm and checking their symptoms then. There are many reported cases where this sort of break has resulted in the cessation of symptoms and one would think this would be an acceptable alternative to a longitudinal study and in many cases it would clearly demonstrate the influence of the wind farm on a person's health.

In addition to the research areas discussed in Appendix C, research is needed to develop more accurate noise propagation models so that the expected range of noise levels over the entire frequency range can be accurately predicted at each residence likely to be affected. The single number A-weighted time averaged values provided by current models do not adequately relate to the disturbance of the noise. There are factors other than the noise level, such as crest factor (ratio of peak to average (or rms) noise level), frequency content, variability over the short and medium terms, difference between the intrusive noise level and ordinary background noise levels, especially at night, which determine how disturbing a noise will be. More research is also needed to establish suitable metrics that take into account the low-frequency nature and variability of the noise from wind farms that is experienced at residences (Salt and Lichtenhan, 2014).

In the Glossary, the definition for decibel is given as, "*A unit of measure used to express the loudness of sound, calculated as the logarithmic ratio of sound pressure level against a reference pressure*". This is incorrect. The decibel rating of a sound pressure is not a measure of loudness – the Phon measures loudness. So the words "*A unit of measure used to express the loudness of sound*" should be replaced with "A unit of measure used to express the sound pressure amplitude associated with a sound in the form of a more manageable logarithmic scale, in place of using the linear scale of Pascals. It is calculated……"

In the glossary, the definition of "A-weighting" is missing. It is a weighting applied to a measured sound pressure level that reduces the importance of low-frequencies and high-frequencies when calculating an overall sound pressure level. It is supposed to approximate the response of a normal ear but it does a very poor job of this.

There is no mention anywhere in the document of the effect of wind farm size (ie number of turbines), wind farm layout, terrain in the wind farm vicinity, atmospheric conditions (including wind shear) and the size of the individual turbines within a wind farm. All of these factors influence noise levels that will be experienced by communities in the vicinity of wind farms. Differences in these factors between some recent wind farms in Australia and wind farms studied in Europe mean that conclusions of earlier studies may not necessarily apply to more recently installed and planned wind farms in Australia.

It is unfortunate that the argument for further research and the suggested areas of further research are relegated to Appendix C, where it is unlikely that any policy makers will find it. Surely the conclusion that further evidence is needed "*to explore the relationships between noise at varying distances from wind farms and other health-related effects such as annoyance, sleep and quality of life*" should occupy a prominent place in the Information Paper. This should be included in an executive summary which unfortunately seems to be missing at the moment.

As stated by Nancy Timmerman and repeated by Salt and Lichtenhan (2014), "the time has come to acknowledge the problem and work to eliminate it".

References

Laratro, A., Arjomandi, M., Kelso, R. and Cazzolato, B. (2014). "A discussion of wind turbine interaction and stall contributions to wind farm noise." Journal of Wind Engineering and Industrial Aerodynamics, **127**, 1—10.

Moller, H and Pedersen, C. (2011). "Low-frequency noise from large wind turbines." Journal of the Acoustical Society of America, **129**, 3727—3744.

Phillips, C. (2011). "Properly interpreting the epidemiologic evidence about the health effects of industrial wind turbines on nearby residents." Bulletin of Science, Technology and Society, **31**, 303—315.

Pierpont, N. (2009). "Wind turbine syndrome: a report on a natural experiment." K-Selected Books, Santa Fe, New Mexico.

Oerlemans, S. (2013). "An explanation for enhanced amplitude modulation of wind turbine noise." In *Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect*, Work Package A1. Renewable Energy, U.K. www.RenewableUK.com

Salt, A. and Lichtenhan, J. (2014). "How does wind turbine noise affect people?" Acoustics Today, **10**, 20—27. Available from www.acousticstoday.org

Schomer, P. and Parmidighantam, P. (2013). "A critical analysis of: Wind turbine health impact study: Report of independent expert panel." Proceedings of the 166th meeting of the Acoustical Society of America, San Francisco, California, 2-6 December. Session 3aNS: Noise. Full paper published in Proceedings of Meetings on Acoustics, **20**, 040008. (2014).
See http://scitation.aip.org/content/asa/journal/poma/20/1/10.1121/1.4870639

Swinbanks, M. (2012). "Numerical simulation of infrasound perception with reference to prior reported laboratory effects." In *Proceedings of Internoise 2012*, New York.

World Health Organisation. (2009). Night noise guidelines for Europe. WHO. Available from www.euro.who.int/__data/assets/pdf_file/0017/43316/E92845.pdf

Low-frequency noise from large wind turbines

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Published in:
The Journal of the Acoustical Society of America

DOI (link to publication from Publisher):
10.1121/1.3543957

Publication date:
2011

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Møller, H., & Pedersen, C. S. (2011). Low-frequency noise from large wind turbines. The Journal of the Acoustical Society of America, 129(6), 3727-3744. DOI: 10.1121/1.3543957

Low-frequency noise from large wind turbines

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(Received 5 July 2010; accepted 20 December 2010)

As wind turbines get larger, worries have emerged that the turbine noise would move down in frequency and that the low-frequency noise would cause annoyance for the neighbors. The noise emission from 48 wind turbines with nominal electric power up to 3.6 MW is analyzed and discussed. The relative amount of low-frequency noise is higher for large turbines (2.3–3.6 MW) than for small turbines ($\leq$ 2 MW), and the difference is statistically significant. The difference can also be expressed as a downward shift of the spectrum of approximately one-third of an octave. A further shift of similar size is suggested for future turbines in the 10-MW range. Due to the air absorption, the higher low-frequency content becomes even more pronounced, when sound pressure levels in relevant neighbor distances are considered. Even when A-weighted levels are considered, a substantial part of the noise is at low frequencies, and for several of the investigated large turbines, the one-third-octave band with the highest level is at or below 250 Hz. It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbors.
 [DOI: 10.1121/1.3543957]

PACS number(s): 43.50.Rq, 43.28.Hr, 43.50.Cb, 43.50.Sr [ADP] Pages: 3727–3744

I. INTRODUCTION

Wind turbines get larger and larger, and worries have emerged that the noise emitted by the turbines would consequently move down in frequency and that the content of low-frequency and infrasonic noise would increase and reach a level, where it may be annoying for the neighbors. The daily press frequently reports on rumbling and annoying noise from large wind turbines, and it is often claimed that it propagates quite far. However, the scientific literature on infrasonic and low-frequency noise from large wind turbines is more limited.

A. Low-frequency sound and infrasound

A few introductory words about low-frequency sound and infrasound are appropriate. For a more comprehensive review of human hearing at low and infrasonic frequencies, see, e.g., Ref. 1.

It is usually understood that the lower limit of the human hearing is around 20 Hz, and the terms *infrasound* and *infrasonic* are used with frequencies below this frequency. The frequency range 20–200 Hz denotes the *low-frequency* range (sometimes with a slightly different upper limit).

However, as a surprise to many people, the hearing does not stop at 20 Hz. If the level is sufficiently high, humans can hear infrasound at least down to 1 or 2 Hz. The sound is perceived through the ears, but the subjective quality differs from that of sound at higher frequencies. Below 20 Hz, the tonal sensation disappears, the sound becomes discontinuous in character, and a sensation of pressure at the eardrums occurs. At a few hertz, the sensation turns into discontinuous separate puffs, and it is possible to follow and count the single cycles of a tone.

At low and particularly infrasonic frequencies, the loudness increases more steeply above the hearing threshold than at higher frequencies,[2–5] and a sound moderately above threshold may be perceived not only loud but also annoying.[6–9] Since there is a natural spread in hearing thresholds, a sound that is inaudible or soft to some people may be loud and annoying to others. Low-frequency noise above the hearing threshold may also affect task performance[10] and cause sleep disturbances.[11] There is no reliable evidence of physiological or psychological effects from infrasound or low-frequency sound below the hearing threshold (see, e.g., Ref. 12).

Infrasound is measured with the G-weighting curve,[13] which covers the frequency range 1–20 Hz. At the normal hearing threshold for pure tones,[2,8,14–17] the G-weighted level is in the order of 95–100 dB. G-weighted sound pressure levels below 90 dB[13] or 85 dB[18] are normally not considered to be detectable by humans.

B. Previous studies

Many studies deal theoretically with generating mechanisms of low-frequency noise in wind turbines, whereas original information on low-frequency noise from complete wind turbines is more limited. In the following, only horizontal-axis turbines are considered.

Hubbard and Shepherd[19,20] reviewed the literature on wind turbine noise especially emphasizing studies carried out at NASA for more than two decades and comprising turbines up to 4.2 MW. It was observed and explained by numerical models that harmonics of the blade-passage frequency arise from differences in the inflow wind velocity across the rotor area and, for turbines with the rotor downwind of the tower, from impulses created by the passage of the blades through the wake of the tower. In particular, the

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latter mechanism is responsible for high levels of discrete-frequency noise in the infrasonic and low-frequency region for downwind turbines. Also "broadband" (stochastic or continuous-spectrum) noise is generated at low and infrasonic frequencies due to turbulence in the inflow. Inflow turbulence is the main reason for broadband noise below some hundred hertz. Propagation of sound from the turbines was also studied, and it was observed and explained by atmospheric refraction that downwind propagation of low frequencies (exemplified with 8–16 Hz) was cylindrical from a certain distance rather than spherical as normally assumed in noise prediction. This means that the level decreases by 3 dB per doubling of distance rather than 6 dB. Room resonances and low sound insulation of houses at low frequencies were used to explain that wind turbine noise is sometimes perceived more readily indoors than outdoors. The infrasonic part of the spectrum was below the normal hearing threshold in all investigated cases of complaints, but it was said to cause perceptible vibrations and rattling of windows and wall-mounted objects, which contributed to negative reactions to wind turbine noise. Using some of the same turbines as examples, Guidati *et al*.[21] showed that the interaction of the blades with the tower also creates impulsive infrasonic and low-frequency noise for upwind turbines, however, considerably less than for downwind turbines.

Legerton *et al*.[22] measured noise from two 450 kW turbines at a distance of 100 m. The levels reported for the one-third-octave bands up to 20 Hz are much below the normal hearing threshold for pure tones, while the levels in the 31.5-Hz band are just below the threshold.

Betke *et al*.[23] and Betke and Remmers[24] presented a technique to reduce wind noise in measurements of low-frequency noise from wind turbines. They used two microphones mounted in the ground with a distance of 10 m and a cross-correlation technique. At a distance of 200 m from a 500 kW wind turbine, the frequency spectrum seemed to be continuous when calculated with a very fine frequency resolution, however, with peaks at the blade-passage frequency and its harmonic. The G-weighted sound pressure level at this distance was 63.9 dB.

Jakobsen[25] reviewed data from the studies mentioned in the previous three paragraphs and sought further information in original measurement reports and by contact to the authors. He estimated the G-weighted levels for ten turbines in the range 50 kW–4.2 MW and found that levels from upwind turbines were around 70 dB or lower at a distance of 100 m, whereas levels from downwind turbines were about 10–30 dB higher. It was concluded that, even close to upwind turbines, indoors as well as outdoors, the G-weighted level would be below the limit of 85 dB given in the Danish guidelines for low-frequency and infrasonic noise[18] (summarized in English by Jakobsen[26]). For downwind turbines, this limit might be exceeded at distances up to several hundred meters. On the other hand, levels of infrasound even from downwind turbines were too low to explain complaints reported in the original studies at distances up to 2 km. In an attempt to find an alternative explanation, Jakobsen estimated the indoor A-weighted levels for the 10–160 Hz frequency range, a measure used by the Danish guidelines for the low-frequency range. The recommended evening/night limit of 20 dB for dwellings was exceeded in all cases but one. On the other hand, in those cases, normal outdoor A-weighted levels were also high enough to explain the complaints (47–61 dB), so it is not possible to tell, if the complaints were caused by the normal noise or the low-frequency noise. (Jakobsen erroneously referred to the Danish evening/night limit as 25 dB.)

Van den Berg[27] noted that the blade passage in front of the turbine tower gives rise to noise in the infrasonic range, but more important, to modulation of noise at higher frequencies perceived as swishing. In a stable atmosphere, which often exists at night, the difference in wind speed between top and bottom of the rotor is much higher than at other times, and this increases the modulation and changes the swishes to "clapping, beating, or thumping." For a wind farm with 17 turbines of each 2 MW, this was heard clearly at distances at least up to 1 km. Measurements were made at night, 100 m from each of two of the turbines as well as 750 m from the nearest row of ten turbines. One-third-octave-band levels up to 20 Hz were much below the normal hearing threshold, even for the closest measurements. Levels were above the normal hearing threshold [ISO 389-7 (Ref. 28)] from 31.5 to 40 Hz and up, even at 750 m.

Pedersen and Møller[29] analyzed indoor low-frequency and infrasonic noise in four houses near one or more wind turbines (0.6–2.75 MW) with distances to the closest turbine of 90–525 m. There were no audible harmonics of the blade-passage frequency, but audible components existed in the low-frequency range, in several cases with some amount of tonal character. G-weighted levels were 65 dB or lower, i.e., much below the normal hearing threshold, and it was concluded that infrasound would not give rise to nuisances. A-weighted levels for the 10–160 Hz frequency range were around or below the Danish evening/night limit for dwellings of 20 dB.[18] The highest levels observed were with a low wind speed (6.6 m/s) but closer to a turbine than people would normally live (90 m) or further away (325 m) in the only measurement that was made at a higher wind speed (9.4 m/s). The measurements were made according to the method in the Danish guidelines, however, without a complainant to appoint measurement positions, where the noise was loudest, which is important in the method.[18] Measurements were not in general corrected for background noise, but substantial effort was undertaken to analyze only periods without disturbances. Additional measurements in two of the houses suggested that people might be exposed to higher levels at other places in the room than measured with the official method. The study was inconclusive regarding the low-frequency noise and was part of the motivation for the present project.

The Hayes Mckenzie Partnership Ltd. consultancy[30] measured infrasound at a distance of 360 m downwind from a wind farm with twelve 1.65 MW turbines. With wind speeds up to 20 m/s, G-weighted levels were up to 80 dB. In another part of the study, low-frequency noise was measured in three houses, where the inhabitants had complained of low-frequency noise from wind farms with 3–16 turbines. Turbine size and distance to the wind farm were only reported for one of the cases (three 1.3 MW turbines, distance 1030 m). It was concluded that, for the 10–160 Hz range, levels are below the criteria proposed by Moorhouse *et al*.[31,32] for the UK Department for Environment, Food, and Rural Affairs (DEFRA), as well as the Danish 20-dB criterion.[18] Nevertheless, the data show that both limits were indeed exceeded in two of the three houses. In one house, this happened occasionally until the microphone was moved to another position in the room. It was argued that, in the first position, the microphone picked up sound from a nearby stream rather than from the turbines. The present authors are skeptical about the idea that moving of the microphone within the same room would reduce low-frequency sound and infrasound from the stream but not from the wind turbines. Both the UK and the Danish guidelines specify the noise to be measured, where it is loudest, and it is not possible to verify from the data, whether the sound in the first position (or both positions) was dominated by sound from the stream. In the second house, complaints were only reported two times during the measurement period, and both the UK and the Danish limits were exceeded at one of these occasions. A window was open at both occasions, and it was said that both sets of guidelines require windows to be closed during measurements. This is not correct, though. The UK documents do not have instructions on window settings during measurements but require extensive questioning of the annoyed person about conditions during annoyance, and it is logical to assume that measurements should be carried out under the same conditions. The Danish guidelines note specifically that measurements should be made with open windows, if the complainant finds that the noise is louder in this condition.

Jakobsen[33] used the apparent sound power (mainly at 8 m/s) from ten turbines in the 850 kW–3 MW range to calculate sound pressure levels at distances of 200–800 m. Outdoor and indoor A-weighted levels for the 10–160 Hz frequency range were derived; the indoor levels were derived by means of sound insulation data used in the Danish regulation for low-frequency noise from high-speed ferries.[34] It was concluded that indoor A-weighted levels for the 10–160 Hz range would not exceed the Danish 20-dB evening/night limit,[18] unless the outdoor A-weighted level for the full frequency range exceeds 45 dB. However, this is not what the data show. With an outdoor level just below 45 dB, indoor levels are above 20 dB in approximately half of the calculated cases. It was argued that insulation measurements of town houses (unpublished data) had shown better sound insulation than the buildings used in the background material for the regulation of noise from high-speed ferries.[35]

Lee *et al*.[36] and Jung *et al*.[37] measured noise from two upwind turbines of respectively 660 kW and 1.5 MW. The A-weighted noise increased with wind speed for the 1.5 MW turbine, whereas it was fairly constant over most of the operating range for the 660 kW turbine. The two turbines were respectively stall and pitch controlled, and the lack of increase in A-weighted noise at higher wind speeds was said to be typical for pitch-controlled turbines and to be one reason for favoring this type of control with large turbines. The infrasonic frequency range was dominated by the blade-passage frequency and its harmonics, and the level increased with increasing wind speed for both turbines. Worries were expressed that infrasound and low-frequency noise would become a problem with modern turbines, where the pitch control limits the A-weighted noise but not the low-frequency and infrasonic noise. It was concluded that the low-frequency part of the noise from both turbines is audible for an average person and would probably lead to complaints, and that the infrasonic part might cause complaints due to rattling noise, e.g., from windows. The distance to the turbines for this conclusion was not reported, but it can be derived from other data in the article that it must have been quite close, in the order of 70–100 m.

Gastmeier and Howe[38] measured the indoor noise at a distance of 325 m from the closest of several 1.8 MW turbines. The wind speed was 5 m/s. The level was said to be at least 30 dB below the normal hearing threshold (from Watanabe and Møller[17]) at all frequencies below 20 Hz. The figure in the article erroneously compared narrow-band levels with pure-tone hearing thresholds, but the present authors estimate that there is nevertheless a fair margin up to the threshold.

Ramakrishnan[39] measured noise close to a single 660-kW turbine and close to a single turbine in a wind farm with more than 50 turbines of each 1.5 MW. G-weighted levels were around 70 dB in both cases.

Harrison[40] noted that since inflow turbulence is essential for low-frequency noise emission, more focus should be on control of turbulence during measurements and predictions. A specific issue is that turbulence is increased in the wake of wind turbines, and this is not taken into account during measurements of noise emission, which are made with single turbines. Barthelmie *et al*.[41] showed that turbulence is markedly increased at distances up to at least four times the rotor diameter. Wake turbulence may thus be important for the emission of low-frequency noise from wind parks.

1. Summary of previous studies

The above studies have used a variety of methods, and most data cannot be compared directly. None of the studies investigated systematically the development of low-frequency and infrasonic noise with turbine size. Some of the studies lack basic information such as information on the turbine(s), measurement distance, direction and height, wind speed, analysis bandwidth, background noise, sound insulation when indoor measurements were made, etc. Nevertheless, it seems possible to make some conclusions.

The passage of the blades through areas of varying wind speed and density modulates the sound at higher frequencies with the blade-passage frequency but also creates infrasonic and low-frequency components. The differences in wind speed and density stem from the varying height above ground, atmospheric turbulence, and the presence of the turbine tower. Noise from the turbine mechanics may also play a role. The modulation of sound at higher frequencies may, due to the low modulation frequency, erroneously be interpreted as infrasound.

For upwind turbines, the level of infrasound is much below the normal hearing threshold, even close to the turbine. On downwind turbines, the passage of the blades through the wake of the tower generates infrasound that may exceed the normal hearing threshold close to the turbine and possibly cause rattling of, e.g., windows even in relevant neighbor distances. Most modern turbines, but not all, are upwind turbines.

For the low-frequency range, results are less conclusive. Indications diverge between studies, and it is not possible from the above to conclude, to which extent low-frequency noise from wind turbines is responsible for nuisances. The answer likely depends on turbine, distance, atmospheric conditions, being indoors or outdoors, etc.

At this place, it is appropriate to mention that, in addition to original studies, a substantial amount of summaries, reviews, white books, information folders, web pages, etc. exist on low-frequency noise and infrasound from wind turbines. Many of these have been made by organizations working keenly against or in favor of wind turbines, and unfortunately, many expositions are of doubtful quality. At some places, a variety of effects and symptoms are reported to be due to infrasound or low-frequency sound without any evidence of the causal relationship. Infrasound and low-frequency sound are often not properly distinguished, and, as a peculiar consequence, low-frequency noise is frequently rejected as the cause of nuisances, just because infrasound can be discarded (usually rightfully as seen in the above). Infrasound is (still) often claimed inaudible, and sometimes even low-frequency noise, or it is reported that both can only be heard by especially sensitive people—which is all wrong. Weighting curves are misunderstood or (mis)used to give the impression of dramatically high or negligibly low levels. Sometimes, political utterances (from both sides) are disguised as scientific contributions.

C. Outline of study

The present project was carried out in cooperation with Delta, a consultancy and official acoustics laboratory for the Danish environmental protection agency. Noise from four large turbines was measured, noise data for 44 other small and large turbines were aggregated, and low-frequency sound insulation to exterior sound was measured for ten rooms in normal living houses. Measurements and data aggregation were carried out by Delta.[42–45] In this article, the data from the project are used to examine the connection between emitted sound power and turbine size. Source spectra are analyzed and discussed, and, in particular, the hypothesis that the spectrum moves toward lower frequencies for increasing turbine size is investigated. Outdoor and indoor spectra at relevant neighbor distances are analyzed and discussed.

II. METHODS

A. Wind turbines

Forty-eight wind turbines were included in the project. Four prototype turbines with nominal electric power above 2 MW were measured by Delta as part of the project (turbines 1–4), while data for seven other turbines above 2 MW were taken from measurements made by Delta outside the project (turbines 5–11).[42,43] Data for 37 turbines with nominal power at or below 2 MW were taken from previous measurements made by Delta.[44] Among the small turbines, a few physical turbines appear more than once, representing the turbine measured at different occasions. All turbines were three-bladed with the rotor placed at the upwind side of the tower.

B. Emitted sound power

The sound power emitted from the turbines was measured in accordance with IEC 61400–11.[46] The principle of this standard is to measure the sound on a reflecting board placed on the ground beneath the turbine at a horizontal distance approximately equal to the turbine's total height. The measured sound pressure level is converted to the sound power level of an imaginary point source at the rotor center that would radiate the same sound in the direction, where the measurement is made. The result is denoted as the *apparent sound power level*, where "apparent" emphasizes that it is not the true sound power but the power as "seen" in the measured direction.

