Wind Turbine Noise

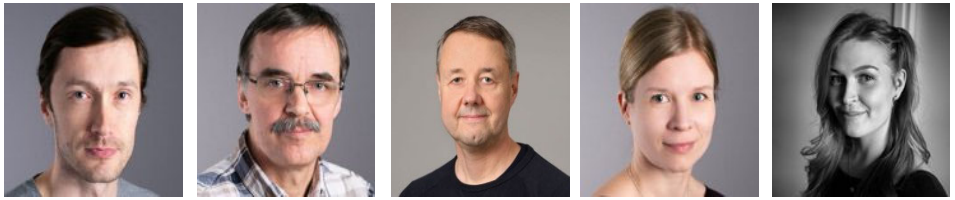
Valtteri Hongisto

valtteri.hongisto@turkuamk.fi 040 5851 888
Research group leader in Turku University of Applied Sciences

Aalto University 11 Nov 2022
"PHYS-E6572 - Advanced Wind Power Technology"

Built Environment Research Group

TURKU AMK
TURKU UNIVERSITY OF APPLIED SCIENCES


Leading disciplines/competences
- Building acoustics
- Environmental acoustics
- Occupational noise
- Air conditioning
- Air quality
- Physical indoor environment
- Environmental psychology
- Psychophysics

Laboratory facilities
- Acoustics laboratory
- Psychophysics laboratory
- Ventilation laboratory

Wind turbine noise
- One of our interests
- Noise measurements
- Noise modeling
- Human perception
- Health effects

Current projects
- Indoor environment in offices
- Underwater noise in Baltic Sea
- School noise
- Impact sound insulation of wooden floors

Objects
- Building products
- Buildings
  - Residences, hospitals, offices, schools
- Human responses
  - Workplace stressors
  - Environmental stressors

Our papers related to WT sound

KANSAINVÄLISET VERTAISARVIOIDUT JULKAISUT - INTERNATIONAL PEER-REVIEWED PAPERS

Rajala, V., Hakala, J., Alakoivu, R., Koskela, V., Hongisto, V. (2022). Hearing threshold, loudness, and annoyance of infrasonic versus non-infrasonic frequencies. Applied Acoustics 198 108981 13+6 pp. Open access at: https://doi.org/10.1016/j.apacoust.2022.108981.

Radun, J., Maula, H., Saarinen, P., Keränen, J., Alakoivu, R., Hongisto, V. (2021). Health effects of wind turbine and road traffic noise on people living near wind turbines. Renewable and Sustainable Energy Reviews 157 112040 (13 pp). Open access at: https://www.sciencedirect.com/science/article/pii/S1364032121013022.

Virjonen, P., Hongisto, V., Radun, J. (2019). Annoyance penalty of periodically amplitude-modulated wide-band sound. The Journal of the Acoustical Society of America, 146(6) 4159–4170.

Keränen, J., Hongisto, V., Hakala, J. (2019). The sound insulation of façades at frequencies 5□5000 Hz. Building and Environment, 156 12-20.

Radun, J., Hongisto, V., & Suokas, M. (2019). Variables associated with wind turbine noise annoyance and sleep disturbance. Building and Environment, 150 339-348.

Hongisto, V., Keränen, J., Oliva, D. (2017). Indoor noise annoyance due to 3-5 MW wind turbines - an exposure-response relationship, The Journal of the Acoustical Society of America 142(4) 2185-2196. Open access at: http://dx.doi.org/10.1121/1.5006903.

KANSAINVÄLISET KONGRESSIJULKAISUT – INTERNATIONAL CONGRESS PAPERS

Hongisto, V., Radun, J., Maula, H., Saarinen, P., Keränen, J., Alakoivu, R. (2022). Finnish study on the health effects of environmental noise among residents living close to a wind power area. Manuscript submitted. Proc. of Internoise 2022, paper 960, 7 pp., 21□24 Aug, Glasgow, UK. Online at: https://internoise2022.org/.

Hongisto, V., Keränen, J., Hakala, J. (2022). The sound insulation of façades at infrasound frequencies. Proc. Euroregio/BNAM20220, 403-405, 9th-11th May, 2022, Aalborg, Denmark. Online at: https://bnam2022.org/wp-content/uploads/2022/05/ERBNAM2022_Proceedings.pdf.

Hongisto, V., Radun, J., Maula, H., Saarinen, P., Keränen, J., Alakoivu, R. (2022). Health effects of environmental noise in a wind power area. Proc. Euroregio/BNAM20220, 11-17, 9th-11th May, 2022, Aalborg, Denmark. Online at: https://bnam2022.org/wp-content/uploads/2022/05/ERBNAM2022_Proceedings.pdf.

Hongisto, V., Virjonen, P. (2019). Annoyance penalty of amplitude-modulated sound. Paper 976. Proc. 23rd Int. Congress on Acoustics ICA 2019, 9-13 Sep, 2019, Aachen, Germany. Available at: http://pub.dega-akustik.de/ICA2019/data/articles/000976.pdf.

Radun, J., Hongisto, V. (2019). Non-acoustic and acoustic variables associated with wind turbine noise annoyance. Paper 610. Proc. 23rd Int. Congress on Acoustics ICA 2019, 9-13 Sep, 2019, Aachen, Germany. Available at: http://pub.dega-akustik.de/ICA2019/data/articles/000610.pdf.

Keränen, J., Hongisto, V. (2018). Long-term measurement of noise immission from wind turbines. Conf. Proc. Euronoise 2018. 2859-2863. ISSN 1116-5147. 27-31 May 2018, Hersonissos, Crete, Greece. Open access at: http://www.euronoise2018.eu/docs/papers/472_Euronoise2018.pdf.

Keränen, J., Hakala, J., Hongisto, V. (2018). Façade sound insulation of residential houses within 5 – 5000 Hz. Conf. Proc. Euronoise 2018. 1549-1553. ISSN 1116-5147. 27-31 May 2018, Hersonissos, Crete, Greece. Open access at: http://www.euronoise2018.eu/docs/papers/259_Euronoise2018.pdf.

Hongisto, V., Oliva, D. (2017). Noise annoyance caused by large wind turbines – a dose-response relationship, 12th ICBEN Congress on Noise as a Public Health Problem, paper 4059, 5 pp., 18-22.2017 Zurich, Switzerland. Available at: http://www.icben.org/2017/ICBEN%202017%20Papers/SubjectArea06_Hongisto_0610_4059.pdf.

KANSALLISET JULKAISUT – FINNISH PAPERS

Hongisto, V., Radun, J., Maula, H., Saarinen, P., Keränen, J., Alakoivu, R. (2022). Tuulivoiman ja tieliikenteen melun terveysvaikutukset. Ympäristö ja Terveys -lehti 1 52-59. Available at: https://www.turkuamk.fi/fi/artikkelit/3010/tutkimus-tieliikennemelu-on-tuulivoimamelua-vakavampi-terveysriski/

Radun, J., Hongisto, V. (2019). Tuulivoimamelun häiritsevyyteen liittyvät ei-akustiset ja akustiset tekijät. Akustiikkapäivät 2019, Oulu, 28-29.10.2019, 301-306, Akustinen Seura ry., Espoo. ISBN 978-952-60-3784-4. http://www.akustinenseura.fi/wp-content/uploads/2019/10/akustiikkapaivat_2019_s301.pdf.

Hongisto, V., Virjonen, P. (2019). Amplitudimoduloidun äänen häiritsevyys ja sanktiointi. Akustiikkapäivät 2019, Oulu, 28-29.10.2019, 284-287, Akustinen Seura ry., Espoo. ISBN 978-952-60-3784-4. http://www.akustinenseura.fi/wp-content/uploads/2019/10/akustiikkapaivat_2019_s284.pdf.

Hongisto V, Keränen J, Hakala J, Julkisivurakenteiden ääneneristävyys pientaajuuksilla, Rakennusfysiikka 2017, 24-26.10.2017, Tampere, 571-576, Tampereen teknillinen yliopisto. ISBN 978-952-15-4023-3.

Hongisto V, Oliva D, Keränen J, Tuulivoimamelun häiritsevyyden riippuvuus äänitasosta, Akustiikkapäivät 2017, s. 164-169, 24-25.8.2017 Espoo, Akustinen Seura ry., Espoo, 2017 (ISBN 978-952-60-3734-9). Open access at: http://www.akustinenseura.fi/wp-content/uploads/2017/08/akustiikkapaivat_2017_s164.pdf

Hongisto V, Keränen J, Tuulivoimamelun pitkäaikaismittaus, Akustiikkapäivät 2017, s. 158-163, 24-25.8.2017 Espoo, Akustinen Seura ry., Espoo, 2017 (ISBN 978-952-60-3734-9). Open access at: http://www.akustinenseura.fi/wp-content/uploads/2017/08/akustiikkapaivat_2017_s158.pdf

Keränen J, Hakala J, Hongisto V, Pientalojen ääneneristävyys ympäristömelua vastaan taajuuksilla 5–5000 Hz - infraäänitutkimus, Akustiikkapäivät 2017, s. 123-128, 24-25.8.2017 Espoo, Akustinen Seura ry., Espoo, 2017 (ISBN 978-952-60-3734-9). Open access: http://www.akustinenseura.fi/wp-content/uploads/2017/08/akustiikkapaivat_2017_s123.pdf.

Hongisto V. ja Oliva D. (2017). Tuulivoimaloiden infraäänet ja niiden terveysvaikutukset. Turun ammattikorkeakoulun raportteja 239, Turku. ISBN 978-952-216-653-1 (pdf). Available at: http://julkaisut.turkuamk.fi/isbn9789522166531.pdf.

Hongisto, V., Suokas, M., Varjo, J., Yli-Kätkä, V.-M. (2015). Tuulivoimalamelun häiritsevyys kahdella tuulivoima-alueella, Ympäristö ja Terveys -lehti, 6 2015 54-59. Available at: https://tuulivoimayhdistys.fi/media/794-hongisto_ym_2015_ymparisto_ja_terveys.pdf

Hongisto, V. (2014) Tuulivoimalamelun terveysvaikutukset, 64 s., Työterveyslaitos, Helsinki, Lokakuu 2014. Available at: https://www.julkari.fi/handle/10024/116854.

Wind Turbine Noise.
1. Fundamentals

Basic definitions of point sources outdoors

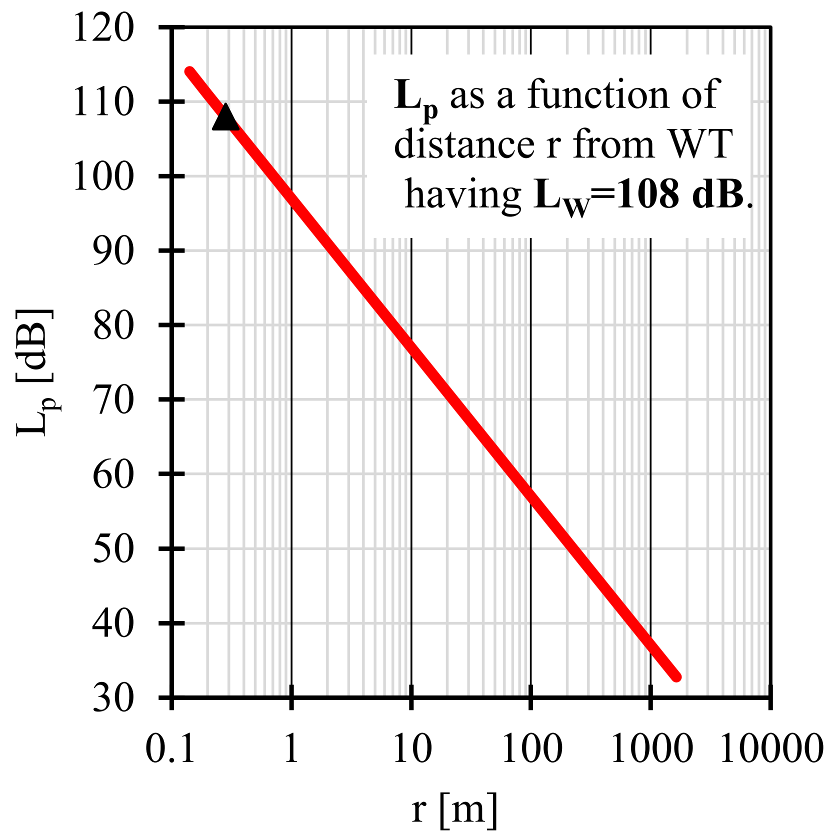
- Sound pressure level, SPL, $\mathbf{L_p}$, describes the amplitude of sound in a specific position
- SPL reduces every time by 6 dB when the distance to source is doubled.
- Sound power level, SWL, $\mathbf{L_W}$, describes the total sound energy produced by a sound source.