Apparent sound power level was determined for one-third-octave bands and as total A-weighted level, L_{WA}. In addition, a special low-frequency measure, L_{WALF}, the apparent A-weighted sound power level for the one-third-octave bands 10–160 Hz was derived. A-weighted sound pressure levels for this frequency range, L_{pALF}, are used by the Danish guidelines for low-frequency noise.[18]

Data were obtained for all turbines in the downwind direction, denoted the *reference direction*, at a wind speed of 8 m/s (10 m above ground). This wind speed is often used in noise regulations, and most analyses in the present article are made for this. Turbines 1–4 were also measured at various other wind speeds. For evaluation of the content of pure tones, tonal audibility, ΔL_{ta}, was determined for turbines 1–4, and to get some insight into a possible directional pattern of the sound radiation, turbines 1–3 were measured at $\pm 60°$ to the sides of the reference direction and in the upwind direction, still at the ground. All turbines were measured in the required frequency range of the standard, 50 Hz to 10 kHz, and most turbines were measured down to 31.5 or 25 Hz. Turbines 1–4 were measured down to 4 Hz.

C. Outdoor sound pressure levels at neighbors

Free-field sound pressure levels, L_p, for downwind neighbor positions were calculated according to the method given by ISO 9613–2,[47] except that one-third-octave bands were used instead of octave bands.

The direction to neighbors is more horizontal than the direction, in which the apparent sound power level was measured, but in lack of more precise information, the sound power level plus directivity factor, $L_W + D_C$, was replaced by the apparent sound power level, L_{WA}, for the reference direction. The attenuation due to atmospheric absorption, A_{atm}, was calculated using data from ISO 9613–1[48] for 10 °C and a relative humidity of 80 %. The "attenuation" due to ground effects, A_{gr}, was set to -1.5 dB, meaning that 1.5 dB is added to the direct sound from the turbine. The two remaining terms of ISO 9613–2 (attenuation due to a barrier A_{bar} and to miscellaneous A_{misc}) were set to zero. If the slant distance from rotor center to the observation point is denoted as d and the attenuation constant is α

$$L_p = L_{WA} - 20\ \mathrm{dB} \cdot \log_{10}\left(\frac{d}{1\ \mathrm{m}}\right) - 11\ \mathrm{dB} - \alpha \cdot d + 1.5\ \mathrm{dB}. \quad (1)$$

This calculation corresponds to the one used in the Danish regulation of noise for wind turbines.[49]

D. Sound insulation

In order to allow calculation of low-frequency noise indoors, the low-frequency sound insulation was measured for ten rooms, two rooms in each of five normal living houses.[45]

The house was exposed to sound from a loudspeaker placed on the ground and directed toward the facade of the house at a horizontal angle of incidence around 45° at the center of the facade. The perpendicular distance from the loudspeaker to the wall was at least 5 m. The loudspeaker was supplied with broadband noise, low-pass-filtered at 250 Hz and equalized to compensate for the loudspeaker response. Outdoor sound pressure levels were measured at the facade at a vertical level approximately 1.5 m above the floor level of the receiving room. *Free-field sound pressure levels* were obtained by subtracting 6 dB from the measured levels. The outdoor setup and measurements share elements with the various methods of ISO 140–5,[50] but no single method is complied with as a whole.

At low frequencies, indoor levels may vary considerably within a room, and there is a general understanding that, for assessment of noise impact, measured levels should reflect high-level areas rather than the room average (see, e.g., Refs. 51–53). To fulfill this, *indoor sound pressure levels* were obtained as the power average of measurements in four arbitrary three-dimensional (3D) corners, i.e., where the floor or ceiling meets two walls. Corners close to possible concentrated transmission paths (e.g., ventilation ducts, windows, or doors) were avoided, though, and the selected corners were to represent all surfaces. Pedersen *et al*.[53] have shown that this method gives a good estimate of the level that is exceeded in 10 % of the room, i.e., close to the room maximum, but avoiding levels that only exist in a small part of the room.

The suitability of the 3D-corner method to estimate the maximum level that people would normally be exposed to in a room is supported by data from Brunskog and Jacobsen,[54] who simulated 100 room/frequency combinations, each with two different reverberation times. They found that the 3D-corner method hits quite centrally a target defined as the maximum level of the room, excluding positions closer to the walls than 1 m (mean error below 1 dB, standard deviation of the error 3–4 dB depending on reverberation time).

The *sound insulation* was measured for one-third-octave bands in the frequency range 8–200 Hz, and it was calculated as the difference between outdoor free-field sound pressure level and indoor sound pressure level.

Additional indoor measurements were made in an attempt to use a method given by the Danish guidelines for low-frequency noise.[18] The method specifies two measurements in areas of the room, where persons would be exposed to sound during normal use of the room (with certain geometrical restrictions) and one measurement near a room corner (0.5–1.0 m from the walls, 1.0–1.5 m above the floor). Measurements were carried out in positions complying with this. However, the method is meant for use in cases of noise complaints, and the two non-corner positions should be positions, where the complainant perceives the noise as being loudest. Without a complainant and without the actual annoying noise, it was not possible to fulfill this. Therefore, even when the geometrical conditions of the method were fulfilled, the measurements did not comply with the method as a whole, and the results are not reported. It must be concluded that the method is unsuitable for measurements of sound insulation, unless some kind of search for maximum level is added to the procedure.

E. Indoor sound pressure levels at neighbors

Indoor sound pressure levels were obtained by subtracting the sound insulation from the outdoor free-field sound pressure levels, both in one-third-octave bands.

F. Statistical methods

Differences were tested in Student's *t*-tests. The highest *p*-values considered significant and reported are 0.05. In two-sample tests, equal variance was not assumed for the two samples, thus the Welch's adaptation of the *t*-test and the Welch-Satterthwaite degrees of freedom (d.f.) were used. One-sided tests were used, whenever the hypothesis contains a specific direction of the possible difference, whereas two-sided tests were used elsewhere. As an example, the hypothesis that the spectrum moves down in frequency for increasing turbine size implies that the relative levels for large turbines are higher at low frequencies and lower at high frequencies. Consequently, one-sided tests were used at low and high frequencies, whereas two-sided tests were used in the intermediate frequency range, chosen as 315–1600 Hz.

III. RESULTS AND DISCUSSIONS

Three turbines, one at 1650 kW and two at 2.3 MW, were added to the material at a late stage, and one-third-octave data are not available for these, thus only L_{WA} and L_{WALF} are reported. Twenty-hertz high-pass filters had unfortunately been inserted during some of the measurements (reference, left, and right directions for turbine 1 and reference direction for turbine 3), so, before data processing, the effect of these filters was counteracted by subtracting the filter response from the measured levels in the affected frequency range. High-frequency electrical noise from the frequency converter affected some of the measurements at frequencies above 5 kHz, and data for turbines 1–4 are

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thus not reported at these frequencies. Some inconsistencies exist in the data given by Delta in different reports, tables, and figures. The results in the present article are based on the least processed data reported, which with few exceptions means emitted sound power levels in one-third-octave bands.

A. Emitted sound power

1. L_{WA} and L_{WALF}

Figure 1 shows L_{WA} and L_{WALF} for all turbines as a function of turbine size. The horizontal axis is logarithmic to match the vertical decibel axis, which is inherently logarithmic. Simple power relations between emitted acoustic power and nominal electric power of the turbine will thus correspond to straight lines, and regression lines are included in the figure.

It is—not surprisingly—seen that both L_{WA} and L_{WALF} increase with increasing turbine size. It is also noted that L_{WALF} increases more steeply than L_{WA}, meaning that the relative amount of low-frequency noise increases with increasing turbine size. The difference in slope of the regression lines for all data (thin lines) is statistically significant ($t = 3.94$, d.f. $= 90.0$, one-sided $p < 0.001$). Since the four smallest turbines may not be representative for modern turbines, regression lines have also been calculated without these turbines (bold lines). The slopes are slightly higher than with all turbines included, and the difference is smaller but still statistically significant ($t = 1.82$, d.f. $= 79.8$, one-sided $p = 0.036$).

The relative amount of low-frequency noise can be expressed as $L_{WALF} - L_{WA}$, and a linear regression of this yields a significant positive slope with all turbines included ($t = 5.42$, d.f. $= 46$, one-sided $p < 0.001$) as well as with the four smallest turbines removed ($t = 2.54$, d.f. $= 42$, one-sided $p = 0.007$).

It is also seen in Fig. 1 that there is some variation between turbines of the same size. As mentioned in Sec. II A, turbines of the same size may be of the same or different make and model, or, for a few turbines below 2 MW, the same physical turbine measured at different occasions.

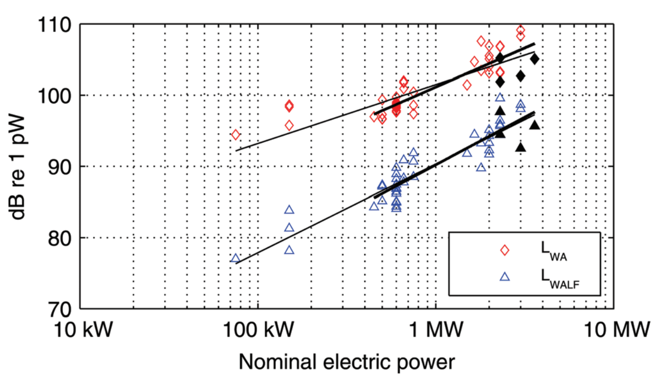

FIG. 1. (Color online) Apparent sound power levels (L_{WA} and L_{WALF}) in the reference direction as a function of turbine size. Wind speed is 8 m/s. Regression lines: all turbines included (thin lines), four turbines below 450 kW excluded (bold lines). Black-filled marks are for turbines 1–4.

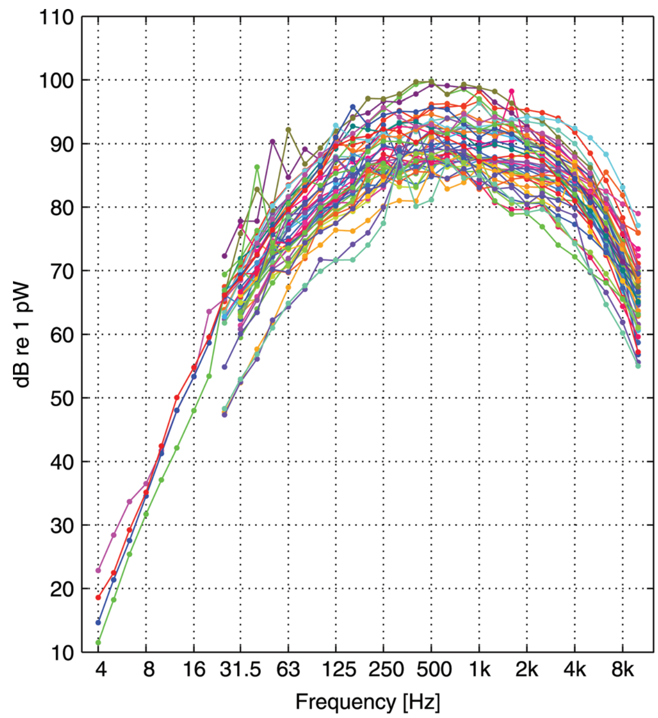

FIG. 2. A-weighted apparent sound power levels in one-third-octave bands. Forty-five turbines with nominal electric power 75 kW–3.6 MW.

2. One-third-octave-band spectra

Apparent sound power levels for one-third-octave bands are shown in Fig. 2.

Regarding the infrasonic part of the spectrum, the G-weighted[13] apparent sound power levels, calculated from the levels in the one-third-octave bands up to 20 Hz, are 122–128 dB for the four turbines, where data is available. Even close to the turbines, e.g., in a distance of 150 m from the rotor center, this will only give G-weighted sound pressure levels of 69–75 dB, which is far below the normal threshold of hearing.[1] This calculation does not account for possible near-field phenomena, e.g., from a closely passing blade.

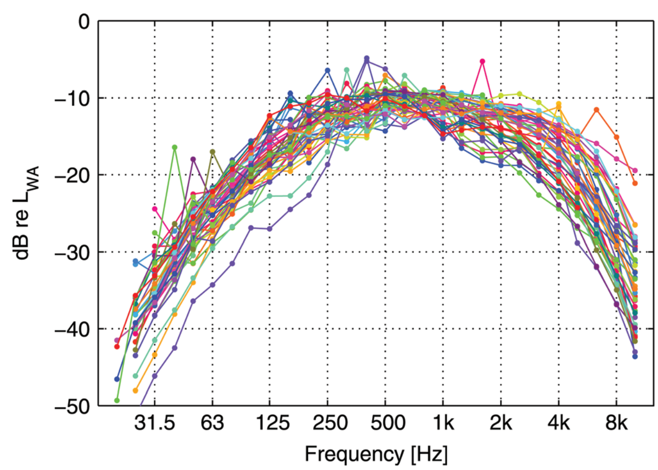

FIG. 3. Normalized A-weighted apparent sound power levels in one-third-octave bands. Forty-five turbines with nominal electric power 75 kW–3.6 MW. (Normalized meaning that L_{WA} for the individual turbine has been subtracted from all one-third-octave-band levels.)

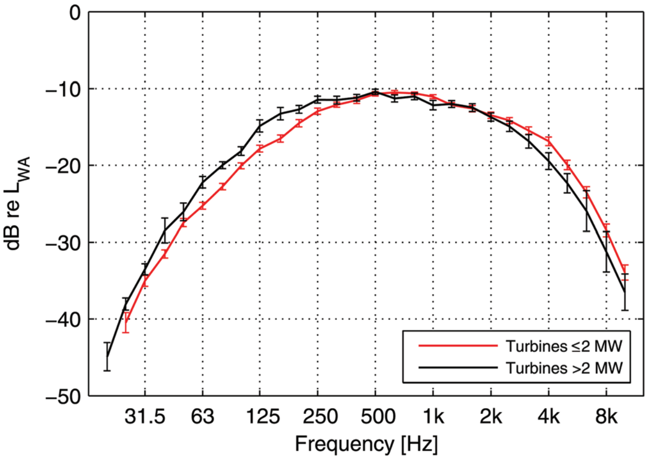

FIG. 4. (Color online) Normalized A-weighted apparent sound power levels in one-third-octave bands, means of two groups of turbines: ≤ 2 MW and > 2 MW. Error bars indicate ± 1 standard error of mean.

At frequencies where data are available for all turbines, the level varies between turbines by 20 dB or more. This is to be expected since the turbines cover a wide range of nominal electric power. In order to show possible spectral differences between turbines more clearly, the one-third-octave-band levels of all turbines have been normalized to the individual turbine's total A-weighted sound power level, L_{WA}. The result is shown in Fig. 3.

A possible difference in spectrum between small and large turbines is investigated by dividing the turbines into two groups: turbines up to and including 2 MW and turbines above 2 MW. Figure 4 shows the mean and the standard error of mean for each of the two groups.

The spectrum of the large turbines lies clearly lower in frequency than that of the smaller turbines. The level difference is significant for all one-third-octave bands in the frequency range 63–250 Hz and at 4 kHz [$t = (3.49, 4.52, 2.81, 3.27, 3.49, 2.63, 2.52, -2.10)$, d.f. = (14.3, 22.1, 17.0, 13.5, 13.6, 23.8, 22.6, 12.5), one-sided $p = (0.002, <0.001, 0.006, 0.003, 0.002, 0.007, 0.010, 0.028)$]. If the four smallest turbines are discarded, the difference is significant at the same frequencies plus 5 kHz [$t = (2.94, 4.09, 2.22, 2.76, 2.97, 1.93, 1.83, -2.07, -1.93)$, d.f. = (11.7, 18.0, 14.5, 11.1, 11.6, 18.7, 20.1, 12.9, 11.7), one-sided $p = (0.006, <0.001, 0.022, 0.009, 0.006, 0.035, 0.041, 0.030, 0.039)$].

The significant differences between small and large turbines are at moderate 1.5–3.2 dB, but as mentioned in the introduction (Sec. I A), at low frequencies, even small differences may affect human perception of the sound. In addition, if low frequencies have a notable impact on requirements of distance to the neighbors, small differences may have large impact on the needed distance.

Figure 5 shows the mean of turbines up to and including 2 MW and individual turbines above 2 MW.

The large turbines lie above the mean of the smaller turbines in virtually every single one-third-octave band below 315 Hz. Some of the turbines have a peak in one or more one-third-octave bands, which may be due to the presence of tonal components. Tones are likely to have their origin in the turbine mechanics, e.g., the gearbox or secondary equipment such as a generator cooling system (see e.g., Wagner *et al.*[55]).

At high frequencies, the picture is disturbed by an atypical pattern above 2 kHz for turbine 6. There is no other data available from this turbine, for example, for another wind speed or another direction, which could be used to verify that this is really noise from the turbine and not electrical noise as with some other turbines (see introductory remarks of Sec. III). If turbine 6 is disregarded at these frequencies, the large turbines lie at or below the mean of small turbines in virtually every one-third-octave band above 2 kHz. The difference between means of the two groups is then significant for all one-third-octave bands in the 2.5–10 kHz range [$t = (-1.83, -2.49, -3.47, -3.18, -2.42, -2.76, -2.64)$, d.f. = (15.2, 15.6, 14.5, 14.8, 4.1, 4.6, 6.3), one-sided $p = (0.044, 0.012, 0.002, 0.003, 0.036, 0.022, 0.018)$].

3. Tonality

The tone analyses show that tones generally vary in level and frequency with wind speed. Figure 6 shows tonal audibility for the most prominent tones of turbines 1–4.

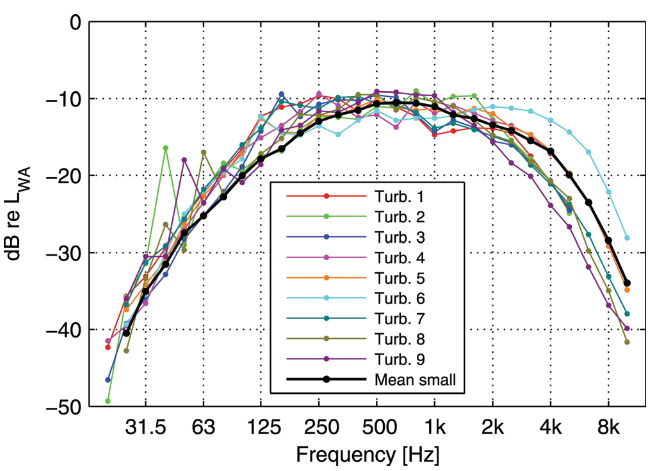

FIG. 5. Normalized A-weighted apparent sound power levels in one-third-octave bands, mean of 36 turbines ≤ 2 MW (bold line) and 9 individual turbines > 2 MW.

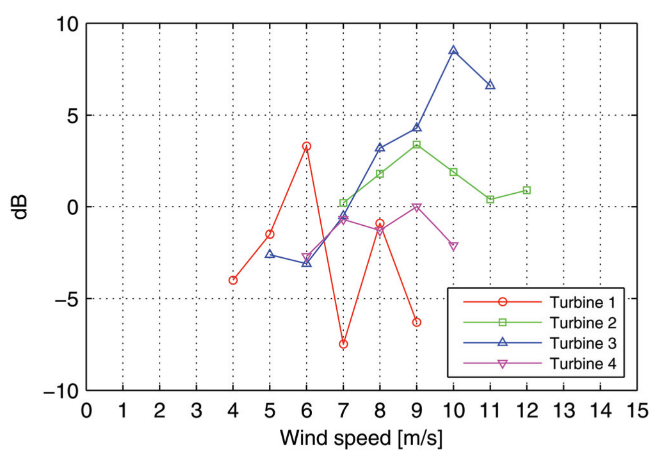

FIG. 6. (Color online) Tonal audibility, ΔL_{ta}, as a function of wind speed for turbines 1–4, reference direction (turbine color code as in Fig. 5).

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Values are below 3–4 dB, except for turbine 3 at high wind speeds. For turbines 1 and 3, the data apply to a tone that varies with wind speed around 110–145 Hz, approximately the same frequency range for both turbines. For turbine 2, the data apply to a tone with a nearly constant frequency around 40 Hz. Turbine 4 has several tones at higher frequencies, and those in the frequency range 800–1400 Hz alternately dominate, depending on wind speed. One-third-octave-band peaks can be identified in Fig. 5 for the two turbines with tonality above 0 dB at 8 m/s (turbine 2, 40 Hz; turbine 3, 160 Hz).

ISO 1996–2 (Ref. 56) specifies a tone penalty to be used, when the tonal audibility exceeds 4 dB. National criteria for tone penalty may vary, e.g., Danish regulation requires that the tonal audibility exceeds 6.5 dB, before a penalty is given.[57]

Only one turbine exceeds the 4 dB limit and only at high wind speeds, where noise regulation may not apply. It is quite surprising that not even the most distinct tone in the one-third-octave-band spectra, the 40-Hz tone of turbine 2, results in a tone penalty. This is most likely an effect of the critical band used for tone assessment being very wide at low frequencies. It is outside the scope of the present article to evaluate if the tones will be perceived as being tonal despite the lack of tone penalty.

4. Directivity

Figure 7 shows the directivity of the three turbines measured.

The data differ somewhat between turbines, and it is difficult to find a general pattern. Both higher and lower levels are seen in other directions than the reference. At the lowest frequencies, a low directivity would be expected, but this is not seen in the data. A measured directivity may reflect a true directivity, but if the main noise source is at one side in the rotor plane, e.g., at the down going blade as shown by Oerlemans and Schepers[58] and Oerlemans *et al.*[59] the measurement in this side is closer to the source, and a false indication of directivity may result.

A possibly source of error for the directivity data is that the measurements for the various directions do not always refer to the same period. Each of the other directions was in fact measured together with the reference direction, but they were not all measured at the same time. Only one data set exists for the reference direction, and thus this cannot apply to all directions. At low frequencies, poor signal-to-noise ratio may be responsible for large uncertainty.

The direction from the turbine to neighbors is typically more horizontal than the direction to the measurement positions. In particular, if sound is radiated from synchronous vibrations in blades and/or tower, chances are that the radiation will be more perpendicular to the rotor plane and/or the tower, i.e., close to the horizontal plane. More knowledge is called for on this issue.

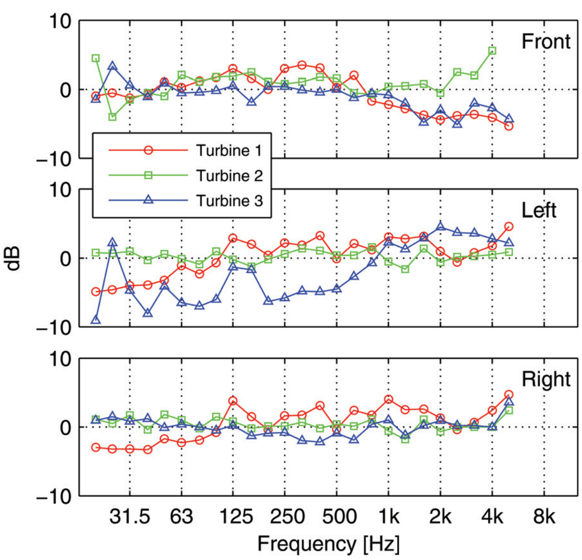

FIG. 7. (Color online) Directivity of turbines 1–3. Wind speed is 8 m/s except for turbine 2, front, which was measured at 10 m/s (and compared to reference direction at 10 m/s). Data missing for turbine 2 front at 5 kHz due to electric noise in the measurement (turbine color code as in Fig. 5).

5. Effect of wind speed

Figure 8 shows L_{WA} as a function of wind speed for the four turbines, where data is available.

The noise increases with wind speed but levels out or even decreases above 7–8 m/s. The four turbines are all pitch-controlled, and the observation is in line with the reports by, e.g., Lee *et al.*[36] and Jung *et al.*[37] for pitch-controlled turbines.

B. Outdoor sound pressure levels at neighbors

For each of the large turbines, the distance needed for the A-weighted sound pressure level to decrease to 35 dB was derived. Pedersen and Waye[60] have shown that around this sound pressure level, the percentage of highly annoyed persons increases above 5%, and the percentage of annoyed persons increases above 10% (Pedersen *et al.*[61]). Pedersen and Nielsen[62] recommended a minimum distance to neighbors so that the wind turbine noise would be below 33–38 dB. A limit of 35 dB is used for wind turbines, e.g., in Sweden for quiet areas.[63] Thus, 35 dB seems as a very reasonable limit for wind turbine noise. It is also the limit that

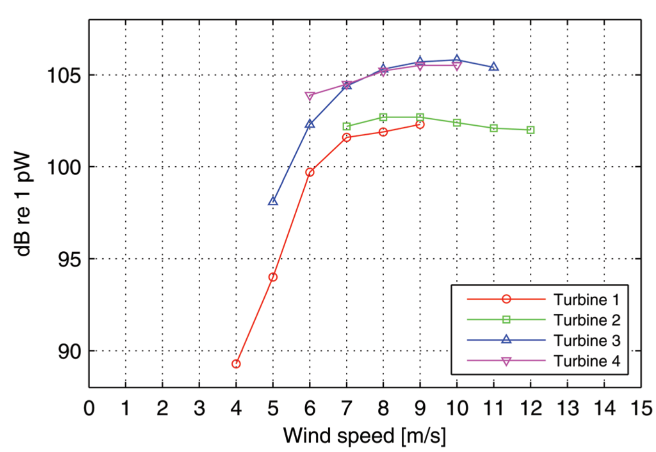

FIG. 8. (Color online) A-weighted apparent sound power level, L_{WA}, as a function of wind speed for turbines 1–4 (turbine color code as in Fig. 5).

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TABLE I. Key figures at the distances from a single turbine, where the total A-weighted sound pressure level is 35 dB. Distances are given as slant distance to rotor center, which, for actual turbine heights, is close to horizontal distance.

	Turbine									
	1	2	3	4	5	6	7	8	9	Mean small
Distance (m)	629	647	879	822	679	758	713	1227	1144	453
L_{pA} (dB)	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
L_{pALF} (dB)	28.8	26.7	28.9	27.6	28.0	29.1	28.8	27.0	27.0	24.8
L_{pALF}–L_{pA} (dB)	−6.2	−8.3	−6.1	−7.4	−7.0	−5.9	−6.2	−8.0	−8.0	−10.2
L_{pG} (dB)	59.1	54.5	55.0	58.0						

applies in Denmark in open residential areas (night) and recreational areas (evening, night, and weekend) for industrial noise[64] (but not for wind turbine noise[49]).

Table I shows the distances for the individual turbines as well as various key figures at the 35-dB distances.

The minimum distance, where a 35-dB limit is complied with, varies considerably between the large turbines, even when the turbines are relatively equal in size (2.3–3.6 MW). The distance varies from slightly over 600 m to more than 1200 m.

The one-third-octave-band spectra at the same distances are shown in Fig. 9.

At these distances, the air absorption plays a role. It affects mainly the high frequencies, and the result is that the shift of the spectrum towards lower frequencies becomes even more pronounced than for the source spectrum (compare with Fig. 5).

It is important to note that, for several turbines, the highest level for a one-third-octave-band is at 250 Hz or lower, even when A-weighted levels are regarded (Fig. 9). It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbors and that the low-frequency sound must be treated seriously in the assessment of noise from large turbines.

In many cases, A-weighted outdoor levels in excess of 35 dB are allowed. As an example, for houses outside official residential or recreational areas, Danish regulation allows 44 dB.[49] For visual reasons, the Danish regulation has a setback distance for dwellings of four times the total turbine height, and at this distance, the level is often below 44 dB for a single turbine. However, 44 dB may certainly occur further away than four times the turbine height, when there are several turbines together in wind farms. Table II lists distances to small wind farms, where the A-weighted sound pressure level is 44 dB, as well as various key figures at those distances.

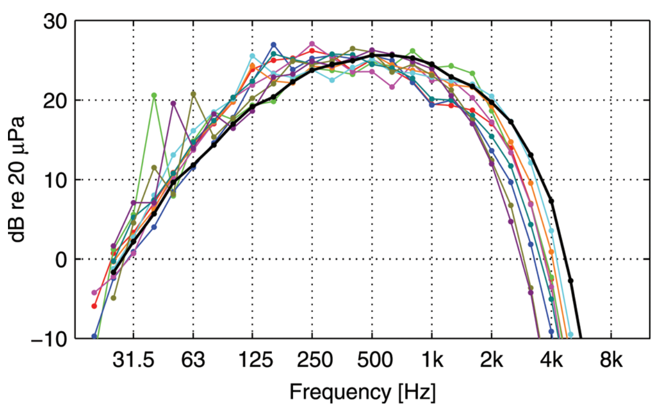

FIG. 9. A-weighted one-third-octave-band sound pressure levels at the distance from a single turbine, where the total A-weighted sound pressure level is 35 dB (see Table I and turbine color code as in Fig. 5).

C. Sound insulation

During the measurements, there were severe problems with background noise at the three lowest frequencies. Eighteen measurements with a signal-to-noise ratio below 1.3 dB were discarded. Consequently, seven room/frequency combinations had to be derived from measurements in only two or three 3D corners. Two room/frequency combinations with measurements from only one 3D corner were not calculated. Figure 10 shows the sound insulation for the ten rooms.

For the frequencies 63–200 Hz, with few exceptions, the rooms have 10–20 dB sound insulation. Toward lower frequencies, the insulation decreases, while the variation between rooms becomes larger. Some rooms show very little or even negative insulation at certain frequencies. A single room has unusually high insulation in the 16–31.5 Hz range. This room was a small room used for storage of furniture and other goods. The room is thus not considered a typical living room, and its data are discarded in further calculations.

Be aware that, for each one-third-octave band, the indoor level refers to the maximum level that people would normally be exposed to in the room (Sec. II D). Thus, in particular, for the higher end of the frequency range, the insulation data are lower than traditional insulation data employed for technical purposes, where room average levels are typically used.

1. Shortcomings of insulation measurements

A shortcoming with the measurement method used is that the exposure is focused at the facade of the house. In the situation of the house being exposed to noise from wind turbines, the whole house, including the roof and, at low frequencies, also the back of the house, will be exposed to nearly the same sound. In the measurement situation, these other surfaces receive much less sound due to loudspeaker directivity, higher distance to the loudspeaker, shadowing, etc.

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TABLE II. Key figures at the distances where the total A-weighted sound pressure level is 44 dB. Wind farm with two rows of each six identical turbines, 300 m distance between turbines in both directions (200 m for small turbines). Observer point centered at long side. Distances are given as slant distance to closest turbine.

	Turbine									
	1	2	3	4	5	6	7	8	9	Mean small
Distance (m)	530	546	831	759	585	679	631	1241	1142	393
L_{pA} (dB)	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0
L_{pALF} (dB)	37.9	35.9	38.1	36.8	37.2	38.3	38.0	36.3	36.3	33.9
$L_{pALF}-L_{pA}$ (dB)	−6.1	−8.1	−5.9	−7.2	−6.8	−5.7	−6.0	−7.7	−7.7	−10.1
L_{pG} (dB)	68.4	63.9	64.6	67.4						

A further problem is that the outdoor free-field sound pressure level is calculated by simply subtracting 6 dB from the measured level at the facade. This assumes that the facade is large enough to be totally reflecting at all frequencies, an assumption which hardly holds at the lowest frequencies. A better solution might have been to measure the free-field level from the loudspeaker at a place without reflecting surfaces (other than the ground), and have used this value in the calculation.

The problems with background noise might have been overcome by using a modern technique that utilizes the correlation between the outdoor and indoor signals, e.g., the maximum-length-sequence (MLS) technique. Alternatively, it might have been possible to increase the signal level by measuring one one-third-octave band at a time rather than the whole low-frequency range simultaneously.

D. Indoor sound pressure levels at neighbors

Figure 11 shows indoor one-third-octave-band levels for all 81 combinations of 9 turbines and 9 rooms at the distance with a total A-weighted outdoor sound pressure level of 35 dB. Be aware that the indoor levels estimate the maximum level that people would normally be exposed to in the room and not the average level of the room (Sec. II D).

Large differences are seen between turbine/room combinations. Most of the variance is attributed to differences in the room sound insulation, except at 63 and 80 Hz, where both room and turbine contribute equally. Values in the upper end of the range at 40 Hz are due to high emission from a single turbine, whereas high values at 200 Hz are due to low sound insulation of a single room.

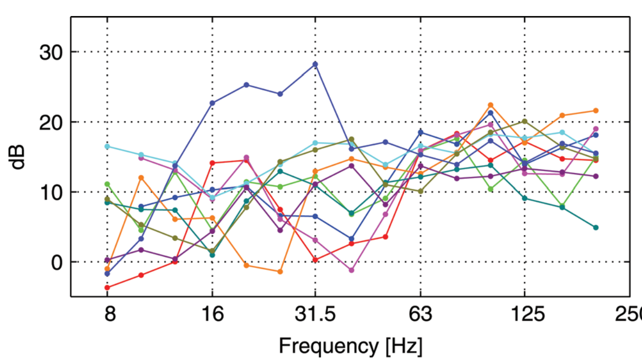

FIG. 10. Sound insulation measured for ten rooms.

It is seen from the inserted hearing threshold (dashed line), that the low-frequency sound will be audible in many turbine/room combinations, mainly at the highest of the low frequencies. The sound will not be very loud, but as mentioned in the introduction, low-frequency sound can be annoying only slightly above the hearing threshold (Sec. I A), and some people may be annoyed by the sound.

Figure 12 shows indoor levels for the situations from Table II where the A-weighted outdoor sound pressure level from a wind farm is 44 dB.

Here, there will be audible sound somewhere in all rooms and with all turbines. In more than half of the cases (48 out of 81), the normal hearing threshold is exceeded by more than 15 dB in one or more one-third-octave bands, and there is a risk that a substantial part of the residents will be annoyed by the sound.

For continuous noise, to avoid sleep disturbance, WHO recommends an indoor limit of 30 dB for the A-weighted sound pressure level,[65] but also notes that, if the noise includes a large proportion of low-frequency noise, "*a still*

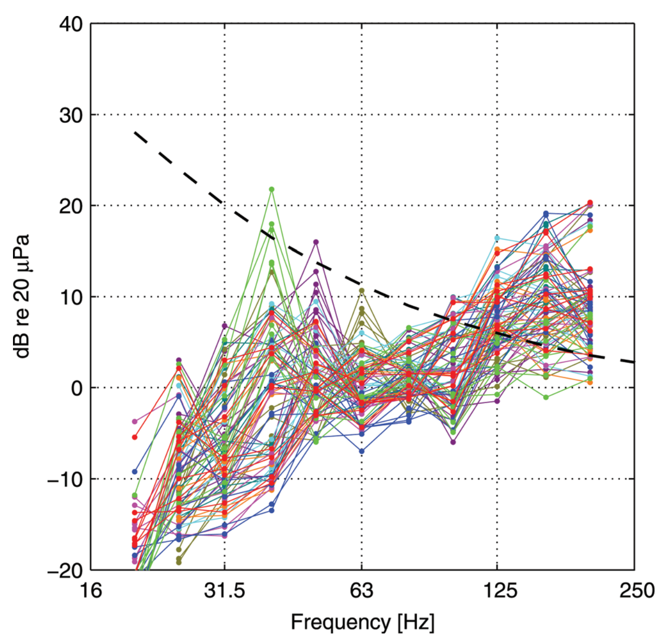

FIG. 11. Indoor A-weighted one-third-octave-band sound pressure levels at the distance from a single turbine, where the total A-weighted outdoor sound pressure level is 35 dB (see Table I); 81 turbine/room combinations. Dashed line is hearing threshold according to ISO 389–7 (Ref. 28) (colors indicate the turbine, color code as in Fig. 5).

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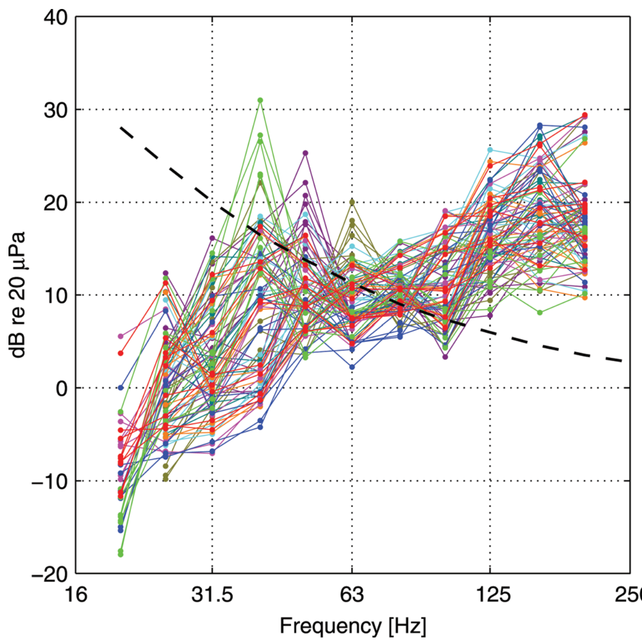

FIG. 12. Indoor A-weighted one-third-octave-band sound pressure levels at the distance from wind farms, where the total A-weighted outdoor sound pressure level is 44 dB (see Table II); 81 turbine/room combinations. Dashed line is hearing threshold according to ISO 389–7 (Ref. 28) (colors indicate the turbine, color code as in Fig. 5).

lower guideline value is recommended, because low-frequency noise …. can disturb rest and sleep even at low sound pressure levels." How much lower is not stated, but unless the level above 200 Hz is exceptionally low, the total A-weighted sound pressure level will obviously exceed, e.g., 25 dB in many of the cases in Fig. 12.

1. Danish indoor limit

The Danish indoor evening/night limit for L_{pALF} in dwellings of 20 dB (Ref. 18) does not apply to measurements in single positions but to levels measured by the method mentioned in Sec. II D. The method uses the power average of measurements in three positions: one position near a corner of the room and two positions where the complainant perceives the noise as being loudest. Assuming that the complainant appoints such positions adequately, the result of the entire method—the power average with a corner position—will still be a level close to the maximum.

It is not possible to find the maximum L_{pALF} by simply adding the one-third-octave-band levels from Fig. 11 or Fig. 12, since the various one-third-octave bands may have their maximum in different areas of the room. However, 40 of the 81 turbine/room combinations of Fig. 12 exceed an A-weighted level of 20 dB for at least one one-third-octave band in the 10–160 Hz frequency range, and it is reasonable to believe that the total for that frequency range, L_{pALF}, will exceed 20 dB for even more combinations.

It should be mentioned that wind turbines have been exempt from the general Danish guidelines for low-frequency sound since 2006, when the regulation for wind turbines was updated.[49] The argument was that indoor L_{pALF} will not exceed 20 dB, if the normal outdoor limits are complied with.[66] This may be true for smaller turbines, but as seen, the indoor level may easily exceed 20 dB with large turbines above 2 MW.

IV. GENERAL DISCUSSIONS

A. Noise versus turbine size

The data material gives a useful overview of the sound power emitted from wind turbines of different sizes, and, with caution, it may be possible to use the data to estimate the apparent sound power level of future, larger turbines. Figure 13 repeats the data for L_{WA} from Fig. 1, now with an extrapolation toward higher nominal electric power, and data for the regression line inserted.

The regression line in Fig. 13 corresponds to the following connection between the apparent sound power, P_A, and the nominal electric power, P_E:

$$P_A = constant_1 \cdot (P_E/1\text{MW})^{slope/10\text{dB}} \quad (2)$$

where *slope* is the slope of the regression line, and $constant_1$ can be derived from the last term of the regression line. Since the slope is 11.0 dB, the exponent is 1.10, meaning that the apparent sound power increases more than proportionally to the nominal electric power. Thus, to the extent that turbines follow the trend of the regression line, a turbine of double size emits more than the double sound power.

The area A of the circle, within which a certain noise limit is exceeded, is of particular interest. The radius of the circle can be found by solving Eq. (1) with respect to d, and, if omitting the atmospheric absorption, which mainly has effect at high frequencies and at long distances, it is found that the area is proportional to the apparent sound power. After insertion of Eq. (2), it follows that

$$A = constant_2 \cdot P_A = constant_2 \cdot constant_1 \cdot \left(\frac{P_E}{1\text{MW}}\right)^{slope/10\text{dB}} \quad (3)$$

where $constant_2$ depends on the noise limit.

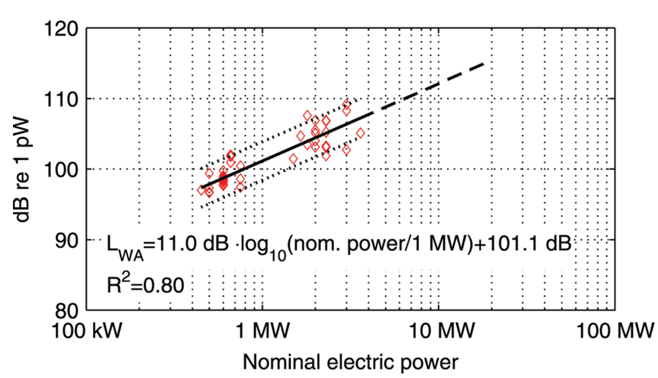

FIG. 13. (Color online) Apparent sound power level (L_{WA}) as a function of turbine size, four turbines below 450 kW excluded, wind speed 8 m/s. Linear regression line, standard error of estimates (s.e.e.) 1.64 dB. Extrapolation dashed, 90 % confidence intervals (dotted) based on s.e.e.

Thus, at the regression line, the noise-occupied area increases more than proportionally to the nominal electric power. This is a remarkable result, when considering today's development with constantly increasing turbine sizes and even, at least in Denmark, replacing many small turbines with few larger turbines. From a noise pollution point of view, this seems as a step back. If the installed nominal electric power is the same, large turbines affect a larger area with noise than small turbines do.

It must be added that the slope of the regression line is not significantly higher than 10 dB [90% confidence interval 9.53–12.40, $p(slope \leq 10\ \text{dB}) = 0.133$]. With a slope of 10 dB, the noise-occupied area is the same for small and large turbines for the same installed nominal electric power.

B. Variation between turbines

The data in Fig. 13 are based on measurements on single turbines. In order to account for variations between different samples of the same model, somewhat higher apparent sound power levels should be used in project planning. According to IEC TS 61400-14,[67] manufacturers should declare values that are 1.645 times the standard deviation between turbines higher than the mean of turbines of the given model. This value corresponds to the upper limit of a 90% confidence interval, meaning that the probability is 5% that a random sample turbine of the actual model emits more noise than reflected by the declared value.

The size of this safety margin thus depends on the variation between turbines of the actual model. The standard deviations in Fig. 13 for turbines of the same size and make range from 1.6 to 3.5 dB, when disregarding turbine sizes that comprise repeated measurements on one or more turbines. Since the standard deviation must be multiplied by 1.645, the margin will typically be several decibels.

Broneske[68] pointed out that manufacturers often declare values that do not have the safety margin specified in IEC TS 61400-14. It is also the present authors' impression that minimum distances to dwellings are often calculated from noise data that lack an appropriate safety margin. Using data without safety margin, such as mean values for a given turbine model, measurements from a single turbine, or "best guess" for future turbines, gives in principle a probability of 50% that the actual erected turbine(s) will emit more noise than assumed, and that noise limits will be exceeded, if the project is planned to the limit.

It is noted that small changes in apparent sound power level may result in sizeable changes in distance requirements. As an example, for a single turbine, 3 dB higher apparent sound power level results in a 41% higher distance requirement.

C. Data from project WINDFARMperception

A study of visual and acoustic impact of wind turbines on residents was carried out by van den Berg *et al.*[69] As part of the study (known as project WINDFARMperception), measured spectra of apparent sound power from wind turbines were collected. Sound power levels at 8 m/s for 28 turbines with nominal electric power in the 80 kW–3 MW range were selected for calculations of sound pressure levels at the neighbors. Only four turbines are above 2 MW, but if three 2-MW turbines are included in the group of large turbines, it is possible to make a relevant comparison of large and small turbines. Figure 14 shows means of turbines < 2 MW and ≥ 2 MW.

Also with these data, the low-frequency part is clearly higher for large turbines than for small. The level differences at 63 and 125 Hz are statistically significant [$t = (2.70, -2.39)$, d.f. $= (12.8, 16.9)$, one-sided $p = (0.009, 0.015)$].

The differences (3.6 and 2.2 dB) are in the same order of magnitude as the differences in the present investigation (compare with Fig. 4).

A comparison with data of the present investigation converted to octave bands shows very similar values in the two investigations, see Fig. 15. Data from the two investigations for the same power group are not significantly different at any frequency. (There is no overlap in original data.)

D. Tonal components

Søndergaard and Madsen[70] conclude (1) that the "*frequency spectra of the aerodynamic noise from the rotor blades of the largest wind turbines does not deviate significantly from the spectra for smaller wind turbines. This means that for the aerodynamic noise the low frequency range is not more prominent for large turbines than for small turbines*," (2) that the observed "*slightly higher …. relative amount of low frequency noise …. is mainly caused by gear tones at frequencies below 200 Hz*," and (3) that this "*is not unusual for prototypes and usually the fully developed commercial wind turbines are improved on the noise emission, especially concerning audible tones in the noise*."

However, these conclusions are not substantiated by adequate statistics or other data analyses. The separation of aerodynamic noise and gear noise referred to is not explained, and data are not given. Regarding the development of noise from prototypes to commercial turbines, no

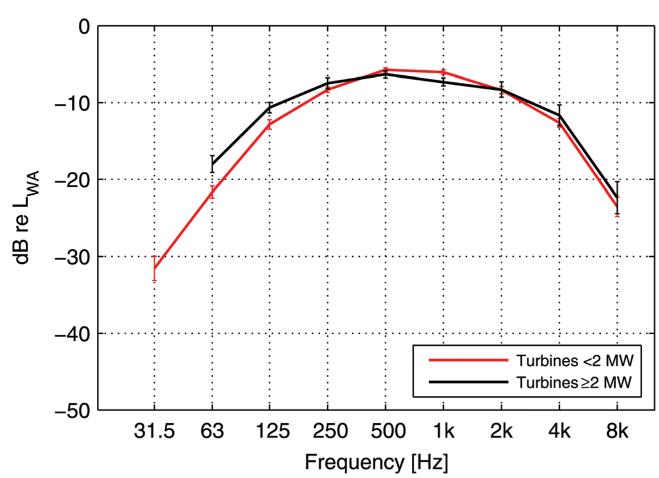

FIG. 14. (Color online) Normalized A-weighted apparent sound power levels in octave bands, means for two groups of turbines: < 2 and ≥ 2 MW. Data from van den Berg *et al.*,[69] Appendix D. Error bars indicate ±1 standard error of mean. (None of the large turbines was measured in the 31.5-Hz octave band).