- SPL produced by a sound source of certain SWL is obtained by equation

$$L_W = L_p + 10 \cdot \log_{10}(S)$$

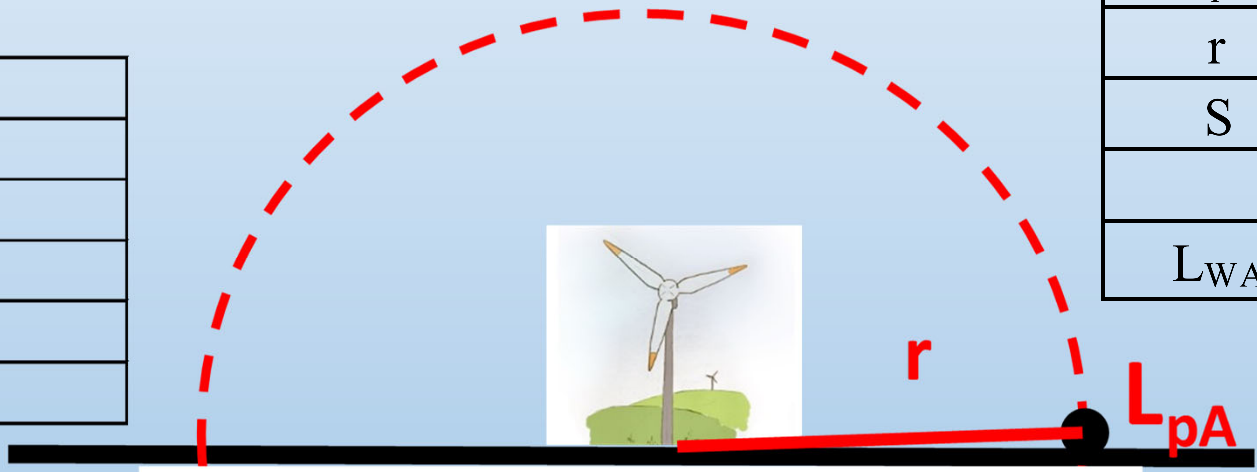
$$L_p = L_W - 10 \cdot \log_{10}(S)$$

  - S [m^2] is the area of spherical measurement surface around the source.
- For point sources, like WTs, $S = 4\pi r^2$, where r is the radius of spherical measurement surface.



Example 11

SWL of a wind turbine is measured at a distance of 200 meters from the tower.
The microphone is located on the ground on top of a reflecting veneer plate.
The position produced 6 dB higher values than the position higher from the ground.
The A-weighted SPL is L_{pA}=58 dB.
Calculate A-weighted SWL, i.e. L_{WA}.

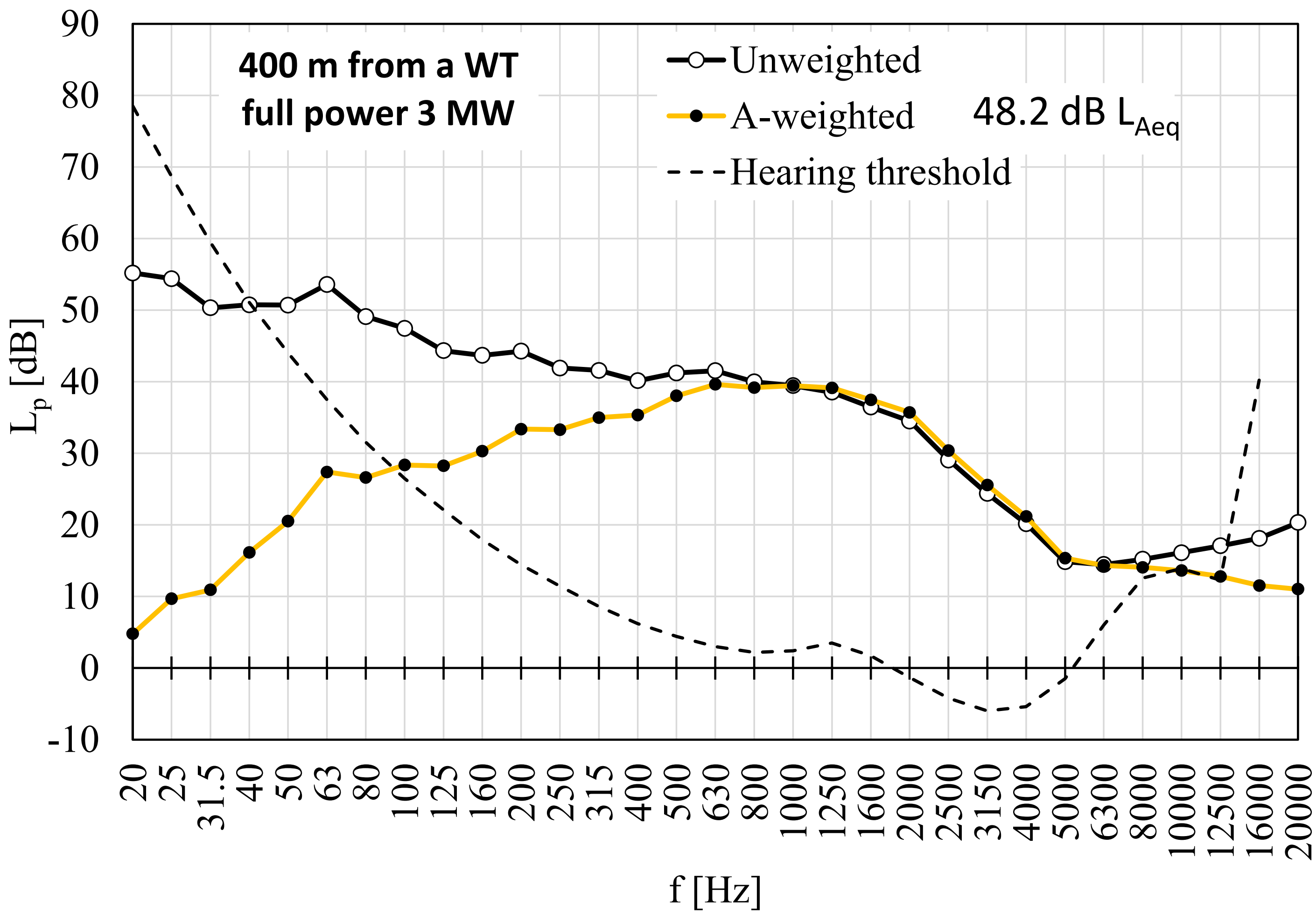


$$L_W = L_p + 10\log_{10} S$$

$L_{pA,plate}$	[dB]	60
L_{pA}	[dB]	54
r	[m]	200
S	[m2]	251320
		54.00
L_{WA}	[dB]	108.0

Frequency, A-weighting, and spectrum of WT sound

- Human can hear frequencies 2-20000 Hz.
- However, sound is nearly always measured within frequencies 20-20000 Hz
- Sensitivity of hearing reduces towards low frequencies
- Therefore, A-weighting is applied different frequencies f to obtain such frequency distribution of sound that corresponds to our perception.
- WT sound is audible only within 50-8000 Hz in the vicinity of a WT.
- Beyond 2 km, the audible band is only 250-2000 Hz



	A
20	-50.4
25	-44.7
31.5	-39.4
40	-34.6
50	-30.2
63	-26.2
80	-22.5
100	-19.1
125	-16.1
160	-13.4
200	-10.9
250	-8.6
315	-6.6
400	-4.8
500	-3.2
630	-1.9
800	-0.8
1000	0.0
1250	0.6
1600	1.0
2000	1.2
2500	1.3
3150	1.2
4000	1.0
5000	0.5
6300	-0.1
8000	-1.1
10000	-2.5
12500	-4.3
16000	-6.6
20000	-9.3

Wind Turbine Noise.
2. Properties and regulations

General regulations for environmental noise

- Environmental noise levels such as roads and industry
- The values are used in environmental planning
- Industrial wind turbines did not exist in 1992.
- This regulation was valid for wind turbines until September 2015.