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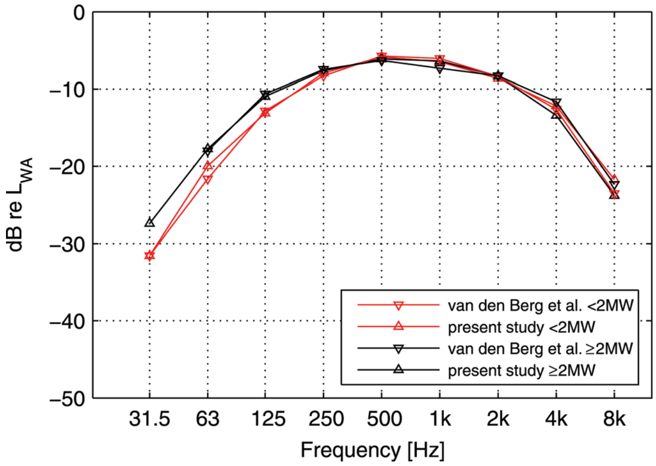

FIG. 15. (Color online) Normalized A-weighted apparent sound power levels in octave bands, means for two groups of turbines: < 2 and ≥ 2 MW and from two investigations: van den Berg *et al*. (Ref. 69), Appendix D and present investigation (converted to octave bands).

data or references are given. If the turbines of the present project are considered, it is unclear, whether turbines 5–11 are prototypes or not, since the turbines are anonymous, and the informations diverge between reports. The original report[43] only specifies turbines 1–4 as prototypes, but a summarizing report[70] refers to all the turbines above 2 MW as prototypes. If turbines 5–11 are indeed prototypes, this means that the third conclusion is made without data for large commercial turbines. If, on the other hand, turbines 5–11 are commercial turbines, it is worth noting that some of these also have obvious one-third-octave-band peaks (Fig. 5), and that their noise emissions (L_{WA} or L_{WALF}) are not lower than those of turbines 1–4, perhaps on the contrary (Fig. 1).

Regarding reduction of tonal noise, Søndergaard and Madsen refer to the tone penalty as a means to guarantee that the tones are actually reduced, before the turbines are put on the market, and they use expressions like "*the necessary tone reduction*"[70] and "*… reduced to a level where there is no penalty according to Danish rules….*"[43,70] They have evidently ignored that the results of their tone analyses will not release a tone penalty to any of the turbines (Sec. III A 3).

A closer look at the data reveals that, even when some of the one-third-octave-band peaks at low frequencies are very distinct, the peaks are not in general responsible for the difference between small and large turbines. Figure 16 shows an imagined situation, where all peaks below 200 Hz have been removed from the large turbines by replacing the level at the peaks with levels obtained by linear interpolation between the levels in the two adjacent one-third-octave bands. One to three peaks have been removed for each turbine, except for turbine 4, which does not have peaks in this frequency range. Only removal of the 40-Hz peak of turbine 2 affects the mean of the large turbines by more than 1.0 dB.

Generally, the large turbines are still above the mean of the small turbines in the low-frequency range. The difference between the means of large (> 2 MW) and small turbines (≤ 2 MW) is still significant in the same one-third-octave bands as they were with the peaks [63–160 Hz (unchanged above 160 Hz): $t = (3.03, 3.59, 2.81, 2.83, 3.18)$, d.f. = (22.4, 23.6, 17.0, 19.2, 18.9), one-sided $p = (0.003, <0.001, 0.006, 0.005, 0.003)$].

The striking similarity with the spectra from van den Berg *et al*.[69] (Fig. 15) supports that the spectra for the large turbines from the present project, including the tones, are representative for wind turbines of such size.

E. Ground reflection

In the calculations of sound pressure levels at the neighbors, the ground reflection is accounted for by adding 1.5 dB to the direct sound. As mentioned in Sec. IIC, the 1.5-dB value is used by Danish regulation.[49] Swedish guidelines add 3 dB to the direct sound (for distances up to 1000 m),[71] a value that also follows from ISO 9613–2 (Ref. 47) for the lowest octave-frequency band mentioned, 63 Hz, irrespective of the ground surface. During measurements of sound emission from the turbines,[46] it is assumed that the ground reflection adds as much as 6 dB to the direct sound. Certainly, a reflecting board is used under the microphone, but the board has only little effect at low frequencies, where the assumed 6-dB reflection is due mainly to the ground itself.

Possible destructive interference between the direct sound and the ground reflection due to elevation of the receiver above ground will have little impact at low frequencies. For example, for a source height of 75 m, a horizontal distance of 800 m, and a receiver height of 1.5 m, the delay between the direct sound and the ground reflection will only be 0.8 ms, which corresponds to a first dip in the sound transmission at 625 Hz.

On this background, it is reasonable to suspect that the addition of 1.5 dB for the ground reflection is too low at low frequencies, and that higher values up to a theoretical maximum of 6 dB would be more appropriate. Thus, the procedure used to calculate outdoor sound pressure levels at the neighbors is likely to underestimate the low-frequency sound.

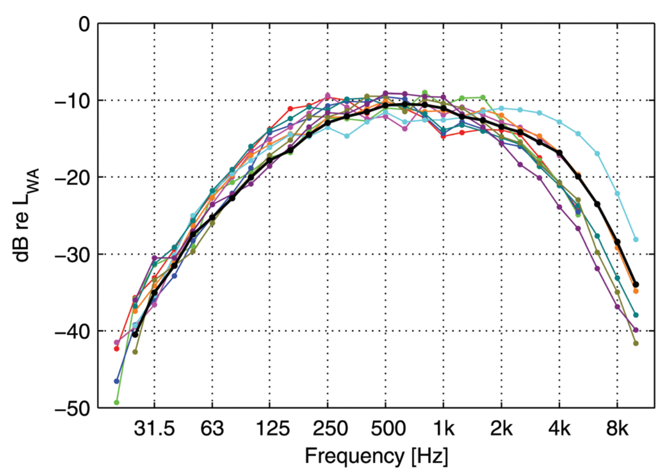

FIG. 16. Normalized A-weighted apparent sound power levels in one-third-octave bands, individual turbines > 2 MW and mean of 36 turbines ≤ 2 MW. Peaks in one-third-octave bands below 200 Hz have been removed from the large turbines by replacing the levels at the peaks by levels obtained by linear interpolation between the levels at the two adjacent one-third-octave-band frequencies (turbine color code as in Fig. 5).

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F. Windows

The measurements of sound insulation were made with closed windows. However, in large parts of the world, many people prefer to sleep with the windows at least slightly open, and WHO recommends that noise limits should permit this.[65,72] In Denmark, indoor measurements of low-frequency noise are usually made with closed windows, but if the complainant finds that the noise is louder with open windows, measurements should also be made for this situation.[18] Therefore, it would have been appropriate to measure the insulation also with slightly open windows and to estimate the resulting indoor sound pressure levels accordingly.

G. Estimated sound power spectra for even larger turbines

In Sec. III A 2, the spectral difference between small and large turbines was seen in terms of differences in the normalized apparent sound power levels for certain one-third-octave bands. As an alternative way, Fig. 17 shows the mean normalized spectra of large and small turbines, but with the data for small turbines shifted one third of an octave down in frequency.

The two curves are very close in the main frequency range, meaning that the spectrum has maintained its shape but shifted about one third of an octave down in frequency from the small to the large turbines (compare with Fig. 4). Differences at the lowest frequencies may be real or be the result of uncertainty due to high background noise at these frequencies, a matter that is not fully expounded in the data material.

For the reader who might think that a shift of a single third octave is very modest, it is worth noting that it is the same as the musical interval of a major third, nearly the difference between two adjacent strings on a guitar.

The logarithmic means of the nominal electric power of the small and large turbines are around 650 kW and 2.6 MW, respectively, thus the downward spectral shift of approximately one third of an octave relates to an upward shift of the nominal electric power by a factor in the order of 4. It would thus be appropriate to suggest a further downward spectral shift of the same amount for future turbines in the 10-MW range.

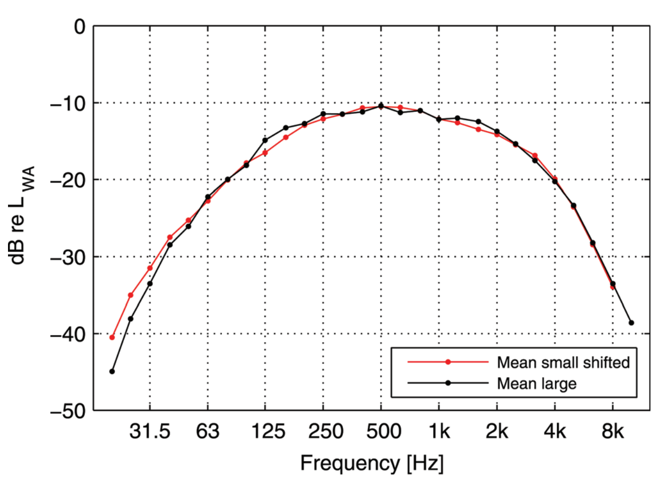

FIG. 17. (Color online) Normalized apparent sound power levels in one-third-octave bands. Mean of two groups of turbines: ≤ 2 and > 2 MW, group of turbines ≤ 2 MW shifted one third of an octave down in frequency. (Turbine 6 disregarded above 2 kHz, see Sec. III A 2.)

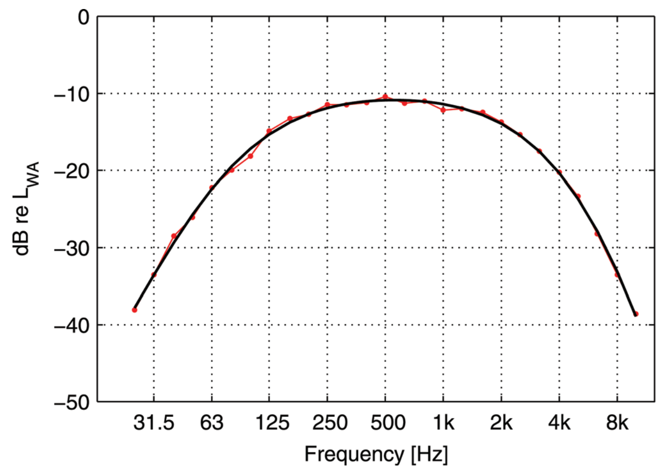

FIG. 18. (Color online) Sixth-order polynomial regression (bold line) for mean of normalized apparent sound power levels (dots and thin line) for the turbines > 2 MW (Turbine 6 disregarded above 2 kHz, see Sec. III A 2.)

As a supplement to the linear regression and the extrapolation for L_{WA} in Fig. 13, estimated spectra have been constructed for turbines around 2.5, 5, and 10 MW for possible (and cautious) use in future projects. Figure 18 shows a sixth-order polynomial regression of the relative spectrum for the turbines of the present project above 2 MW.

Table III gives relative one-third-octave-band levels for 2.5 MW turbines from the regression and, for 5 and 10 MW turbines, data shifted one sixth and one third of an octave, respectively, down in frequency. In addition, the table gives estimated absolute levels based on the linear regression of L_{WA} in Fig. 13. Note that the estimates are based on means of turbines and that they do not include a safety margin as mentioned in Sec. IV B.

The table values for the absolute level in one-third-octave bands are shown in Fig. 19.

H. Atmospheric conditions

All previous calculations assume spherical sound propagation, i.e., a 6 dB reduction of sound pressure level per doubling of distance. During certain atmospheric conditions, e.g., with temperature inversion or low-level jets, there may be a sound reflecting layer in a certain height, and thus the propagation beyond a certain distance is more like cylindrical propagation, which only gives 3 dB reduction per doubling of distance. This was observed for low frequencies, e.g., by Hubbard and Shepherd[19] and explained, e.g., by Zorumski and Willshire[73] and Johansson.[74] Above sea, Swedish guidelines generally assume cylindrical propagation beyond a distance of 200 m,[71] a distance supported by data by Bolin *et al.*,[75] who showed reflection in a height in the order of 100–200 m.

With cylindrical propagation beyond 200 m, the following equation applies (for distances above 200 m):

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TABLE III. Estimated relative and absolute A-weighted sound power levels for turbines around 2.5, 5, and 10 MW based on sixth-order polynomial approximation of mean relative spectrum for turbines above 2 MW from Fig. 18 and L_{WA} from linear regression of Fig. 13. Relative levels moved, respectively, 1/6 and 1/3 of an octave down for 5 and 10 MW turbines. Approximation adjusted by +0.38 dB to achieve a total relative spectrum of 0 dB, which the mean of relative data (and its approximation) does not necessarily sum up to. Note that the estimates are based on means of turbines and that they do not include a safety margin as mentioned in Sec. IV B.

Frequency (Hz)	Relative to L_{WA}						Absolute					
	1/3-octave-band levels			Octave-band levels			1/3-octave-band levels			Octave-band levels		
	2.5 MW	5 MW	10 MW	2.5 MW	5 MW	10 MW	2.5 MW	5 MW	10 MW	2.5 MW	5 MW	10 MW
25	−37.4	−35.3	−33.2				68.1	73.5	78.9			
31.5	−33.2	−31.1	−29.0	−27.2	−25.2	−23.3	72.3	77.7	83.1	78.3	83.6	88.8
40	−29.0	−27.0	−25.3				76.5	81.8	86.8			
50	−25.3	−23.6	−22.0				80.2	85.2	90.1			
63	−22.0	−20.5	−19.1	−16.7	−15.3	−14.0	83.5	88.3	93.0	88.8	93.5	98.1
80	−19.1	−17.9	−16.8				86.4	91.0	95.3			
100	−16.8	−15.8	−15.0				88.7	93.0	97.1			
125	−15.0	−14.2	−13.4	−10.0	−9.3	−8.6	90.5	94.6	98.7	95.5	99.5	103.5
160	−13.4	−12.8	−12.3				92.1	96.0	99.8			
200	−12.3	−11.9	−11.5				93.2	96.9	100.6			
250	−11.5	−11.2	−11.0	−6.8	−6.5	−6.3	94.0	97.6	101.1	98.7	102.3	105.8
315	−11.0	−10.8	−10.6				94.5	98.0	101.5			
400	−10.7	−10.6	−10.5				94.9	98.2	101.6			
500	−10.5	−10.5	−10.5	−5.8	−5.8	−5.8	95.0	98.3	101.6	99.7	103.0	106.3
630	−10.5	−10.6	−10.7				95.0	98.2	101.4			
800	−10.7	−10.8	−11.0				94.8	98.0	101.1			
1000	−11.0	−11.3	−11.5	−6.3	−6.5	−6.8	94.5	97.5	100.6	99.2	102.3	105.3
1250	−11.5	−11.9	−12.4				94.0	96.9	99.7			
1600	−12.4	−12.9	−13.5				93.1	95.9	98.6			
2000	−13.5	−14.3	−15.1	−8.8	−9.5	−10.2	92.0	94.5	97.0	96.7	99.3	101.9
2500	−15.1	−16.0	−17.2				90.4	92.8	94.9			
3150	−17.2	−18.4	−20.0				88.3	90.4	92.1			
4000	−20.0	−21.6	−23.3	−14.7	−16.1	−17.8	85.5	87.2	88.8	90.8	92.7	94.3
5000	−23.3	−25.3	−27.5				82.2	83.5	84.6			
6300	−27.5	−29.9	−32.8				78.0	78.9	79.3			
8000	−32.8	−35.6	−38.5	−26.1	−28.7	−31.5	72.7	73.2	73.6	79.4	80.1	80.6
10 000	−38.5	−41.9	−45.2				67.0	66.9	66.9			
L_{WA}							105.5	108.8	112.1	105.5	108.8	112.1

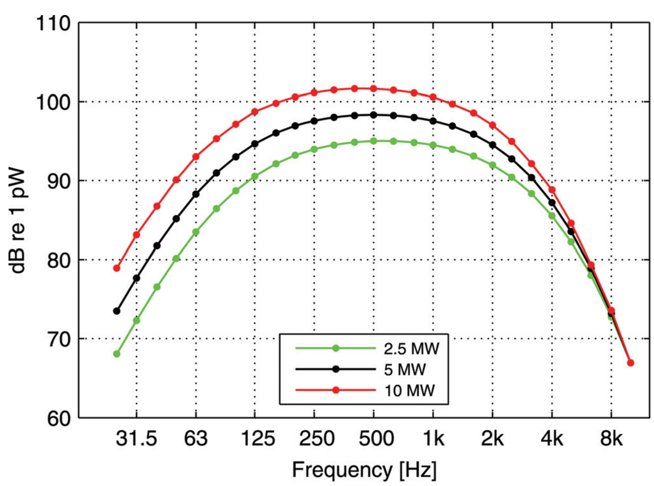

FIG. 19. (Color online) Estimated A-weighted sound power levels in one-third-octave bands for turbines around 2.5, 5, and 10 MW. Values and assumptions are taken from Table III.

$$L_p = L_{WA} - 20\ \text{dB} \cdot \log_{10}\left(\frac{200\ \text{m}}{1\text{m}}\right) - 10\ \text{dB} \cdot \log_{10}\left(\frac{d}{200\ \text{m}}\right) - 11\ \text{dB} - \alpha \cdot d + 1.5\ \text{dB}. \quad (4)$$

Table IV and Fig. 20 show key figures and sound pressure levels in one-third-octave bands, respectively, at the distances from the turbines, where the A-weighted sound pressure level has decreased to 35 dB, assuming cylindrical propagation beyond 200 m.

Much longer distances (1414–3482 m) are needed than with pure spherical propagation, and the low-frequency character of the spectrum has become even more pronounced (compare with Table I and Fig. 9). Cylindrical propagation may thus explain case stories, where rumbling of wind turbines is claimed to be audible kilometers away. A worst-case scenario combining temperature inversion with a wind park acting as a line source in a certain distance range could theoretically reduce the geometrical attenuation in that range to zero. However, more knowledge is needed about atmospheric conditions and the occurrence of various phenomena.

Also other phenomena related to the atmospheric conditions deserve some attention. It is normally assumed that the

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TABLE IV. Key figures at the distances, where the total A-weighted sound pressure level is 35 dB, cylindrical propagation assumed beyond 200 m. Distances are given as slant distance to rotor center, which, for actual turbine heights, is close to horizontal distance.

	Turbine									
	1	2	3	4	5	6	7	8	9	Mean small
Distance (m)	1476	1414	2373	2100	1562	1829	1776	3482	3152	827
L_{pA} (dB)	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
L_{pALF} (dB)	29.7	28.2	30.3	29.2	29.4	30.7	30.0	29.7	29.6	25.6
L_{pALF}-L_{pA} (dB)	−5.3	−6.8	−4.7	−5.8	−5.6	−4.3	−5.0	−5.3	−5.4	−9.4
L_{pG} (dB)	60.4	56.2	57.1	60.0						

wind speed increases logarithmically with increasing height above ground, starting from zero speed at a height equal to the *roughness length* of the ground surface. Thus, knowing the roughness length, the wind speed at all heights can be determined from measurements in a single height. The wind speed in a height of 10 m is used as a reference for measurements of wind turbine noise.[46]

However, several studies have shown that actual wind-speed profiles vary a lot and often deviate substantially from the assumed logarithmical profile.[76–79] In a stable atmosphere, which often exists at night, variations with height can be much larger than assumed with high wind speed at turbine height and little wind at ground. A large variation of wind speed across the rotor area increases the modulation of the turbine noise, and the normal "swish–swish" sound turns into a more annoying, "thumping," impulsive sound as reported by, e.g., van den Berg[27,80,81] and Palmer.[82] The effect is more prominent with large wind turbines, where the difference in wind speed between rotor top and bottom can be substantial. The effect is usually not reflected in noise measurements, which are mainly carried out in the daytime, when the logarithmic profile is more common.

Another consequence of large wind speed variation with height is that the turbine may emit noise corresponding to a high wind speed—and much higher than assumed from the wind speed measured at 10 m—while it is all quiet at the ground. Thus, there is more turbine noise than expected and less wind; hence, the turbine noise will not be masked with natural wind-induced sound, as it might have been with the assumed logarithmic wind profile.

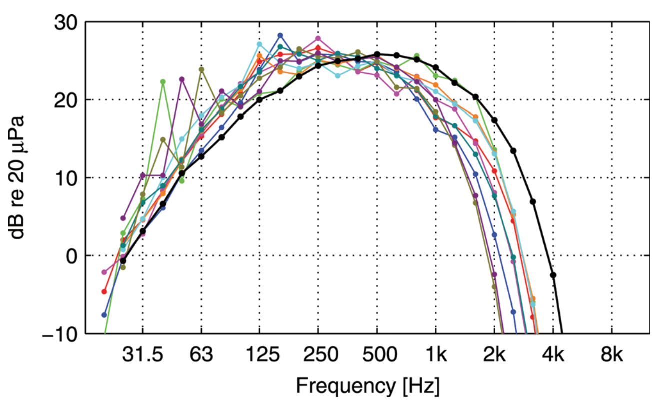

FIG. 20. A-weighted sound pressure levels in one-third-octave bands at the distances, where the total A-weighted sound pressure level is 35 dB (see Table IV). Cylindrical propagation assumed from 200 m (turbine color code as in Fig. 5).

Several authors have argued that the logarithmic wind-speed profile and the 10-m reference height are inadequate with the size of modern turbines (e.g., Refs. 77, 78, 80, 83), and a revised IEC 61400-11 will use the actual wind speed in the turbine hub height as a reference.[84] Wind profiles and statistics for the actual place can then be applied in noise prediction and regulation.

V. CONCLUSIONS

The results confirm the hypothesis that the spectrum of wind turbine noise moves down in frequency with increasing turbine size. The relative amount of emitted low-frequency noise is higher for large turbines (2.3–3.6 MW) than for small turbines (≤ 2 MW). The difference is statistically significant for one-third-octave bands in the frequency range 63–250 Hz. The difference can also be expressed as a downward shift of the spectrum of approximately one third of an octave. A further shift of similar size is suggested for turbines in the 10-MW range.

When outdoor sound pressure levels in relevant neighbor distances are considered, the higher low-frequency content becomes even more pronounced. This is due to the air absorption, which reduces the higher frequencies a lot more than the lower frequencies. Even when A-weighted levels are considered, a substantial part of the noise is at low frequencies, and for several of the investigated large turbines, the one-third-octave band with the highest level is at or below 250 Hz. It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbors.