Valtioneuvoston päätös 993-1992	Day time 07-22 T =15 h	Night time 22-07 T =9 h
Regulated values outdoors	$L_{A,eq,T}$ [dB]	$L_{A,eq,T}$ [dB]
Residential areas, recreational areas, health care accommodations	55	50
New areas	55	45
Educational areas	55	-
Residential areas for holiday seasons, camping areas, protected natural areas	45	40
Regulated values indoors	$L_{A,eq,T}$ [dB]	$L_{A,eq,T}$ [dB]
Living, patient and accommodation rooms	35	30
Education and meeting spaces	35	-
Service and office rooms	45	-

NOTE. If the noise includes impulsive or narrow-band character, 5 dB is added to the measured or predicted value before comparing to the tabulated values.

Regulations for wind turbines

- The values are used in environmental planning
- The values concern only **outdoor** noise levels
- Indoor noise levels are regulated in STM 1545-2015

- The regulated values for wind turbine noise are 5 dB tighter during night time and 10 dB tighter during daytime

Valtioneuvoston asetus 1107-2015

	Daytime $L_{Aeq,07-22}$ [dB]	Night time $L_{Aeq,22-07}$ [dB]
Permanent residence	45	40
Holiday residence	45	40
Health care facility	45	40
Educational facility	45	-
Recreational areas	45	-
Camping areas	45	40
Natural parks	40	40

Health-based regulations for indoor noise

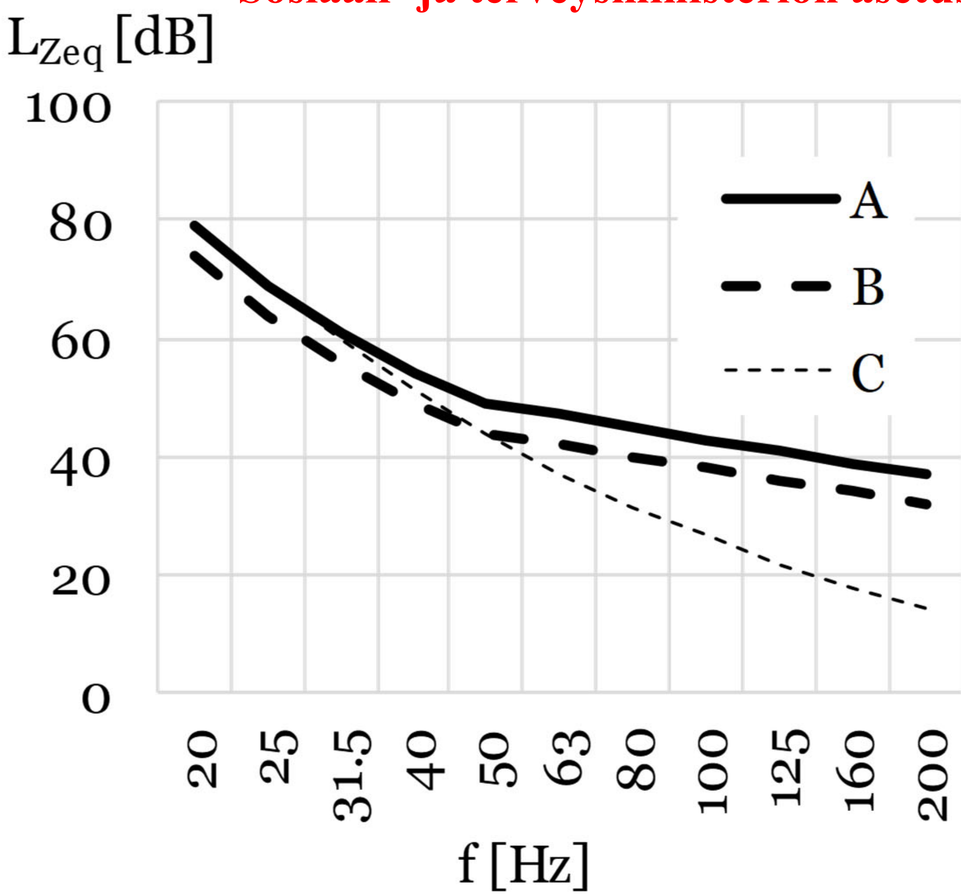
Sosiaali- ja terveysministeriön asetus 545-2015	Daytime 07-22 T=15 h	Night time klo 22-07 T=9 h	Night time 22-07 T=1h
Residential dwellings, service houses for elder and handicapped, day care centres etc.	$L_{A,eq,T}$ [dB]	$L_{A,eq,T}$ [dB]	$L_{A,eq,T}$ [dB]
Living rooms	35	30	
Other rooms and kitchens	40	40	
Sleeping rooms, sounds causing sleep disturbance			25
Meeting and education dwellings			
Communication rooms	35	-	-
Other meeting rooms	40		
Work rooms (from clients' point of view)			
Office rooms, rooms for clients	45	-	

NOTE: Penalty for impulsive sound is either 5 or 10 dB depending on the nature of the sound.
Penalty for tonal sound is either 3 or 6 dB depending on the nature of the sound.

Specific health-based regulations for sound level of low frequency noise in sleeping rooms

Sosiaali- ja terveysministeriön asetus 1545-2015

f [Hz]	Daytime 07-22 $L_{Zeq,1h}$ A	Night time klo 22-07 $L_{Zeq,1h}$ B	Hearing threshold C
20	79	74	78.5
25	69	64	68.7
31.5	61	56	59.5
40	54	49	51
50	49	44	44
63	47	42	37.3
80	45	40	31.5
100	43	38	26.6
125	41	36	22
160	39	34	18
200	37	32	14.3



Design guidelines and standards

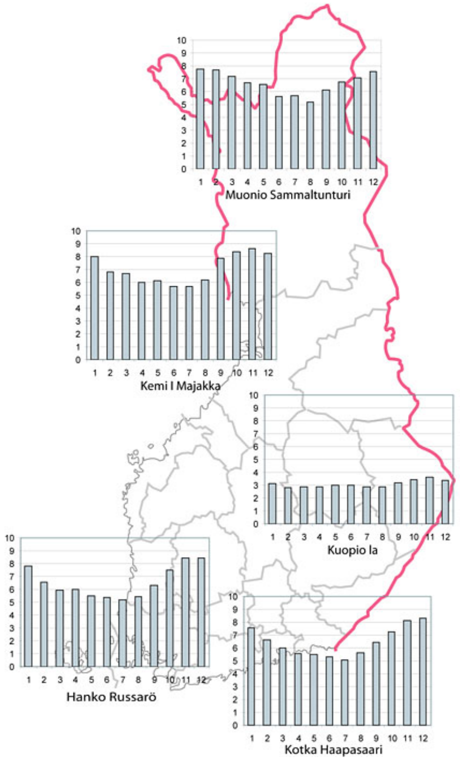
- Ministry of the Environment – Wind power documents
  - http://www.ymparisto.fi/fi-FI/Elinymparisto_ja_kaavoitus/Elinymparisto/Tuulivoimarakentaminen/Tuulivoimarakentaminen(25775)
- General guideline for wind power planning
  - Ympäristöministeriö (2016). Ympäristöhallinnon ohjeita 5-2016
  - http://julkaisut.valtioneuvosto.fi/handle/10024/79057
- Noise modeling:
  - Ympäristöministeriö (2014). Ympäristöhallinnon ohjeita 2-2014.
  - https://helda.helsinki.fi/handle/10138/42937
- Emission measurement:
  - Ympäristöministeriö (2014). Ympäristöhallinnon ohjeita 3-2014.
  - https://helda.helsinki.fi/handle/10138/42938
  - IEC 61400-11
- Immission measurement
  - Ympäristöministeriö (2014). Ympäristöhallinnon ohjeita 4-2014.
  - https://helda.helsinki.fi/handle/10138/42939