Indoor levels of low-frequency noise in neighbor distances vary with turbine, sound insulation of the room, and position in the room. If the noise from the investigated large turbines has an outdoor A-weighted sound pressure level of 44 dB (the maximum of the Danish regulation for wind turbines), there is a risk that a substantial part of the residents will be annoyed by low-frequency noise even indoors. The Danish evening/night limit of 20 dB for the A-weighted noise in the 10–160 Hz range, which applies to industrial noise (but not to wind turbine noise), will be exceeded somewhere in many living rooms at the neighbors that are near the 44 dB outdoor limit. Problems are much reduced with an outdoor limit of 35 dB.

The turbines do emit infrasound (sound below 20 Hz), but levels are low when human sensitivity to these frequencies is accounted for. Even close to the turbines, the infrasonic

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sound pressure level is much below the normal hearing threshold, and infrasound is thus not considered as a problem with turbines of the investigated size and construction.

The low-frequency noise from several of the investigated large turbines comprises tones, presumably from the gearbox, which result in peaks in the corresponding one-third-octave bands. The tone penalty does not guarantee that the tones are removed or reduced, since they are not sufficiently distinct to release a penalty at all. The spectral difference between large and small turbines remains statistically significant, even if the one-third-octave-band peaks are removed.

The above conclusions are based on data for turbines in the range of 2.3–3.6 MW nominal electric power. It must be anticipated that the problems with low-frequency noise will increase with even larger turbines.

The emitted A-weighted sound power increases proportionally to the nominal electric power or likely even more. Consequently, large turbines affect the same area—or possibly even larger areas—with noise, when compared to small turbines with the same total installed electric power.

There are differences of several decibels between the noise emitted from different turbines of similar size, even for turbines of the same make and model. It is therefore not feasible to make calculations down to fractions of a decibel and believe that this holds for the turbines actually set up. A safety margin must be incorporated at the planning stage in order to guarantee that the actual erected turbines will comply with noise limits. An international technical specification exists for this, but it is often not used.

Under certain atmospheric conditions, e.g., temperature inversion, the noise may be more annoying and—in particular the low-frequency part—propagate much further than usually assumed. More knowledge is needed on such phenomena and their occurrences.

ACKNOWLEDGMENTS

The measurements were carried out by Delta. Financial support was obtained from the Energy Research Programme under the Danish Energy Agency, and from Aalborg University.

[1]H. Møller and C. S. Pedersen, "Human hearing at low frequencies," Noise Health **6**(23), 37–57 (2004).
[2]L. D. Whittle, S. J. Collins, and D. W. Robinson, "The audibility of low frequency sounds," J. Sound Vib. **21**(4), 431–448 (1972).
[3]H. Møller and J. Andresen, "Loudness of pure tones at low and infrasonic frequencies," J. Low Freq. Noise Vib. **3**(2), 78–87 (1984).
[4]M. A. Bellmann, V. Mellert, C. Reckhardt, and H. Remmers, "Perception of sound and vibration at low frequencies," collected papers from the *Joint Meeting "Berlin 99" of ASA, EAA and DAGA*, Berlin, Germany (1999), Abstract in J. Acoust. Soc. Am., **105**, 1297.
[5]ISO 226 *Acoustics—Normal Equal-Loudness-Level Contours* (International Organization for Standardization, Geneva, Switzerland, 2003).
[6]J. Andresen and H. Møller, "Equal annoyance contours for infrasonic frequencies," J. Low Freq. Noise Vib. **3**(3), 1–9 (1984).
[7]H. Møller, "Annoyance of audible infrasound," J. Low Freq. Noise Vib. **6**(1), 1–17 (1987).
[8]Y. Inukai, N. Nakamura, and H. Taya, "Unpleasantness and acceptable limits of low frequency sound," J. Low Freq. Noise, Vib., Act. Control, **19**(3), 135–140 (2000).
[9]J. K. Subedi, H. Yamaguchi, Y. Matsumoto, and M. Ishiharatil, "Annoyance of low frequency tones and objective evaluation methods," J. Low Freq. Noise, Vib., Act. Control. **24**(2), 81–96 (2005).
[10]K. P. Waye, J. Bengtsson, A. Kjellberg, and S. Benton, "Low frequency noise 'pollution' interferes with performance," Noise Health. **4**(13), 33–49 (2001).
[11]K. P. Waye, A. Clow, S. Edwards, F. Hucklebridge, and R. Rylander, "Effects of nighttime low frequency noise on the cortisol response to awakening and subjective sleep quality," Life Sci. **72**, 863–875 (2003).
[12]B. Berglund and T. Lindvall (Eds.) "Community noise," Archives of the center for Sensory Research, 2 (1), Stockholm University and Karolinska Institute, 1995, prepared for the World Health Organization.
[13]ISO 7196, *Acoustics—Frequency-Weighting Characteristic for Infrasound Measurements* (International Organization for Standardization, Geneva, Switzerland, 1996).
[14]N. S. Yeowart and M. J. Evans, "Thresholds of audibility for very low-frequency pure tones," J. Acoust. Soc. Am. **55**(4), 814–818 (1974).
[15]S.Yamada, T. Kosaka, K. Bunya, and T. Amemiya, "Hearing of low frequency sound and influence on human body," in *Proceedings of Conference on Low Frequency Noise and Hearing*, Aalborg, Denmark (May 7–9, 1980), pp. 95–102.
[16]U. Landström, R. Lundström, and M. Byström, "Exposure to infrasound—Perception and changes in wakefulness," J. Low Freq. Noise Vib. **2**(1), 1–11 (1983).
[17]T. Watanabe and H. Møller, "Low frequency hearing thresholds in pressure field and in free field," J. Low Freq. Noise Vib. **9**(3), 106–115 (1990).
[18]*Lavfrekvent støj, infralyd og vibrationer i eksternt miljø (Low Frequency Noise, Infrasound and Vibrations in the External Environment)*, Orientering fra Miljøstyrelsen, nr. 9 (Danish Environmental Protection Agency, 1997).
[19]H. H. Hubbard and K. P. Shepherd, "Aeroacoustics of large wind turbines," J. Acoust. Soc. Am. **89**(6), 2495–2508 (1991).
[20]K. P. Shepherd and H. H. Hubbard, "Physical characteristics and perception of low frequency noise from wind turbines," Noise Control Eng. J. **36**(1), 5–15 (1991).
[21]G. Guidati, R. Bareiß, and S. Wagner, "An investigation of blade-tower-interaction noise (BTI) for horizontal axis wind turbines in upwind and downwind configuration. First steps towards modeling of aeroelastic effects," in *Proceedings of the 8th IEA Joint Action Symposium on Aerodynamics of Wind Turbines,* Lyngby, Denmark (1994), pp. 249–255.
[22]M. L. Legerton, D. M. J. P. Manley, J. W. Sargent, D. J. Snow, and P. Styles, "Low frequency noise & vibration levels at a modern wind farm," in *Proceedings of the 25th International Congress on Noise Control Engineering, Inter-Noise 96*, Liverpool, Turkey, pp. 459–462.
[23]K. Betke, M. Schultz-von Glahn, O. Goos, and H. Remmers, "Messung der Infraschallabstrahlung von Windkraftanlagen" (Measurement infrasound emission from wind turbines), in *Proceeding of DEWEK '96. 3rd German Wind Power Conference* Wilhelmshaven, Germany (1996), pp. 207–210.
[24]K. Betke and H. Remmers, "Messung und Bewertung von Tieffrequentem Schall," (Measurement and assessment of low-frequency sound), Fortschr. Akustik, DAGA 1998, pp. 472–473.
[25]J. Jakobsen, "Infrasound emission from wind turbines," J. Low Freq. Noise, Vib., Act. Control **24**(3), pp. 145–155 (2005).
[26]J. Jakobsen, "Danish guidelines on environmental low frequency noise, infrasound and vibration," J. Low Freq. Noise, Vib., Act. Control **20**(3), 141–148 (2001).
[27]G. P. van den Berg, "Do wind turbines produce significant low frequency sound levels," *11th Int. Meeting on Low. Frequency Noise Vib. its Control.*, Maastricht, The Netherlands (2004).
[28]ISO 398-7, *Acoustics—Reference Zero for the Calibration of Audiometric Equipment—Part 7: Reference Threshold of Hearing under Free-Field and Diffuse Field Listening Conditions* (International Organization for Standardization, Geneva, 2005).
[29]C. S. Pedersen and H. Møller, *Vurdering af lavfrekvent støj og infralyd fra decentrale el-elproducerende anlæg (Assessment of Low-Frequency Noise and Infrasound from Local Electricity-Producing Plants)* (Department of Acoustics, Aalborg University, Aalborg, Denmark, 2005).
[30]"The measurement of low frequency noise at three UK wind farms,' Hayes McKenzie Partnership, Ltd., for Department Trade Industri (DTI), Contract No. W/45/00656/00/00, URN No. 06/1412, UK, 2006.
[31]A. Moorhouse, D. Waddington, and M. Adams, "Proposed criteria for the assessment of low frequency noise disturbance," Project Rep. DEFRA NANR45, University of Salford, 2005.
[32]A. Moorhouse, D. Waddington, and M. Adams, "Procedure for the assessment of low frequency noise complaints," Project Rep. DEFRA NANR45, University of Salford, 2005.
[33]J. Jakobsen, *Lavfrekvent støj fra vindmøller*(*Low-Frequency Noise from Wind Turbines*), Memorandum (Danish Environmental Protection Agency (Miljøstyrelsen), May 31, 2006).

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[34]*Bekendtgørelse om miljøgodkendelse af hurtigfærgeruter*(*Statutory Order on High-Speed Ferries*), Bekendtgørelse No. 821(Danish Ministry of the Environment, København, 1997).
[35]*Vurdering af lavfrekvent støj fra færger, part 2: Revideret metode til beregning af lydtrykniveauet indendørs* (*Assessment of Low-Frequency Noise from Ferries, Part 2: Revised Method for Calculating the Sound Pressure Level Indoors*), Delta Akustik & Vibration, Arbejdsrapport fra Miljøstyrelsen nr. 10, 1997.
[36]S. Lee, S.-H. Shin, C. Cheong, S.-S. Jung, and W. Cheung, "Low-frequency noise emission characterisation of upwind-type large wind turbines," in *Proceedings of the International Congress on Noise Control Engineering, Inter-Noise 2007*, Istanbul, Turkey.
[37]S. S. Jung, W.-S. Cheung, C. Cheong, and S.-H. Shin, "Experimental identification of acoustic emission characteristics of large wind turbines with emphasis on infrasound and low-frequency noise," J. Korean Phys. Soc. **53**(4), 1897–1905 (2008).
[38]W. J. Gastmeier and B. Howe, "Recent studies of infrasound from industrial sources," Can. Acoust. **36**(3), 58–59 (2008).
[39]R. Ramakrishnan, "Characteristics of wind turbine noise," Can. Acoust. **3**, 122–123 (2009).
[40]J. P. Harrison, "Inadequacy of wind turbine noise regulations and their application," Can. Acoust. **37**(3), 156–157 (2009).
[41]R. J. Barthelmie, L. Folkerts, F. T. Ormel, P. Sanderhoff, P. J. Eecen, O. Stobbe, N. M. Nielsen, "Offshore wind turbine wakes measured by sodar," J. Atmos. Ocean.ic Technol. **20**, 466–4772003.
[42]B. Søndergaard and C. Ryom, "Low frequency noise from large wind turbines—Sound power measurement method," Rep. AV 135/08, Delta, April2008.
[43]B. Søndergaard and K. D. Madsen, "Low frequency noise from large wind turbines—Results from sound power measurements," Rep. AV 136/08, Delta, revised version December2008.
[44]B. Søndergaard and K. D. Madsen, "Low frequency noise from large wind turbines—Results from previous sound power measurements," Rep. AV 137/08, Delta, May 2008.
[45]D. Hoffmeyer and B. Søndergaard, "Low frequency noise from large wind turbines—Measurements of sound insulation of facades," Rep. AV 1097/08, Delta, 2008.
[46]IEC 61400-11*Wind Turbine Generator Systems—Part 11: Acoustic Noise Measurement Techniques*, 2nd ed. (International Technical Commission, Geneva, 2002 plus Amendment 1 2006).
[47]ISO 9613-2*Acoustics—Attenuation of Sound during Propagation Outdoors—Part 2: General Method of Calculation* (International Organization for Standardization, Geneva, 1996).
[48]ISO 9613-1, *Acoustics—Attenuation of Sound during Propagation Outdoors—Part 1: Calculation of the Absorption of Sound by the Atmosphere* (International Organization for Standardization, Geneva, 1993).
[49]*Bekendtgørelse om støj fra vindmøller* (*Statutory Order on Noise from Wind Turbines*), Bekendtgørelse nr. 1518 af 14, december 2006 (Danish Ministry of the Environment, 2006).
[50]ISO 140-5, *Acoustics—Measurement of Sound Insulation in Buildings and of Building Elements—Part 5: Field Measurements of Airborne Sound Insulation of Facade Elements and Facades* (International Organization for Standardization, Geneva, 1998).
[51]J. Jakobsen, "Lavfrekvent støj, infralyd og vibrationer; Rumakustiske forhold ved lave frekvenser" (Low-frequency noise, infrasound vibrations; Room Acoust. conditions At. Low. frequencies), Rep. AV67/96, Delta Akustik & Vib., 1996.
[52]C. Simmons, "Measurement of sound pressure levels at low frequencies in rooms. Comparison of available methods and standards with respect to microphone positions," Acta. Acust. **85**(1), 88–100 (1999).
[53]S. Pedersen, H. Møller, and K. P. Waye, "Indoor measurements of noise at low frequencies—Problems and solutions," J. Low Freq. Noise, Vib., Act. Control **26**(4), 249–270 (2007).
[54]J. Brunskog and F. Jacobsen, "Measurements of low-frequency noise in rooms," Memorandum (Danish Environmental Protection Agency, 2008).
[55]S. Wagner, R. Bareiß, and G. Guidati, *Wind Turbine Noise* (Springer, Berlin, Germany).
[56]ISO 1996-2*Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 2: Determination of Environmental Noise Levels*, 2nd ed. (International Organization for Standardization, Geneva, 2007).
[57]Måling af ekstern støj fra virksomheder *(Measurement of External Industrial Noise)*, Vejledning nr. 6 (Danish Environmental Protection Agency, 1984).
[58]S. Oerlemans and G. Schepers, "Prediction of wind turbine noise and comparison to experiment," in *Proceedings of Second International Meeting on Wind Turbine Noise*, Lyon, France (2007).
[59]S. Oerlemans, M. Fisher, and T. Maeder, "Reduction of wind turbine noise using optimized airfoils and trailing-edge serrations," AIAA. J. **47**(6), 1470–1481 (2009).
[60]E. Pedersen and K. P. Waye, "Perception and annoyance due to wind turbine noise—A dose-response relationship," J. Acoust. Soc. Am. **116**(6), 3460–3470 (2004).
[61]E. Pedersen, F. van den Berg, R. Bakker, and J. Bouma, "Response to noise from modern wind frams in The Netherlands," J. Acoust. Soc. Am. **126**(2), 634–643 (2009).
[62]T. H. Pedersen and K. S. Nielsen, "Genevirkning af støj fra vindmøller," (Annoyance noise from wind turbines), Report 150, Delta Akustik & Vib., 1996.
[63]*Buller från vindkraft—Riktvärden för ljud från vindkraft (Noise from Wind Turbines—Recommended Limits For Sound From Wind Turbines)*, Naturvårdsverket (Stockholm, 2009).
[64]*Ekstern støj fra virksomheder*(*External Ind. Noise*), Vejledning nr. 5 (Danish Environmental Protection Agency, 1984).
[65]B. Berglund, T. Lindvall, and D. H. Schwela (eds.), *Guidelines for Community Noise* (World Health Organization, Geneva, Switzerland, 1999).
[66]"Høring af udkast til bekendtgørelse om støj fra vindmøller" (Hearing of draft statutory order on noise from wind turbines), Miljøstyrelsen, 30. October2006.
[67]IEC TS 61400-14, *Wind turbines—Part 14: Declaration of Apparent Sound Power Level and Tonality Values* (International Technical Commission, Geneva, 2005).
[68]S. Broneske, "Comparison of wind turbine manufacturers' noise data for use in wind farm assessments," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).
[69]F. van den Berg, E. Pedersen, J.e Bouma, and R. Bakker, "WINDFARMperception—Visual and acoustic impact of wind turbine farms on residents," Final Rep. 3., University of Groningen, University of Gothenburg, June 2008.
[70]B. Søndergaard and K. D. Madsen, "Low frequency noise from large wind turbines—Summary and conclusions on measurements and methods," Rep. AV 140/08, Delta (revised version December 2008.
[71] "Ljud från vindkraftverk" (Sound from wind turbines), Rapport 6241, Naturvårdsverket, Stockholm, Sweden, 2001.
[72]*Night Noise Guidelines for Europe* (World Health Organization, Copenhagen, Denmark, 2009).
[73]W. E. Zorumski and W. L. Willshire, "Downwind sound propagation in an atmospheric boundary layer," AIAA. J. **5**, 515–523 (1989).
[74]L. Johansson, "Sound propagation around off-shore wind turbines," in *Proceedings of 10th International Congress on Sound and Vibration*, Stockholm, Sweden (2003), pp. 1481–1487.
[75]K. Bolin, M. Boué and I. Karasalo, "Long range sound propagation over a sea surface," J. Acoust. Soc. Am. **126**(5), 2191–2197 (2009).
[76]G. P. van den Berg, "Wind gradient statistics up to 200 m altitude over flat ground," in *Proceedings of First International Meeting on Wind Turbine Noise*, Berlin, Germany (2005).
[77]P. Botha, "The use of 10 m wind speed measurements in the assessment of wind farm developments," in *Proceedings of First International Meeting on Wind Turbine Noise*, Berlin, Germany (2005).
[78]W. K. G. Palmer, "Uncloaking the nature of wind turbines—Using the science of meteoroly," in *Proceedings of Second International Meeting on Wind Turbine Noise*, Lyon, France (2007).
[79]D. Bowdler, "Wind shear and its effect on noise assessment," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).
[80]G. P. van den Berg, "Effects of the wind profile at night on wind turbine sound," J. Sound Vib. **277**, 955–970 (2004).
[81]G. P. van den Berg, "The beat is getting stronger: The effect of atmospheric stability on low frequency modulated sound of wind turbines," J. Low Freq. Noise, Vib., Act. Control **24**(1), 1–24 (2005).
[82]W. K. G. Palmer, "A new explanation for wind turbine whoosh—wind shear," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).
[83]M. Almgren, S. Schönfeld, and J. Grönlund, "Sound emission and sound propagation for wind turbines in forest terrains," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).
[84]B. Søndergaard, "The next version of the IEC 61400-11 measurement method," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).

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Lori & Sherm

From: "Colin Hansen" <colin.hansen@adelaide.edu.au>
Date: Thursday, August 30, 2018 8:23 PM
To: <sol@midstatesd.net>
Subject: Re: Wind farm noise

Dear Mr Fuerniss

Thank you for your message. I am very sorry to hear of your predicament with wind turbines near your house and more proposed turbines. I certainly sympathise with your situation as that many turbines so close to your residence is clearly unacceptable. I can give you some free advice but I am not able to be directly involved in any legal proceedings. Based on your message, I have the following comments.

1. 45 dBA is an unusually high allowable noise limit. In my state in Australia, the limit is 40 dBA for a commercial farming area and 35 dBA for a rural residential area. Some states are currently working on legislation that will limit noise to 35 dBA at all residences in rural areas. This is substantially lower than the levels that you have to put up with and I would regard 45 dBA as very excessive.

2. The dBA scale underestimates annoyance and sleep disruption of low-frequency noise. Vertigo has also been reported by many people living near wind farms.

3. It is difficult to demonstrate problems to courts when they visit wind farm sites for a number of reasons, including
(a) The wind may not be blowing sufficiently to cause the wind farm to emit its worst case noise.
(b) The wind farm operator can run the turbines at low noise and low power output to minimise noise during a court visit.
(c) Worst case noise usually occurs at night as that is when mid and high frequency background noise is usually lowest and it is also when more favourable meteorological conditions exist that maximize noise downwind of the turbines.

4. For the reasons mentioned above, long term noise monitoring is needed over several months to properly evaluate existing wind farm noise levels.

5. 2000 ft set back is way too short. In the one state in Australia where setback distances have been legislated, it is 3,300 ft. Even this is way too close as we have many instances of serious complaints from people living 10,000 ft or more from the nearest 3 MW turbine in a 37 turbine wind farm.

6. Wind farm noise is quite different in character to traffic noise, which the WHO uses as a basis of its recommended exterior noise levels, and wind farm noise can be considerably more disturbing at the same dBA level for most people. This is a result of its low-frequency energy content which becomes more noticeable as the distance from the wind turbines increases and as mid and high frequency background noise from other sound sources decreases.

7. People have widely varying hearing thresholds and sensitivity to low-frequency noise such that some people are completely unaware of noise that is causing severe annoyance and associated medical problems for other people. This results in some journalists and misguided academics (see Simon Chapman's rantings on http://theconversation.com/profiles/simon-chapman-1831) claiming that wind farm noise is at too low a level to affect people and unfortunately courts also have access to these articles. This makes any litigation very difficult to win.

I wish you the very best in your fight for your rights to not have your environment, sleep and health disrupted by intrusive noise.

Best wishes

Colin Hansen

APPENDIX O

OPERATION AND MAINTENANCE PLAN

Class II
Item no.: 964106.R00
2007-06-29

Mechanical Operating and Maintenance Manual

V90 – 3.0 MW, VCRS 60 Hz

Onshore/Offshore (Mk 7)

History of this Document

Rev. no.	Date	Description of changes
00	2007-06-29	First edition

Table of Contents

Please see Mechanical Drawings & Parts List

1 Preface

This manual applies to the wind turbine **V90 - 3.0MW, VCRS 60 Hz, Mk-7.**

It is the turbine owner's responsibility that only qualified persons operate the turbine.

Do not operate the turbine before, as a minimum, having studied the following carefully:

- ✓ 960314 Safety Regulations for Operators and Technicians
- ✓ 950173 User Guide

Do not hesitate to contact your plant manager or Vestas' Service Department if you need more detailed explanations.

Vestas Wind Systems A/S

Alsvej 21

DK-8900 Randers

Telephone: +45 9730 0000

2 Updating of the Manual

The manual will continuously be brought up to date. Corrections to each specific chapter are listed for the past year under the heading of "History of this Document".

3 The Header

The latest revision date of a specific chapter is stated in the header of the chapter. Class II indicates that the document is only handed out according to agreement with Vestas' Technology Department.

Each specific chapter has its own item number followed by a revision number (Rx).

First editions have revision number R0.

4 Contents

Supplier Drawings

Safety Regulations for Operators and Technicians, V90-3MW/V100-2.75MW

History of this Document

Rev. no.:	Date:	Description of change
0	2005-06-23	First edition
1	2005-09-19	947554 replaced by 959055; Chap. 9: “However, the capacitors in the converter and AGO2 section might be energized.” inserted Chapter 10 Converter and AGO2 Sections Figure numbers updated
2	2006-01-17	Reference to 947554 added again page 12
3	2006-03-03	Chapter 18.1.1. New wind speed limit 23m/s
4	2006-05-08	Language revision. Inserted: section 14.2 Access to roof, text and picture.
5	2006-09-11	Reference to V100 added Section 19 updated with new pictures and new text.

Contents ....Page

1. Introduction

A turbine connected to the grid implies certain elements of danger if it is handled without exercising proper caution.

For safety reasons, at least two persons have to be present during a work procedure.

The work must be properly carried out in accordance with this manual and other related manuals. This implies, among other things that personnel must be instructed in and familiar with relevant parts of this manual.

Furthermore, personnel must be familiar with the contents of the “Substances and Materials” regulations.

Caution must especially be exerted in situations where measurement and work is done in junction boxes that can be connected to power.

Consequently the following safety regulations must be observed.

2. Stay and Traffic by the Turbine

Do not stay within a radius of 400m (1300ft) from the turbine unless it is necessary. If you have to inspect an operating turbine from the ground, do not stay under the rotor plane but observe the rotor from the front.
Make sure that children do not stay by or play nearby the turbine. If necessary, fence the foundation. The access door to the turbine must be locked in order to prevent unauthorised persons from stopping or damaging the turbine due to mal-operation of the controller.

3. Address and Phone Number of the Turbine

Note the address and the access road of the turbine in case an emergency situation should arise. The address of the turbine can often be found in the service reports in the ring binders next to the ground controller. Find the phone number of the local life-saving service.

4. Controller and Operating Panel

Only authorised or instructed persons are allowed to open the doors of the controller cabinet.

Picture 1

Before inspecting or working on the turbine, the remote control MUST be deactivated. Use the breaker-key and set it in position "local".
Remember to activate the remote control when the inspection or the work has been completed.

5. Emergency Stop Buttons

For safety reasons please note the location of the 4 emergency stop buttons. The buttons are located (Figure 1 Locations of emergency stop buttons and trip F60 in nacelle) at:

- Ground controller (at the bottom of the turbine).
- Gearbox (pos. 1).
- Yaw ring (pos. 2).
- Nose cone (pos. 3, only local stopping function)
- Nacelle controller (pos. 4).
- Trip F60 (pos. 5).

The emergency stop buttons are red with a yellow background. An emergency stop is activated by pressing one of the red buttons. When an emergency stop is activated, the controller switches to "EMERGENCY STOP" mode meaning that no power will be supplied to the contactor solenoids, the blades will pitch (full feathering), the brake will be applied and the turbine will stop. The yaw system, the hydraulic pump, the gear oil pump and the nacelle ventilator will also stop. Consequently, all moving parts will be brought to a standstill.
However, the power supply to the light, the nacelle, the hub and the ground controllers will still be on. The stop button in pos. 3 is not an emergency stop button but a local stopping function.

Remember: The hydraulic system is still under pressure. Due to the accumulators, up to 6 litres of hot oil will pour out, if the hydraulic system is intervened.

Please note: When the emergency stop buttons are activated, the brake is activated.

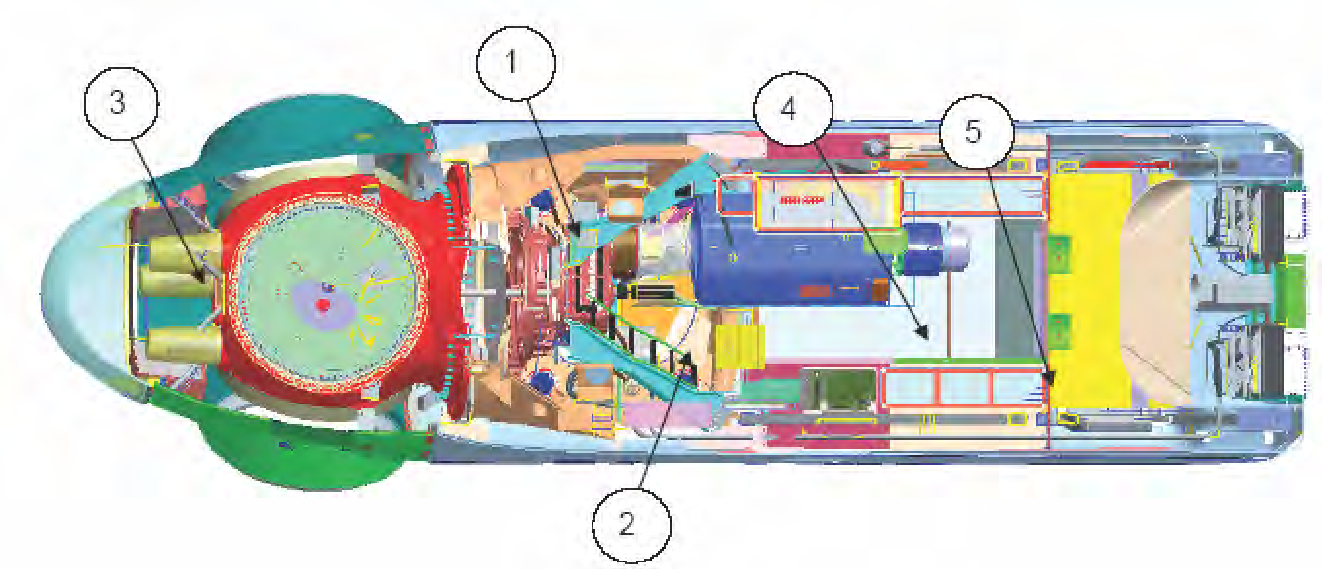
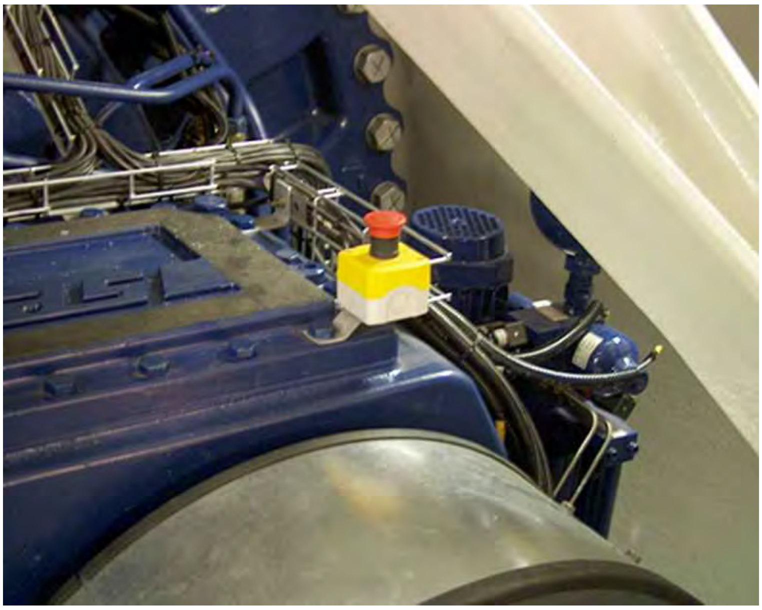


Figure 1 Locations of emergency stop buttons and trip F60 in nacelle


Picture 2 Yaw ring emergency stop button (pos. 2, Figure 1)



Picture 3 Gearbox emergency stop button (pos. 1, Figure 1)

Picture 4 Emergency stop button at nacelle controller (pos. 4, Figure 1)

Picture 5 Emergency stop button in hub (pos. 3, Figure 1)

Picture 6 The trip F60 button (pos. 5, Figure 1)

5.1 Trip F60

Trip F60 is situated on the nacelle controller (pos. 4). Trip F60 disconnects the high voltage supply for the turbine. When disconnected, only the control system in the turbine is supplied from the UPS for approx. 6 hours. Usually, the local power station must take part when the turbine is connected to the grid.

5.2 Lift (Optional)

If a lift is installed, it has several emergency stop buttons.
Note: These buttons only stop the lift; emergency stop buttons for turbine do not apply to the lift.

5.3 Internal Crane

The crane is equipped with an emergency stop button. This only applies to the crane and otherwise the emergency stop buttons in the turbine do not apply to the crane.

6. Practical Advice at Inspection

When inspecting the machinery, always look very closely for oil spills and loose bolts. Dirt must be wiped off, otherwise it can be difficult to determine whether there is a significant leak.
Loose bolts in the structure mean danger. They must be tightened immediately. If it is a matter of several bolts or repetitions, please contact Vestas Wind Systems A/S service department.

7. Influence by Lubricants

The lubricants used in the turbine can be aggressive. Lubricants must not get in contact with skin or clothes.
At inspection of a gearbox if removing a cap while the oil is still hot, be careful not to breathe in the hot oil vapours.

8. High Voltage Installations

As a basic rule it is not allowed to dismount cover or open locked doors to the high voltage installations.
An operator/service technician is only allowed to move around behind the covering when the high voltage is disconnected, locked and visibly earthed. The work must be carried out and approved by authorised personnel only (power station or selected coupling leader). One of these persons must give permission to access the HV installation.
Work done on high voltage installations must be carried out in accordance with national regulations and related Vestas Wind Systems A/S manuals.

9. Grid Drop-Out

A grid drop-out causes an EMERGENCY STOP. The blades pitch out of the wind (full feathering); the yaw system, the hydraulic pump and the nacelle ventilator stop. Consequently, all moving parts will be brought to a standstill except for emergency lubrication system for the gearbox. The power supply for the light and the nacelle, hub and ground controllers is partly off. However, the capacitors in the converter and AGO2 section might be energized.

10. Converter and AGO2 Sections

WARNING:
If working on the converter section or AGO2 section, note that the capacitors inside can be charged to 800 V and those in the filters can be charged to 690 V. The capacitors are discharged to below 50 V in 5 minutes after disconnection from the grid. Switch Q7 and Q8 must be turned off.
Before opening the cabinet, check the DC-link-voltage in picture 17.
Before working on the converter/AGO2, check the DC-link-voltage with a Fluke multimeter.

11. Turbine Standstill

After a period of maximum 14 days without grid connection, necessary equipment for humidity- and temperature control must be installed in the turbine in order to fulfil the following requirements:

- For 90 % of the shutdown period, the relative humidity (RH) must not exceed 45 %.
- The RH must be between 45% and 60% for max. 10% of the shutdown period only.
- Within a period of 12 hours, the temperature in the turbine must not drop more than 10° C.
- The temperature and humidity must be logged.

During a period without grid connection, the following inspections must be carried out on a monthly basis:

- Check the functionality of the equipment as regards humidity and temperature.
- Check the RH and temperature logging in accordance with the requirements mentioned above.
- Check the emergency lubrication.
- Recharge emergency lubrication batteries (only every 3 months).
- Check the blade locking system.
- Check that the brake is released and without pressure.

12. Overspeed Guard

If the turbine rotation exceeds its limit, the overspeed guard (VOG) is activated, and the turbine will go into EMERGENCY STOP mode. The state of failure cannot be reset until the VOG has been de-energized.

13. Inspection of the Turbine

At inspection of the turbine, the following procedure must be followed.

When inspecting the turbine there must always be at least two persons present.
Full feathering of the blades is done by pressing <PAUSE>. When the rotor comes to a standstill or rotates slowly, activate the <Emergency stop button> to stop the turbine.

It is now possible to climb the turbine but remember as a minimum to wear:

- Safety footwear suitable for climbing towers.
- H-belt with fall protection device fastened directly to the H-belts D-ring on your chest.
- Safety helmet.

Always make sure that there is nobody above you in the turbine when you start the ascent.
If you bring tools, lubricants etc. with you, keep these in a rucksack or a bag which is attached to the safety belt.

During the ascent the fall protection and the supporting strap **MUST** be mounted. Do not mount the fall protection hook on the aluminium ladder rungs or on the fittings for the ladder, as they might brake in case of falling. Instead the swivel eye plate (yellow) must be used.
Close the trap doors of the landings when passing them.
Please notice the location of the emergency stop buttons and Trip F60 in the nacelle.

When working on the electrical part of the controller, the controller must be disconnected by the circuit breaker (marked Q7, Q26 and Q27) in the board arrangement and locked by means of a padlock. Only authorised personnel must have access to the key/keys.
When working on the terminal of the generator, inspecting the generator cables or the controlling as such, the generator must be disconnected by the circuit breaker (Q8 and Q23) in the board arrangement and locked by means of a padlock. Only authorised personnel must have access to the key/keys.

When working on the yaw system, the yaw motors must be disconnected in the control panel at the contactors F35.1 and F35.2.

Always make sure that there is nobody below the turbine while you are working in the nacelle. Even a small screw is highly dangerous when falling from a height of 60m or more.
Unauthorised persons must under no circumstances move the covering plates which cover rotating or electrical parts, especially the high voltage installation. Be cautious that safety straps are not caught on any rotating shafts during stay in the nacelle while the turbine is in operation.

Before entering the hub or working on rotating parts in the nacelle, make sure that the rotor is locked and that the blades are fully feathered. See section “Operating the Rotor Locking System” on how to activate the rotor locking system.
Before descent, close the nacelle skylights and the service hatch. Make sure that you have gathered all tools and remember that the red emergency stop buttons must be off.
If the blades are iced up, it is highly dangerous to stay below or close to the rotor. If the turbine is to be restarted with iced up blades, the operator must be very careful and make sure that no persons are nearby because of the risk of falling pieces of ice.

Do not stay in the nacelle while the turbine is in operation, unless if checking for gear and generator noise.

Any oil or grease spills must be cleaned up because of the risk of slipping.
Make sure that the covering and the locking of the high voltage installations are undamaged.
Make sure that the high voltage cable between the high voltage installations in the nacelle and the bottom are undamaged and do not have any visible mechanical damages, such as having been squeezed/cut by cable binders, mechanical parts etc.

When working in the nacelle, spinner or roof, please pay attention to safety hooking points. See figure 3.

When working on the roof of the nacelle, secure a safety line on the roof rail. See Picture 11 Hooking points on the roof.

Special caution must be taken when climbing lattice towers when it is wet or icy. Moreover special cautions must be taken when climbing on the outside of the lattice tower, since the back of the blade is close to the lattice tower when the blade is turning around its longitudinal axis. This happens if anyone pushes <PAUSE> or <EMERGENCY STOP> and also at an unintended EMERGENCY STOP.

14. Safety Equipment

See Figure 2 Safety Equipment

1. Safety helmet.
2. H-belt (delivered by Vestas).
3. Lanyards: one line with a fall damper device, one line with a shortening device (delivered by Vestas).
4. Fall protection device (delivered by Vestas).
5. Rubber-soled footwear properly tightened.

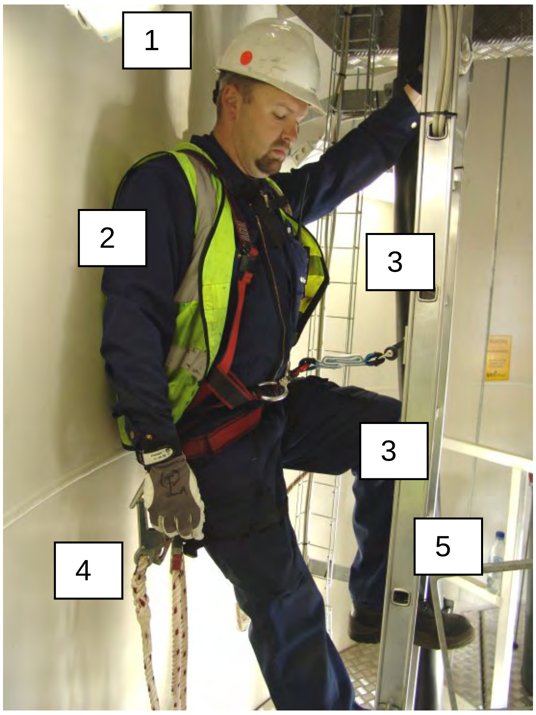


Figure 2 Safety Equipment

When climbing the tower, fasten the fall protection device directly to the H-belt's D-ring. Only one person is allowed on each ladder section at a time.

If a service lift is installed in the turbine, bring along the safety equipment in it.

14.1 ResQ Emergency Rescue Equipment

In case the escape route via the tower should be cut off by fire or other unforeseen events, a rescue and descent device is located in the nacelle behind the main controller section in an aluminium box. Please see user manual for rescue equipment, item number 959055 (VCS, 50 Hz turbines) or 947554 (VCRS, 60 Hz turbines).

Picture 7 Fixing Point for ResQ descent device

- Fixing point for ResQ descent device.
- Open the left service hatch.
- Lift the arm above the opening.
- Fasten the ResQ descent device to the arm.
- Ready for lowering, SWL 2000kg.

14.2 Access to Roof

Place the ladder on machine foundation at the rear of the nacelle to gain access to nacelle roof as shown in the picture below.

Picture 8 Ladder to roof

15. Hooking Points and Safety Chains

A number of hooking points is installed at different locations in the nacelle. A hooking point is shown in Picture 9 Hooking point.

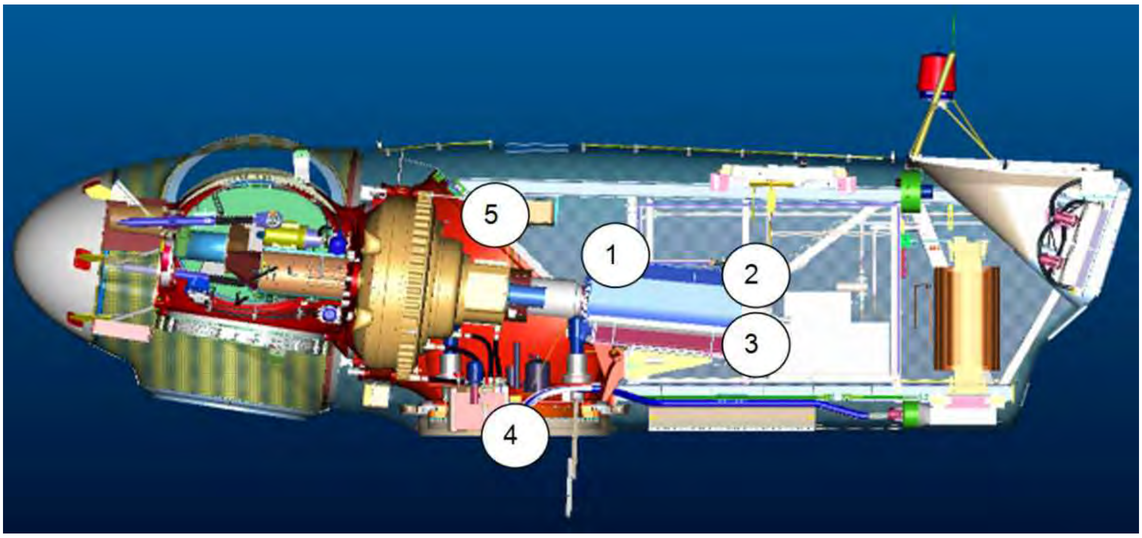


Figure 3 Hooking points in the nacelle and position of safety chains

Picture 9 Hooking point

Picture 10 Safety chains must be mounted when the bottom hatch is open (Figure 3)

Picture 11 Hooking points on the roof

16. Precautions in Case of Fire

At any type of fire in or near a turbine, the power to the turbine must always be disconnected at the main high voltage circuit breaker. To disconnect supply, switch off by pushing the red button (marked TRIP F60) on the nacelle controller in the nacelle. In the tower bottom the power supply is switched off by pushing the red button situated on the breaker in the high voltage section. If it is impossible to get to the main circuit breaker, contact the power station for a disconnection of the grid.

In case of a fire during an uncontrolled operation, do under no circumstances approach the turbine. Evacuate and rope off the turbine in a radius of minimum 400m (1300ft). In case of a fire in a non-operating turbine, the fire can be put out by means of a powder extinguisher.

CAUTION **Use of a CO2 extinguisher in a closed room can result in lack of oxygen.**

17. Directions for Use of Rotor Lock

To avoid accidents and near-accidents, which can be prevented via mechanical locking of the rotor, the following guidelines must be followed:

IN GENERAL:
Besides following the requirements listed in this document, it is important also to use ones common sense and assess the specific situations.

When the wind speed exceeds the values of the mechanical design of the locking system, it is not allowed to work in a turbine as listed below.

A technical solution must be prepared before starting work on a turbine that cannot be locked mechanically.

The work listed below must not be carried out before the turbine has been mechanically locked.

Mechanical rotor locking must be used in connection with:

1. Hub and blades:
   a. stay in hub and nose cone
   b. stay on/near the blade is not allowed unless both the rotor and the blade has been locked

2. Work on gearbox and gear oil system if this involves:
   a. disassembly and adjustment of mechanical parts
   b. tensioning
   c. activation of shrink disc
   d. internal inspection – unless it is a visual inspection

3. Work on coupling and braking system if this involves:
   a. disassembly and adjustment of mechanical parts

b. tensioning
c. inspection of coupling
d. lubrication

4. Work on generator if this involves:
a. disassembly and adjustment of mechanical parts
b. tensioning
c. work on slip ring systems/units

5. Work on yaw system
In addition to rotor locking, the turbine must be secured against unintentional yawing, if this involves:
a. disassembly of mechanical parts
b. yaw brakes cannot be activated

6. Work on electricity in the nacelle, if this involves:
a. that the turbine controller is switched off and work at rotating parts of the drive train has to be carried out.

7. Work on hydraulics for pitch as well as brake system, if this involves
a. disassembly of mechanical parts
b. that the pumps are out of operation

8. Work on the turbine's exterior
In addition to rotor locking, the turbine must be secured against yawing, if this involves:
a. use of crane
b. use of front lift
c. use of other lifts or scaffold systems

9. Replacement of components, if this involves:
a. replacement of components, sensors, etc. close to unshielded rotating parts of the drive train.

18. Operating the Rotor Locking System

The rotor must not be locked unless it is necessary, however always when servicing the hub and it must be unlocked as soon as possible after the service operation, which caused the locking.

If the rotor has to be locked for more than 48 hours, it must be bolted to the main foundation, following the procedure description in section 18.2.

18.1.1 Operating the hydraulic rotor locking system for normal service

The rotor locking system must not be set or used at wind speeds exceeding 23 m/s.

The rotor locking system must not be used while the rotor is rotating.

Pitching of blades is not allowed while the rotor is locked, except at wind speeds below 15 m/s. In this case only one blade may be pitched at a time.

The rotor locking system is located at the upper right hand side of the main gear,
see Picture 12 Rotor locking system.