Specific features of WT noise

- Temporal variation:
  - WTs are OFF 8% of time annually and
  - WTs run at full speed only about 5% of time annually
- Sound levels in residential yards are under 40 dB L_{Aeq} in most old WT areas and in every new WT area
- Levels above 40 dB possible around WT areas erected before 2014
- Spectrum resembles road traffic noise or airplane noise
- Weak amplitude modulation: level variation with 0.7 Hz (2 beats per 3 seconds)
- Occasional impulsiveness due to amplitude modulation
- Tonality due to gear boxes
- Lack of night-time control

Typical power curve

- Full power is usually reached when wind speed at hub height v_{hub} **> 12 m/s**
- Max noise emission when v_{hub} 12…18 m/s
- Shutdown when
  - $v_{hub} < 3$ m/s
  - $v_{hub} > 18$ m/s
- **Noise modeling is made using maximum noise emission**
- Mean monthly v_{hub} is 5-8 m/s in windy areas
- Thus, noise emission is 5-15 dB below the maximum most of the time.



Data Sheet
E-101 / 3050 kW Operating Modes

ENERCON
ENERGY FOR THE WORLD

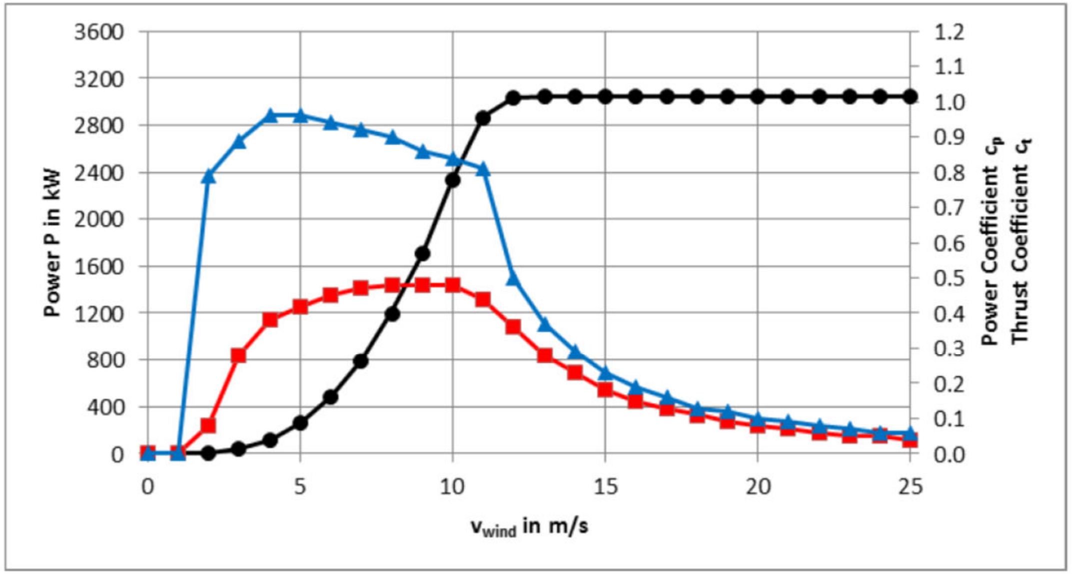


Fig. 1: Power, c_p and c_t curve E-101 / 3050 kW operating mode 0

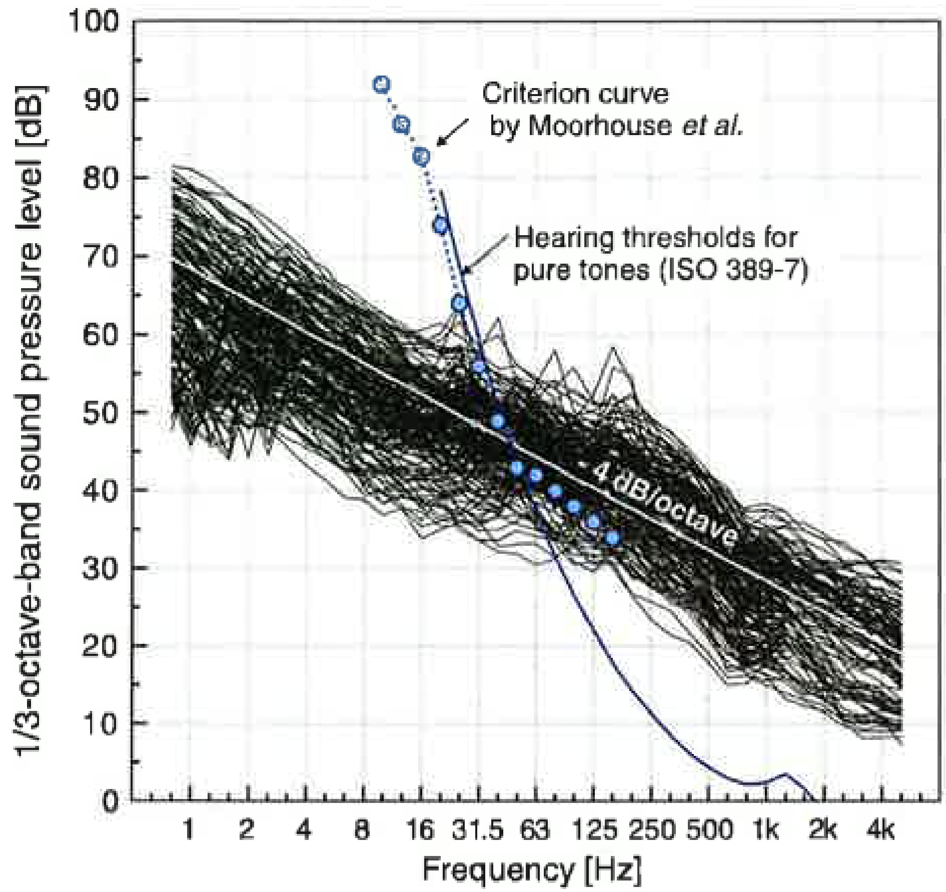
◆—◆—◆	Power P in kW
▲—▲—▲	c_t value
■—■—■	c_p value

Table 5: Calculated sound power level in dB(A), based on wind speed at hub height

5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s	12 m/s	13 m/s	14 m/s	15 m/s
89.5	93.1	98.5	100.9	102.7	104.0	104.9	105.3	105.5	105.5	105.5