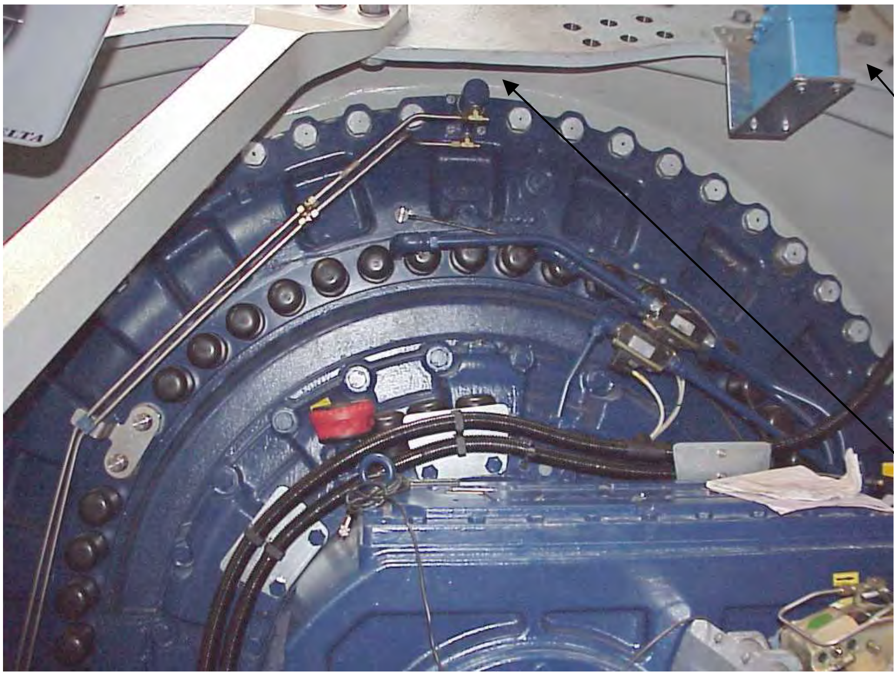
1. Set the turbine to PAUSE mode and select test picture 11.7 (Manual Pitch and Brake), where the brake can be activated.

2. Align the locking system position holes in the hub with the locking system mandrels by "manoeuvring" the brake (press [*]) until the V-notch marking (pos. 1) on the hub is aligned with pointer on machine foundation (see pos. 2). See Picture 13.

3. At the correct position set the handle in "+" position and pump the locking system mandrels out. Observe at the right side during the pumping! See Figure 4.

4. The locking takes place with the hydraulic hand pump located above the main gear on right hand side. The locked position of the handle is 45°. When locking set the handle in ”+" position (the handle perpendicular to the gearbox centre shaft). When unlocking set the handle in "-" position and pump in the locking system mandrels.

5. When the mandrels are fully out or in, set the handle in "lock" position, see Figure 4.
   Verify the fully in or out position by looking at picture 11.7.B at the operator panel.



Picture 12 Rotor locking system

Picture 13 Alignment markings seen from machine foundation side

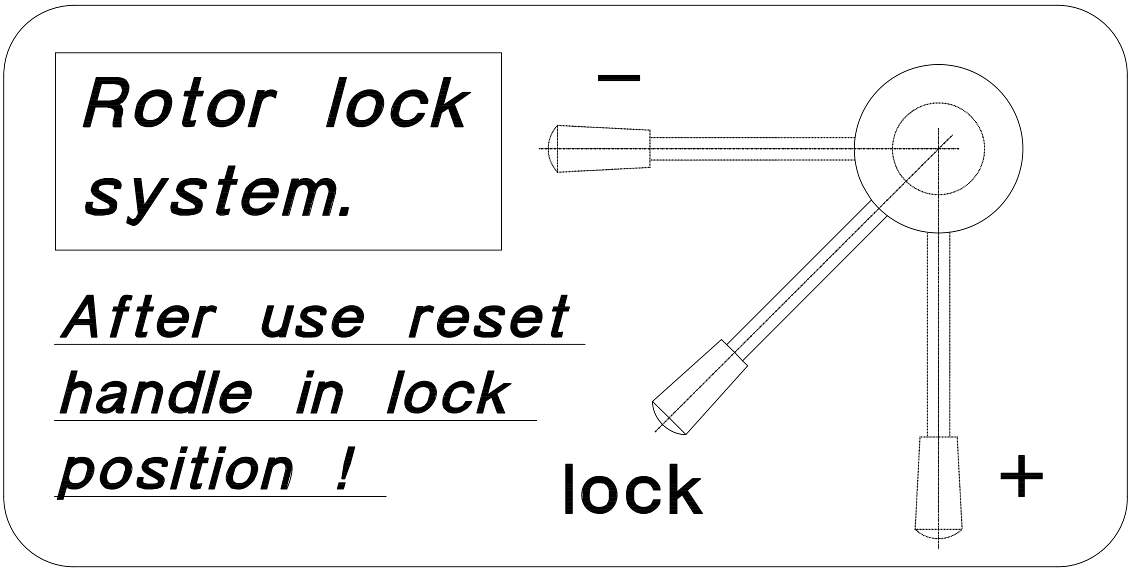


Figure 4 Handle positions

18.2 Operating the Manual Rotor Locking System with Bolts

The manual rotor locking system is used in case of servicing:

- Gearbox repairs
- Gearbox replacements
- Transport of nacelle
- Turbine standstill for long period of time: > 48 hours

The manual rotor lock must be used as an alternative to the hydraulic rotor lock
The following components must be used when operating the manual rotor lock.

Item number	Description	Quantity
950461	Centering mandrels	3
782137	M42 special nut	16
782138	Washer	16
782139	M42 special bolt	16
782142	Shim for rotor lock	16
782141	Hex.soc.h.scr.M16x60 yellow	16x8 = 128

Prior to mounting the manual rotor lock:

- Set the turbine in PAUSE mode and activate the <emergency stop button> to activate the disc brake.

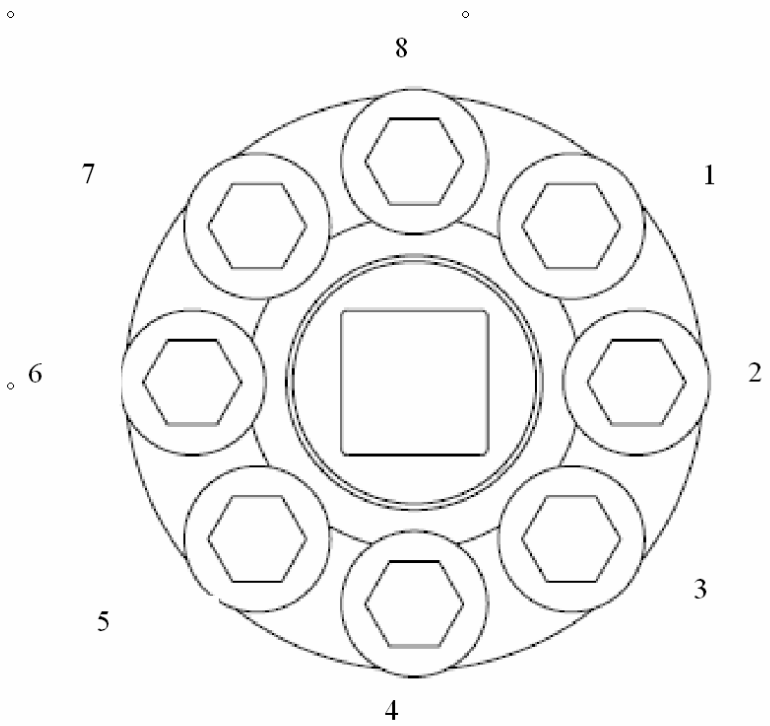
18.2.1 Mounting the manual rotor lock

1. Turn the hub until the highest point points up and one of the blade bearings points downwards.
2. Lock the rotor with the hydraulic rotor lock or mount the three centering mandrels using 3 x 2 M20x40 from in front of the hub flange and into the locking holes of the main foundation.
3. Place 16 x M42 bolts (782139) 5 on each side and 6 in the top.
4. Insert 16 shims (782142) so the bolt is placed in the slot and the shims. Use a small hammer for mounting to ensure there is no space between the shim and the hub/main foundation.
5. Screw on the special nut, with washer underneath so it hits the hub flange.
6. Tighten the yellow M16 special bolts (782141) following this procedure:
   Tighten the 8 M16 bolts to 70Nm. Then tighten the 8 M16 bolts to 140Nm in a circular way and proceed with this operation with the first 3 bolts again, so you at the end have tightened 11 bolts to 140Nm.
   (see figure on the following page)

NOTE

Do not at any time remove the centering mandrels when the M 16 bolts are not tightened.

Tightening force sequence, the full sequence has to be used.



Bolt nr.	Torque Nm
1	70
2	70
3	70
4	70
5	70
6	70
7	70
8	70
1	140
2	140
3	140
4	140
5	140
6	140
7	140
8	140
1	140
2	140
3	140

Figure 5

18.2.2 Dismantling the manual rotor lock after service work

1. Loosen all the M16 special bolts.
2. Loosen and remove all M42 special nuts.
3. Remove all the M42 special pin bolts
4. Remove the centering mandrels or pull back the hydraulic rotor lock.

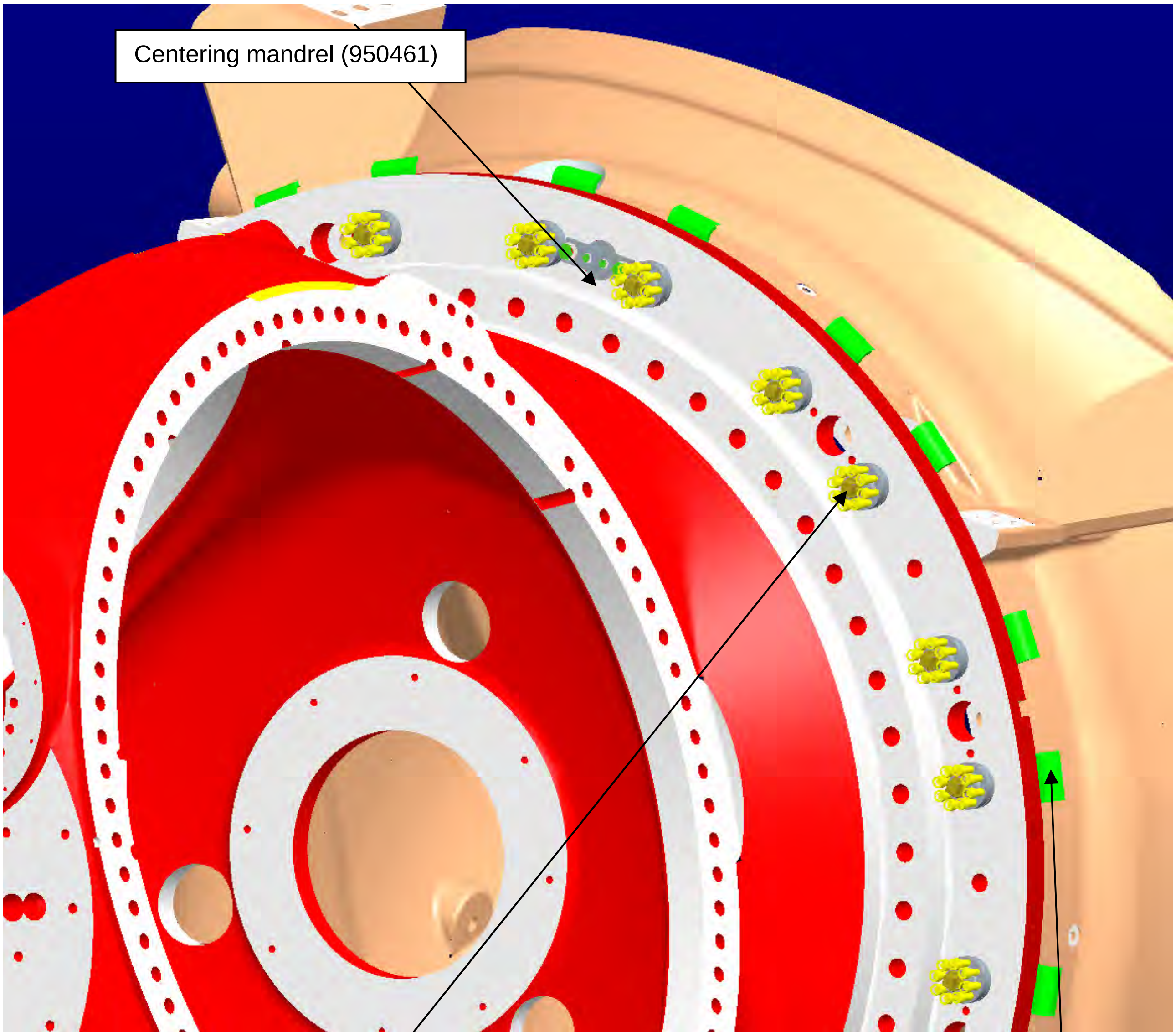


Figure 6

950084.R1

All these components are shown in an additional document 958627.

19. Operating the Internal Crane

Limitations on use:

- Lift or landing to floating vessels is not permitted for any crane constellation.
- Lift or lowering of personnel is not permitted for any crane constellation.
- Do not use any of the crane constellations for external operation above wind speed 15 m/sec 10 min.
- Do not operate the crane without correct authorization.

After 50 lifts with 12000 kg load the crane must be recertified:

- Inspect all welding on both trolleys for cracks. Repair or replace damaged items.
- Inspect all welding on lattice construction for cracks. In case of cracks Vestas Technology must be contacted.
- Replace all bolts, nuts and washers on bridge and trolley.
- Check rollers for free rotation, replace if malfunction.
- Perform overload test.

Attach chain to prevent accidental access to hazardous area.
Open the service hatch and secure it to transformer partition wall.
Keep the service hatch closed after hoisting operation is completed.
The internal crane and the traverse must be fastened in parked position when turbine in operation.

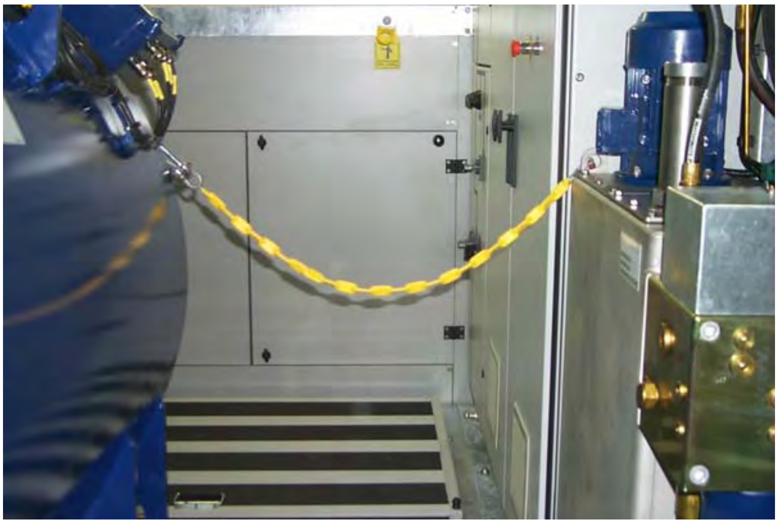


Figure 7 Attach chain


Figure 8 Service Hatch

Release the chain from the chain box.


Figure 9 The chain box

The crane can be moved longitudinally by a winch mounted on the machine foundation.

Figure 10 The Crane Winch placed on foundation.

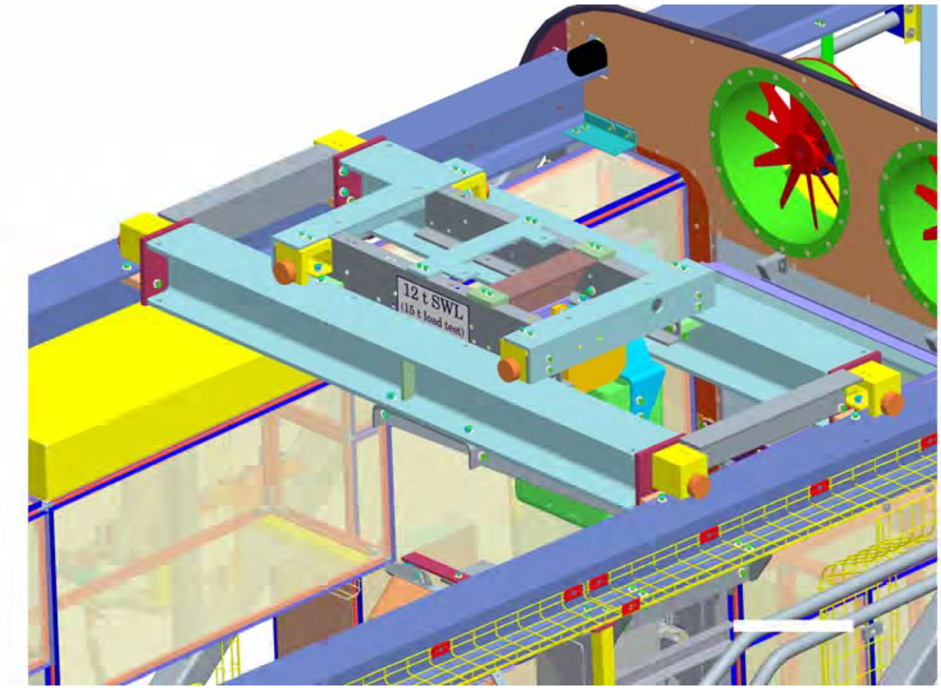


Figure 11 The crane in parked position

General crane functions:

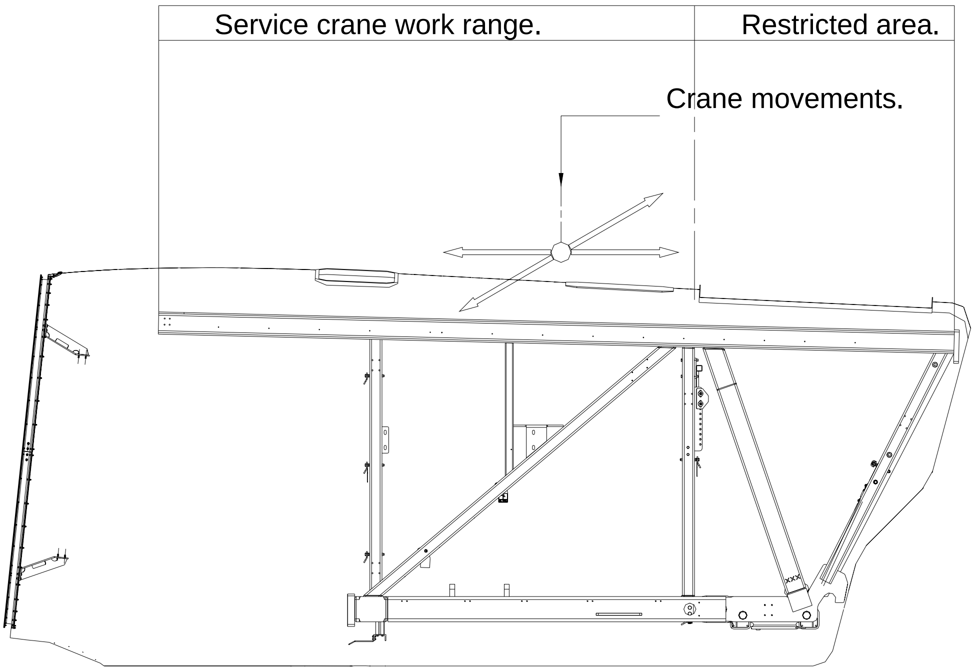
The internal nacelle overhead traverse trolley support 4 lifting functions, each with specific manual.

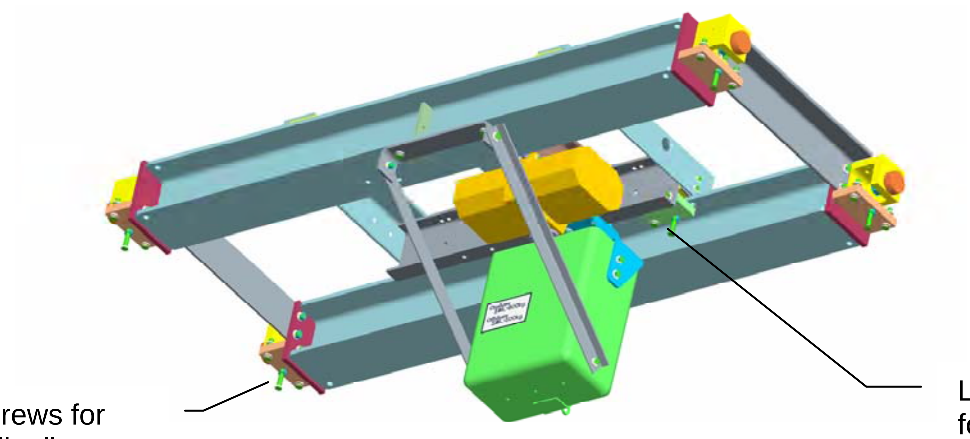
- Normal service operation. Max. Work load is 800 kg.

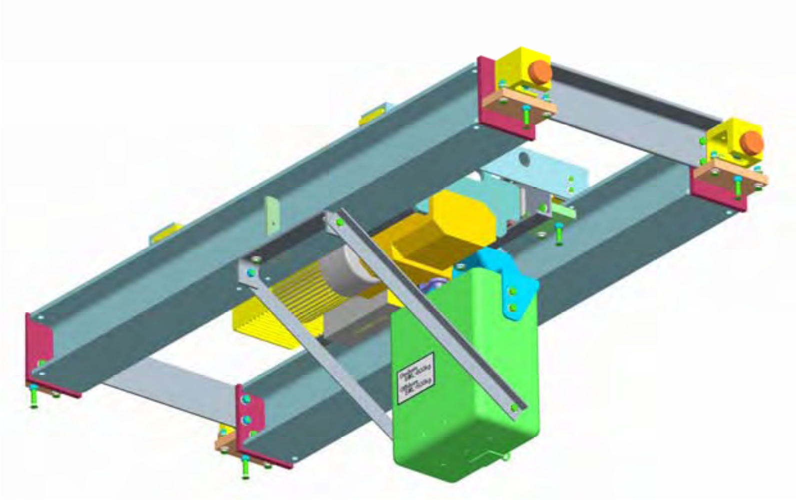
Prior to lowering the trolley must be locked in sideways direction by tightening lock screws ¼ extra turn after contact and in longitudinally direction locked by keeping the steel wire tensioned and tightening lock screw for longitudinally direction by tightening lock screws ¼ extra turn after contact .
Warning:
Visual inspect:

- The bridge and trolley for corrosion, wear, defect bolts and connections before using the crane.
- Winch for oil/grease leaks and corrosion.

The crane must not be used before defects are repaired.