Spectrum of WT sound

- The largest number of measurements have been conducted in Japan
- The results indicate a slope of -4 dB per octave doubling
- Individual curves usually have weak or modest tonal characteristics (peaks)
- Equivalent levels involve the effect of amplitude modulation



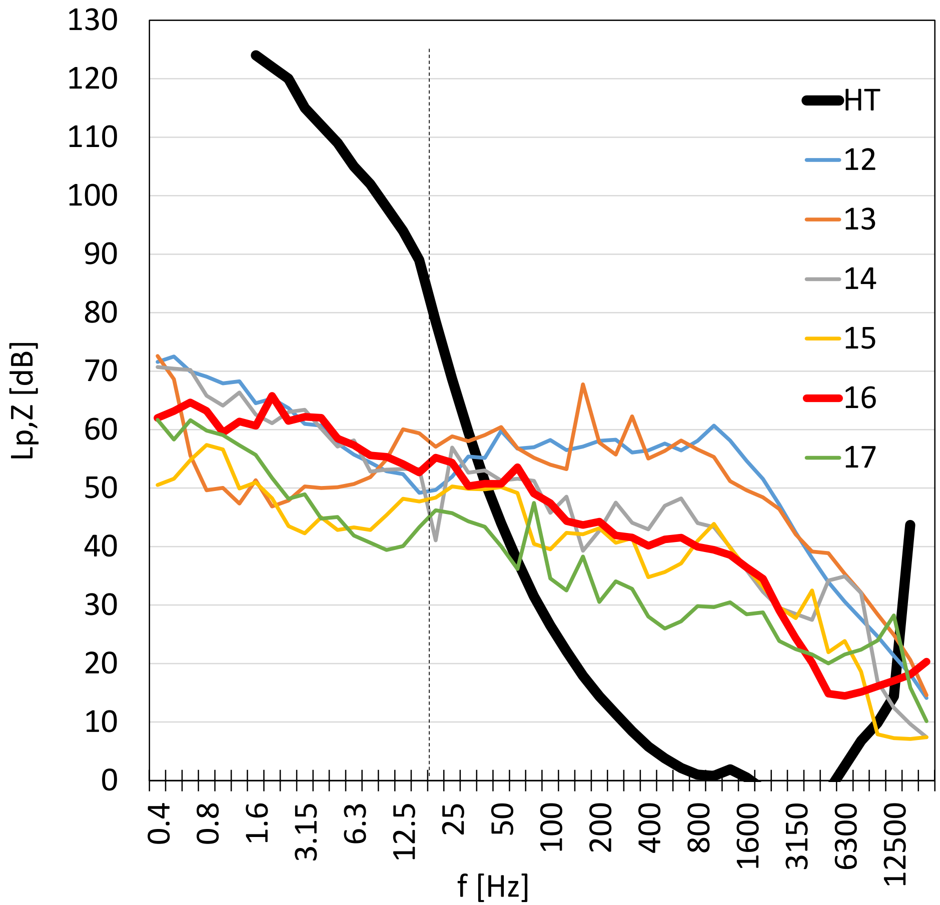
(a) Measurement results of WTN at 164 points around 29 wind farms.

Tachibana et al. (2014) *Noise Con Eng J*

Frequency spectrum of WT sound

No.	Description	L_{Aeq}
12	Road traffic noise along a busy street.	66.1
13	Ventilation fan inlet on the yard of a school.	64.3
14	Yard of a apartment house. Electric power plant running 35 m away (16 MW	52.1
15	Road traffic noise on the yard of a residence.	48.6
16	Wind turbine 0.4 km away. Power output at maximum level (3.3 MW).	48.2
17	Airplane noise on the yard of a residence.	39.4

- Spectrum of WT sound is very similar to that measured in other living environments
- Furthermore, infrasound levels are much below the hearing threshold level, HT.

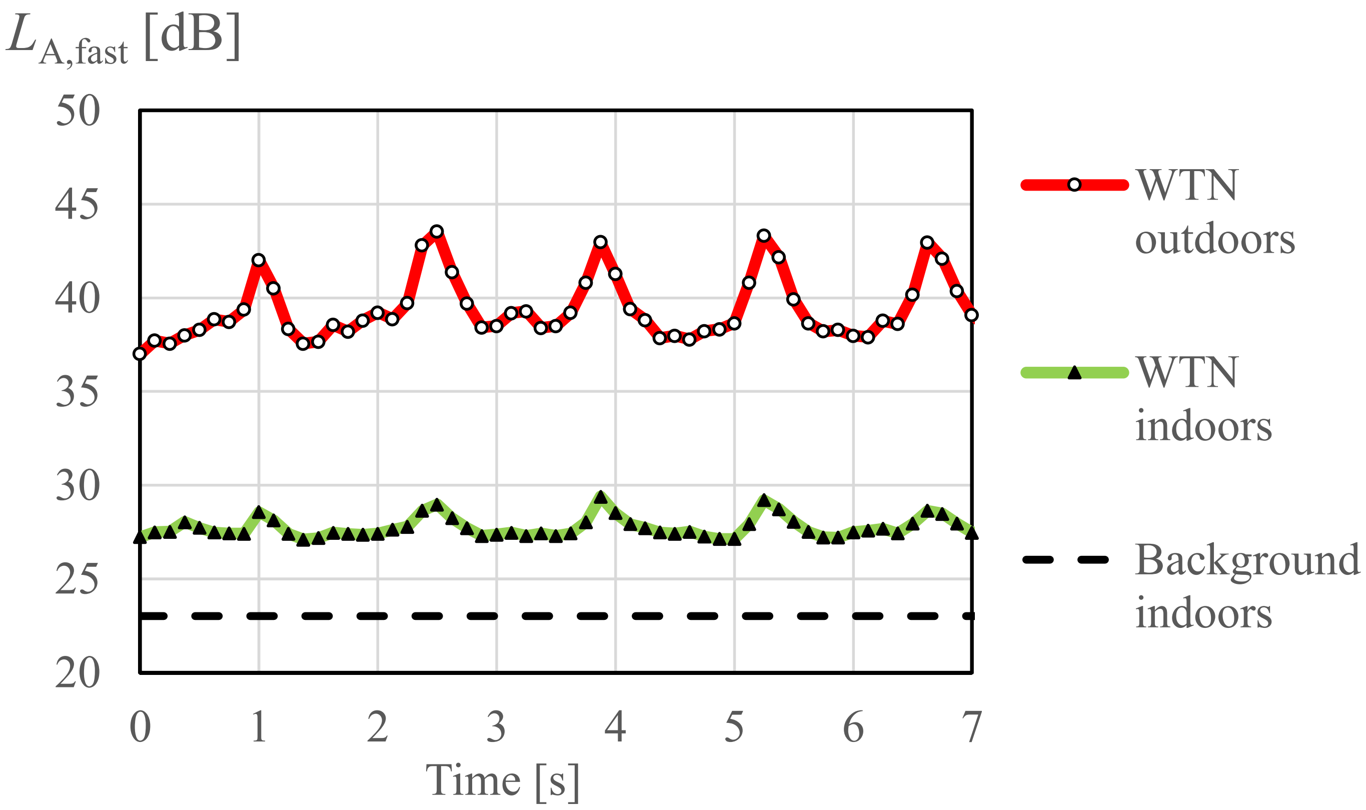


Hongisto & Oliva, 2017 Turku AMK

Amplitude modulation

AM2_+28dB

- Amplitude modulation is caused by the blade movement
- Variation of SPL occurs with certain
  - Modulation frequency, f_{AM}.
  - Modulation depth, D_{AM}.
- The figure is an example of AM sound recorded 1.5 km from 7 WTs outdoors and indoors, simultaneously.
- What are the values of
  - $f_{AM} = ?$
  - $D_{AM} = ?$



Fukushima et al. 2013 *Internoise*

Prevalence of AM in Japan

- D_{AM} < 4 dB most of the time
- D_{AM} > 4 dB only occasionally.
- Finnish data has not been published.

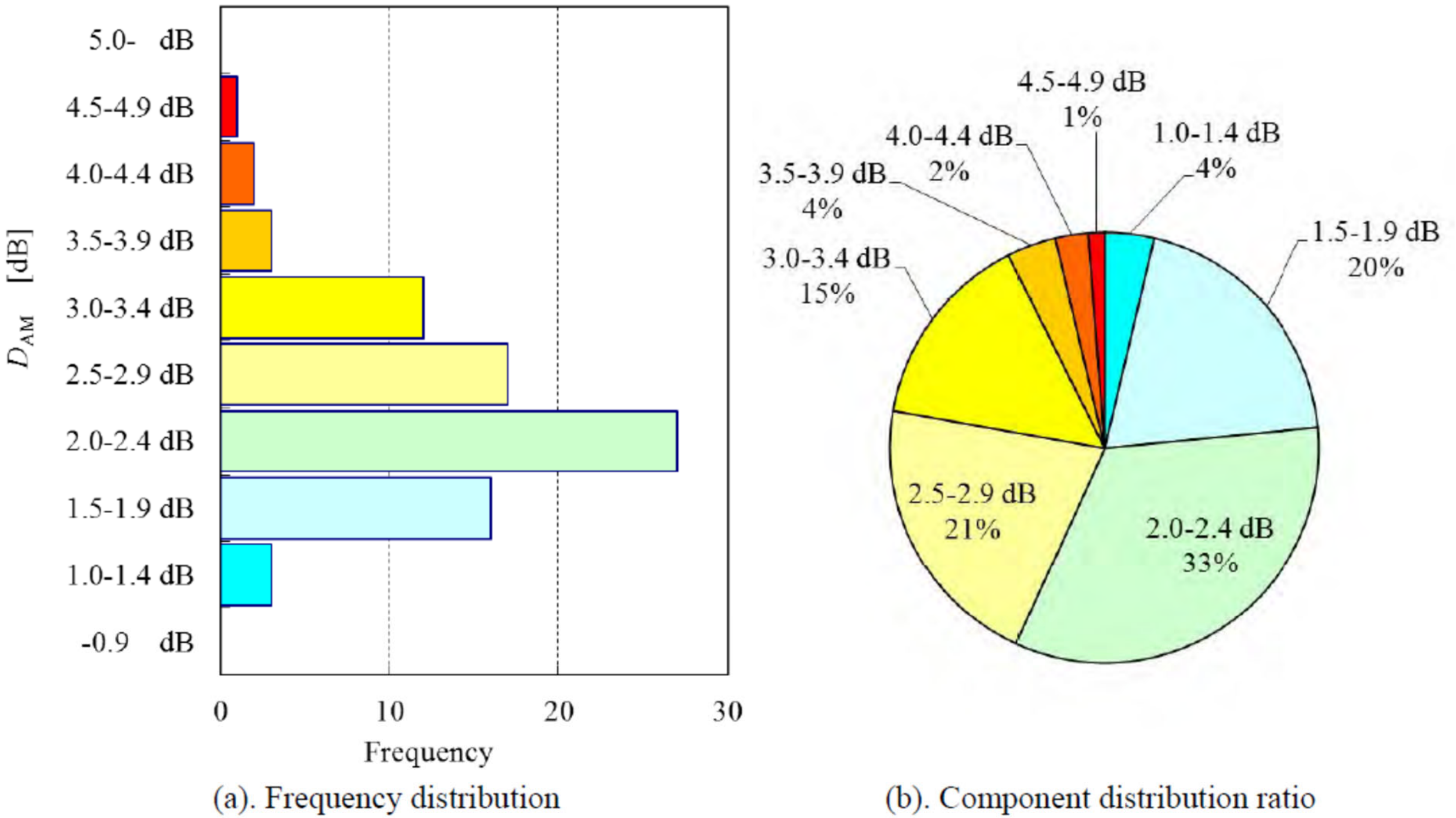
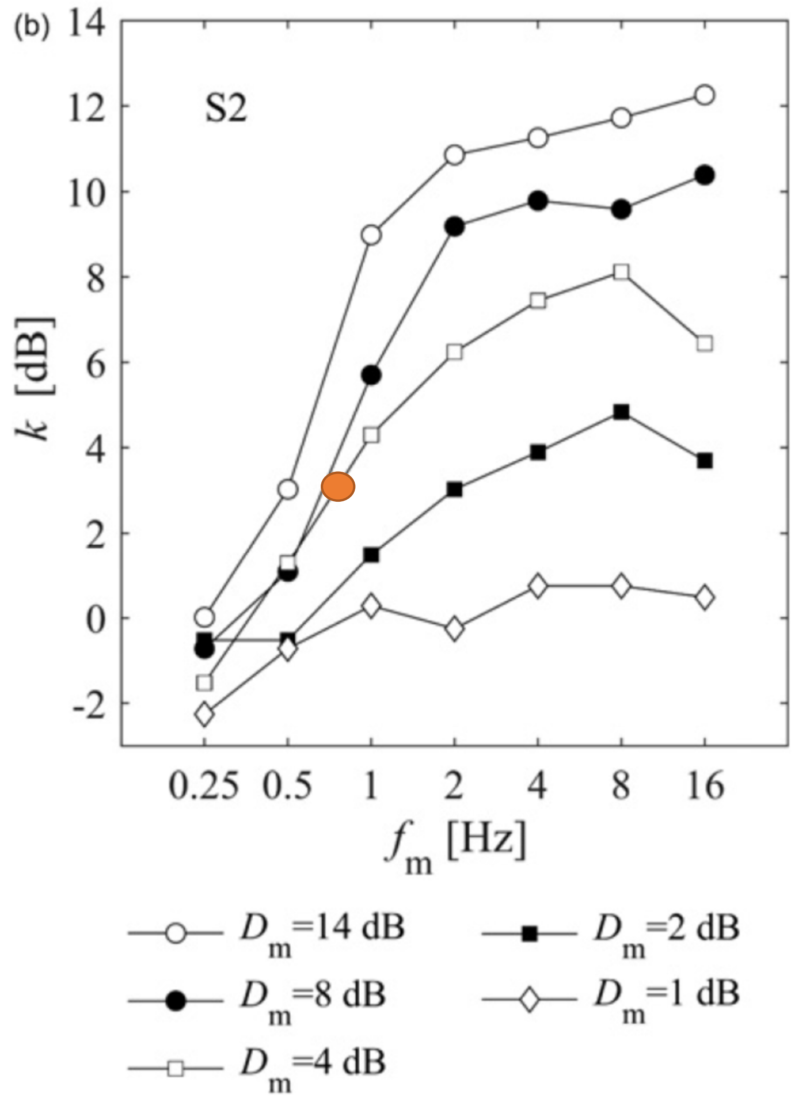


Figure 8 – Frequency distribution of the AM depth D_{AM} of WTN in the residential areas around 18 wind farms in Japan.