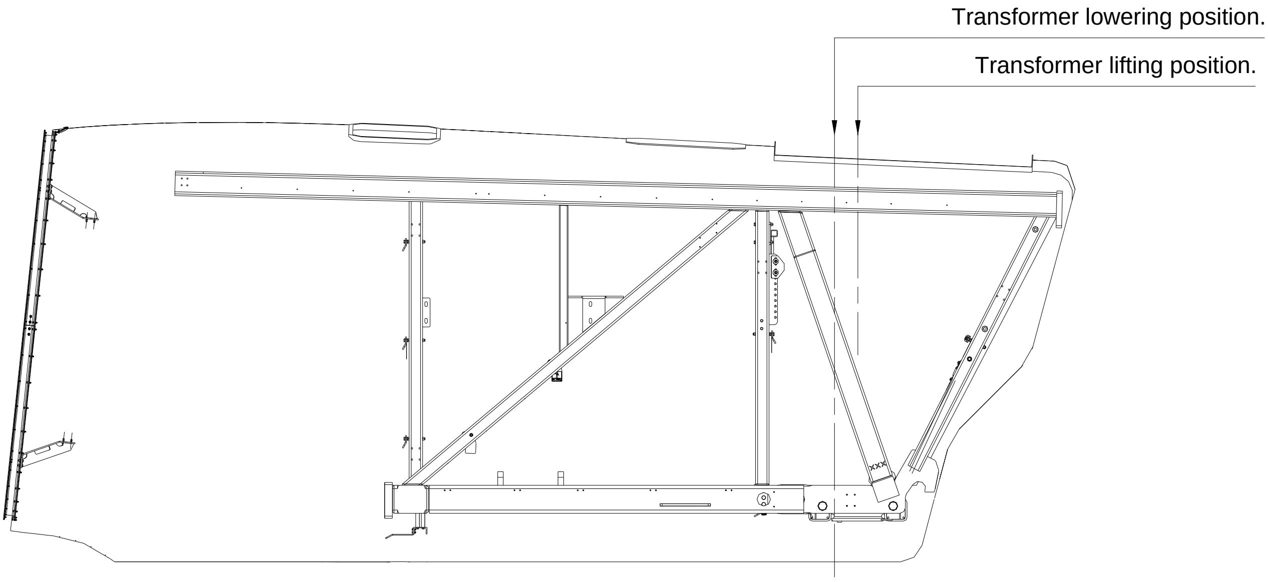






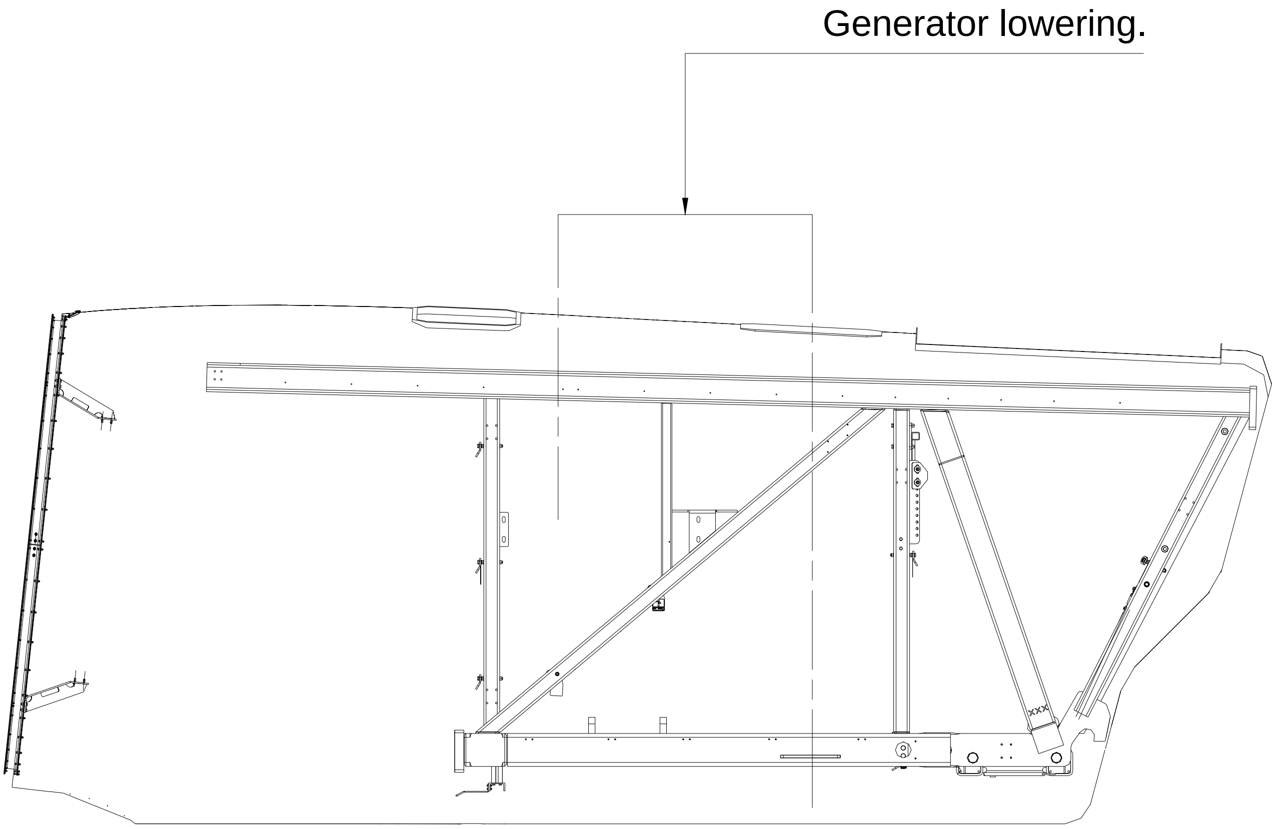
- Lifting transformer. Max. work load is 12000 kg.

This operation is only to be done by authorized personnel.



- Lifting generator. Max. Work load is 12000 kg.

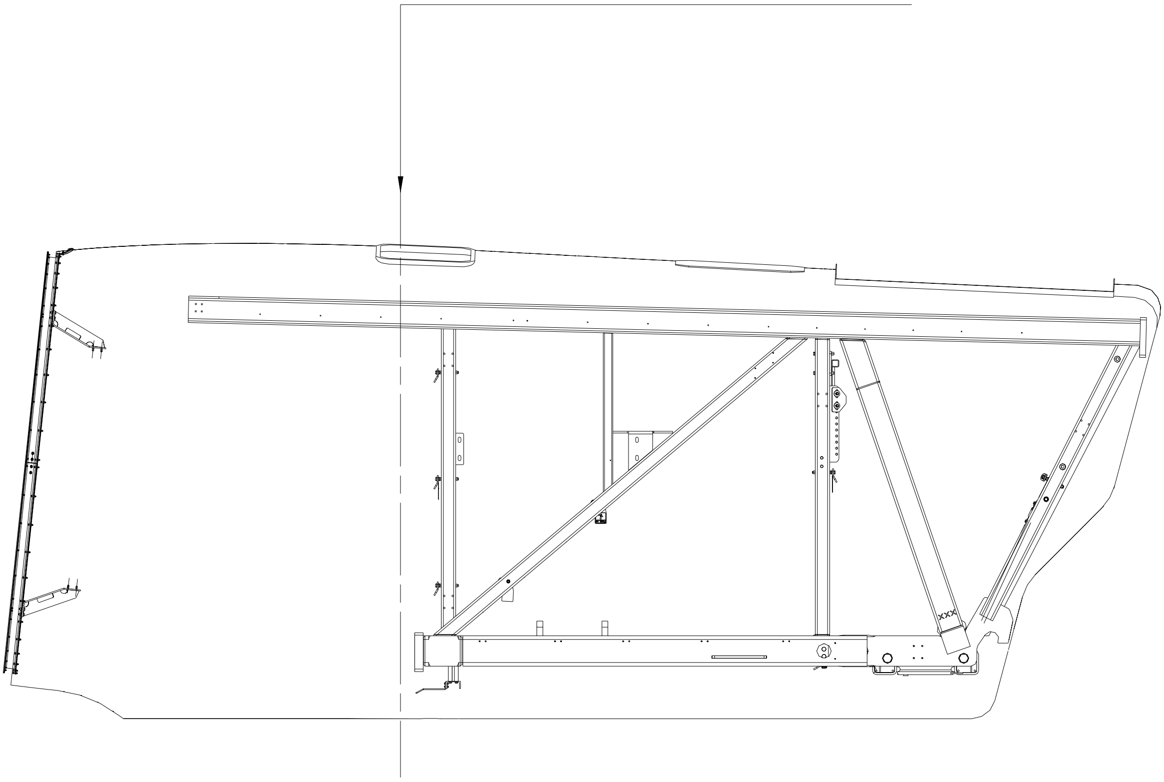
This operation is only to be done by authorized personnel.



Internal crane for lifting components in the hub:

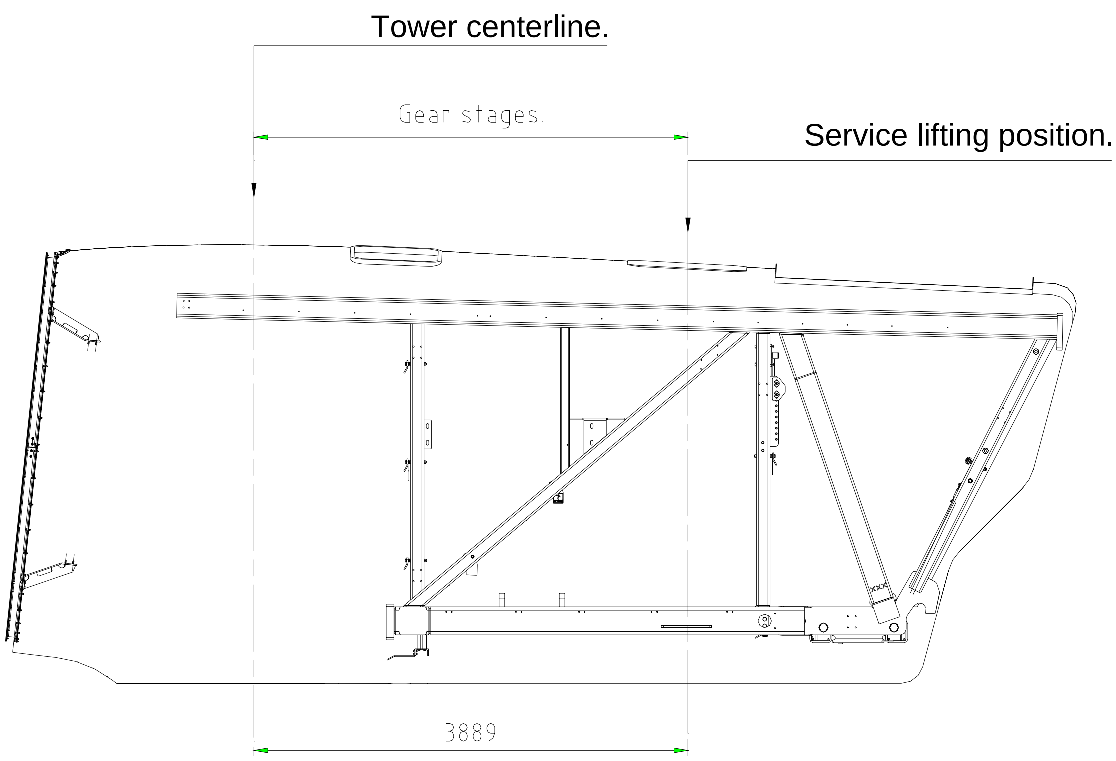
This operation is only to be done by authorized personnel.

Hub components position.



Internal crane for lifting gear stages, Max. work load is 12000 kg:

This operation is only to be done by authorized personnel.



Memorandum

Date: July 3, 2018

To: NECEC Noise Permitting Team

From: Gabriel Weger and Chris Howell, Burns & McDonnell

Subject: Independent Review of the Sound Assessment for NECEC

Tech Environmental, Inc. (TE) completed an independent peer review of the acoustic impacts of the New England Clean Energy Connect (NECEC). The purpose of the review was to determine if the sound assessment submitted for NECEC was reasonable and technically correct according to standard engineering practices, and to determine if the Maine DEP can use the information to draw conclusions about compliance of the NECEC with the Maine Noise Regulations.

One question James Beyer asked was, "Does a DC line produce a different sound level than an AC line." AC and DC transmission lines produce similar types of sounds. However, the amplitudes of the sound levels produced are different for each type of line. Table 5-1 of the application provides the audible noise levels at the edge of the right-of-way during fair and foul weather conditions for each of the AC lines (345-kV AC H-Frame, and 345-kV AC Lattice Structure) and DC lines (320 kVDC). The worst-case sound levels for each type of line are shown under the "75 feet from center of structure" heading.

TE provided several comments and information requests in their review. The requests along with Burns & McDonnell's responses are provided below:

1. Tonal noise with regards to local ordinances.

[TE Remarks]

If a proposed noise source generates Tonal Sound, a type of noise contained in the Maine Noise Regulations but not in the local ordinances, then those local ordinances will not be applied "in lieu of" the Maine Noise Regulation. Thus, establishing if NECEC sound sources will create Tonal Sound is important in evaluating the Application. As discussed below, transmission line noise is undoubtedly Tonal Sound. The information on Tonal Sound from the substations is incomplete.

[Burns & McDonnell Response]

At the direction of CMP's legal counsel, Pierce Atwood, it was established that the local noise ordinance would take precedent over the MDEP noise regulation requirements, provided the local sound level limits are within 5 dB of the MDEP sound level limits, and addresses the same types of noises. Whether the ordinance addresses tonal noise or not, would not factor into the consideration.

Because the standard is not more than 5 dBA higher than MDEP regulations, the local municipal standard is applicable. Though there is some ambiguity about whether the noise ordinance "limits or addresses the various types of noises contained in this regulation or all the types of noises generated by the development," it seems reasonable to rely on MDEP's past conclusions on Site Law permit applications (e.g. CMP's Maine Power Reliability Program projects) that the provision does not apply when the local standard is applicable. Thus, it is reasonable to conclude that the MDEP's Site Law noise rule, including its "tonal penalties" provision, does not apply to those NECEC substations within municipalities having local noise ordinances. Tonal noise is not a type of noise but, rather, is a quality of noise. This is consistent with other approved applications that MDEP has reviewed in the past.

2. Transmission line noise.
[TE Remarks]
We recommend the Department request the following additional information regarding the transmission line noise assessment:

1. Update the assessment to include tonal noise and discussion of the 5-dBA Tonal Sound Penalty.
2. Provide supporting documentation from the acoustic modeling.
3. List all property boundaries (show on maps, identify land owners) where the 345-kV, AC transmission line broadband sound levels under wet conductor conditions are predicted to exceed 40.0 dBA without a tonal noise penalty.
4. Provide a mitigation strategy for each instance in Item 3.

[Burns & McDonnell Response]
Audible noise (AN) from the transmission lines is generated in two ways. The first is a 120-Hz hum (i.e., $2f$ noise) that is associated with magnetic-field caused vibrations in the lines and is directly related to the amount of voltage carried on the line. Because the voltage on the line does not change, the $2f$ noise does not change. The second mechanism for a transmission line to generate noise happens at higher frequencies associated with corona on the lines. Corona is the partial electrical breakdown of the insulating properties of air around the conductors of a transmission line when the voltage gradient exceeds a certain critical value. In a small volume near the surface of the conductors, energy and heat are dissipated, and some of this energy is released in the form of pressure fluctuations that result in AN. Corona-generated AN can be characterized as a hissing, crackling sound, and is not considered to be tonal. Corona-generated AN is of concern primarily for high-voltage transmission lines operating at voltages of 345 kV and higher.

The Bonneville Power Administration (BPA) Corona and Field Effects Program was used to calculate the expected AN from the transmission lines. The model calculates total AN based on data from actual field surveys, and laboratory tests. The surveys would measure total noise from a variety of transmission lines and conductor combinations. The measured transmission line AN would include both $2f$ and corona noise. Therefore, the model predictions account for both $2f$ and corona generated AN.

AN associated with $2f$ and corona may be of similar amplitude during fair weather conditions. Coronal noise typically increases during foul weather conditions, but $2f$ noise will remain constant regardless of meteorological conditions. Studies have shown that tonal noise is difficult to measure and is generally not warranted.[1] Because tonal noises are not expected during foul weather periods when AN would be loudest, there is no need to apply a tonal penalty to the predicted values presented in the NECEC Site Law Application.

In general, the AN levels for the transmission lines and conductors were modeled based upon conservative assumptions and/or program defaults for conditions relating to the operation of existing transmission lines and for the expected conditions of the new, 345 kV AC and 320 kV DC transmission lines, during fair and foul weather conditions. General model inputs are as follows:

INPUT	DC Line Values	AC Line Values
Number of Phases	2	3
Total Number of Conductors	4	5
Pole-Ground Voltage	+/- 320 kV DC	345 kV AC
Wind Velocity	2.0 mi/hr	2.0 mi/hr
Rain Rate	1.0 in/hr	1.0 in/hr
Altitude	1100 ft	400 ft
Vertical Height of Audible Noise Microphone	5 ft	5 ft
Conductor Sag	28.60 ft	28.60 ft
OPGW Sag	8.64 ft	8.64 ft
OHSW Sag	7.42 ft	7.42 ft
OPGW Diameter	1.974 in	1.974 in
OHSW Diameter	0.433 in	0.433 in
Bundle Center Midspan Height	34 ft	32 ft
Number of Subconductors	2	2
Subconductor Diameter	1.545 in	1.545 in
Bundle Spacing	18 in	18 in
Line-Ground Voltage	320 kV DC	209.145 kV AC
Phase Angle	0	A,B,C top to bottom/left to right
Phase Current	1,200 MVA	2,626 MVA
ROW Width	200 ft	200 ft

[1] V. L. Chartier and R. D. Stearns. "Formulas for Predicting Audible Noise from Overhead High Voltage AC and DC Lines." IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No, IT January 1981, pp. 121-129.

Because it would be impractical to analyze every portion of the transmission line for every distance and conductor combination, worst-case and conservative conditions were selected for the analysis. As noted in the report, transmission line conductor AN levels at the edges of the various ROWs, in fair weather conditions, will be well below the applicable noise limits. The maximum AN levels at the edge of ROW under fair weather conditions are expected to be approximately 28 dBA. The potential 120-Hz hum portion of the transmission line noise would be generated during fair weather conditions, along with minimal corona noise, if any. The 120-Hz hum would not increase due to a change in weather conditions, as it is not dependent on moisture in the air. This tonal portion of the transmission line AN would be well below any applicable regulation, even with a 5-dB penalty added.

The non-tonal portion of transmission line AN, corona, varies with weather conditions. Moisture in the air increases AN associated with corona effects. The expected maximum AN produced by a typical conductor at the closest edge of ROW, under foul weather/wet conditions, is expected to be approximately 41 dBA. The increase from the 28-dBA fair weather sound level is due to the increase in corona noise. The 120-Hz hum or the tonal portion of the AN would not increase under foul weather. Therefore, the AN level under foul weather/wet conditions would not be tonal as defined by the MDEP, since it would be dominated by the corona noise, if not the ambient noise. No tonal penalty would be added to the measured sound level under these conditions, the transmission line AN is expected to be below the applicable State or local sound level regulation identified along the transmission line path, and therefore no mitigation is required or proposed.

3. Merrill Road Substation.
[TE Remarks]
We recommend the Department request the following <u>additional information</u> regarding the Merrill Road Substation noise assessment:

1. Provide the ground factor "G" used in the CadnaA modeling.
2. Provide octave band sound power levels for all noise sources used in the acoustic modeling.
3. Provide the CadnaA-predicted octave band sound levels, by source and the total, at receptor PL-5 and discuss why a Tonal Sound is, or is not, produced at that receptor.

[Burns & McDonnell Response]
The ground factor for the CadnaA modeling was 0.5 for all areas. The City of Lewiston Code of Ordinances Appendix A Section 19 does not address tonal noise. Octave band sound levels are not required by the ordinance and would not assist in determining compliance. The modeled overall sound levels for each sound source are provided in Table 5-8 of the NECEC Site Law Application. Octave band sound levels modeled for the noise emitting equipment were based on

historical projects' equipment of similar size. The equipment octave bands would likely change based on the vendor selected and their supplied sound data; however, the overall sound levels would be specified to meet those provided in the application. Equipment vendors have not been selected at this point in the project.

4. Larrabee Road Substation.
[TE Remarks]
We recommend the Department request the following additional information regarding the Larrabee Road Substation noise assessment:

1. Provide the ground factor "G" used in the CadnaA modeling.

[Burns & McDonnell Response]
The ground factor for the CadnaA modeling was 0.5 for all areas.

5. Fickett Road Substation

[TE Remarks]
We recommend the Department request the following additional information regarding the Fickett Road Substation noise assessment:

1. Provide the ground factor "G" used in the CadnaA modeling.
2. Provide octave band sound power levels for all noise sources used in the acoustic modeling.
3. Provide the octave band CadnaA model results, by source and the total, at Receptors PL-1 and PL-2, and discuss why a Tonal Sound is, or is not, produced at those receptors. Clearly explain where a 5-dB penalty has, or has not, been added to the table results.

[Burns & McDonnell Response]
The ground factor for the CadnaA modeling was 0.5 for all areas. Octave band sound levels are not required by the ordinance and would not assist in determining compliance. The modeled overall sound levels for each sound source are provided in Table 5-15 of the NECEC Site Law Application. Octave band sound levels modeled for the noise emitting equipment were based on historical projects' equipment of similar size. The equipment octave bands would likely change based on the vendor selected and their supplied sound data; however, the overall sound levels would be specified to meet those provided in the application. Equipment vendors have not been selected at this point in the project.

At locations PL-1 and PL-2, Dry Air Cooler noise dominates substation-generated sound. Though some cooling fans can be tonal in nature, the equipment vendor, ABB, provided sound data for the dry air coolers that established the units would not emit tonal sounds. Therefore, a tone would not be present at these locations and a tonal penalty would not need to be applied.

6. Coopers Mills Road Substation

[TE Remarks]

We recommend the Department request the following additional information regarding the Coopers Mills Road Substation noise assessment:

1. Provide the ground factor "G" used in the CadnaA modeling.
2. Verify the three existing transformers were included in the CadnaA model, or redo the acoustic modeling with the three existing transformers added to the proposed new sound sources.
3. Provide a firm commitment to construct the two sound walls described in the Response to Information Request #8, or equivalent sound mitigation.

[Burns & McDonnell Response]

The ground factor for the CadnaA modeling was 0.5 for all areas. The three existing sources mentioned are included in the model, along with six (6) air-cooled shunt reactors and three (3) sets of capacitor banks. The existing source sound levels are provided in the table below.

The two sound walls may be necessary for compliance depending on the final design of the substation. If required, the sound walls' final design will be appropriate such that modeling will demonstrate compliance with the sound level limits at the property line.

Equipment	Modeled Sound Level
Transformer 1	82 dBA SPL at 3 feet
Transformer 2[a]	68 dBA SPL at 3 feet
Transformer 3[a]	65 dBA SPL at 3 feet
Capacitor Banks (3)	80 dBA SWL
Reactors [b] (6)	87 dBA SWL

(a) Source sound levels established by field measurements at Coopers Mills Substation.
(b) Sources based on reactor sound data from Albion Road Substation which has the same units.