Annoyance of AM WT sound

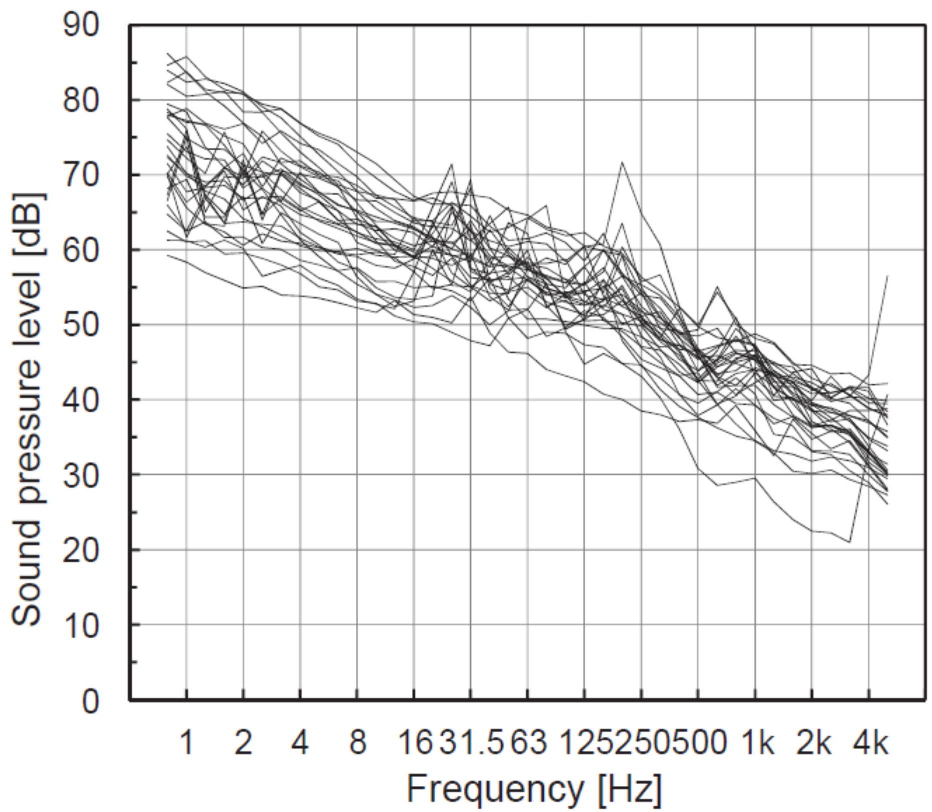
- Virjonen et al. (2019) found that the annoyance penalty, *k*, due to AM in sound can be 0-12 dB depending on f_{AM} (f_m) and D_{AM} (D_m)
- For typical WT noise, f_m=0.7 Hz and D_m<4 dB, and penalty would be at most **k = 3 dB**.
- That is, if the equivalent level of the AM wind turbine sound is 35 dB L_{Aeq}, it feels like a steady state sound at 38 dB L_{Aeq}.
- Finnish regulations do not give penalty for AM.
- However, the tighter regulated level for WT noise was partially driven by AM.



Virjonen et al. (2019) *J Acoust Soc Am*

Tonality

- Tonality means that audible tones can be distinguished in the sound.
- Presence of tonality can be determined by
  - Listening
  - Investigating the one-third octave band spectrum
  - Investigating FFT spectrum by ISO 1996-2
- Regulations involve constant penalty k for tonal sounds to be added over the L_{Aeq}.
- Thus, the new value $\boldsymbol{L}_{\mathbf{Aeq}}+\underline{\boldsymbol{k}}$ is expected to represent the noise annoyance better than L_{Aeq} alone.
  - VnP 993/92 [1], ***k* = 5 dB**
  - STM 545-2015 [2], ***k* = 3 / 6 dB**
- Penalty of 5 dB means that the setback distance to the WTs must be almost twofold larger.

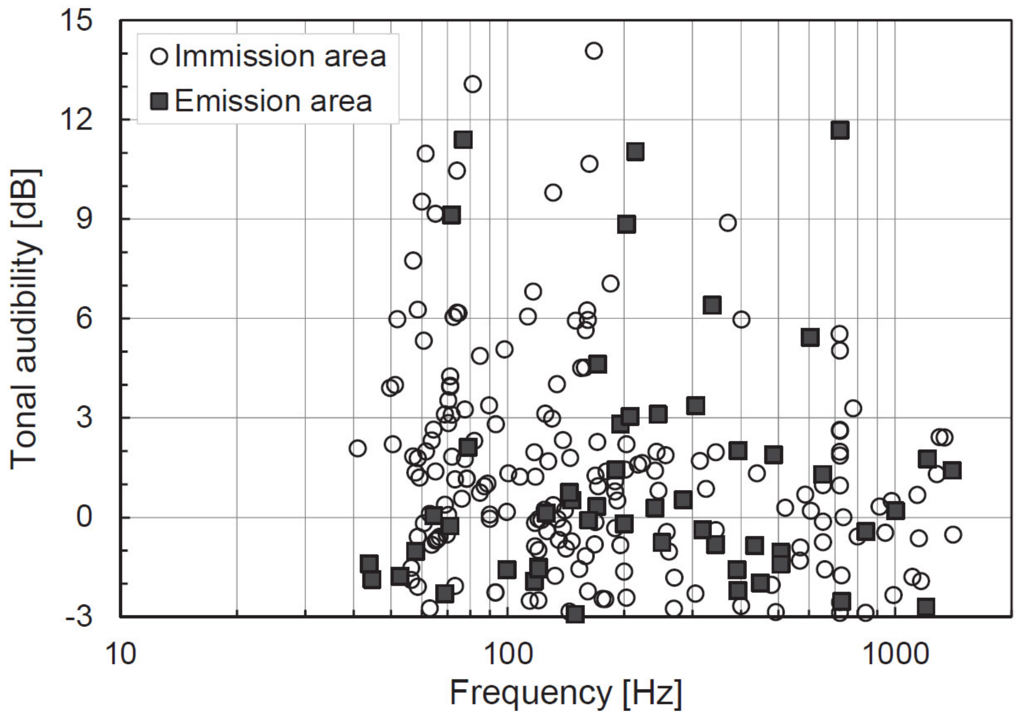


(a) In emission areas (29 points)

Yokoyama et al. (2016) *Internoise*

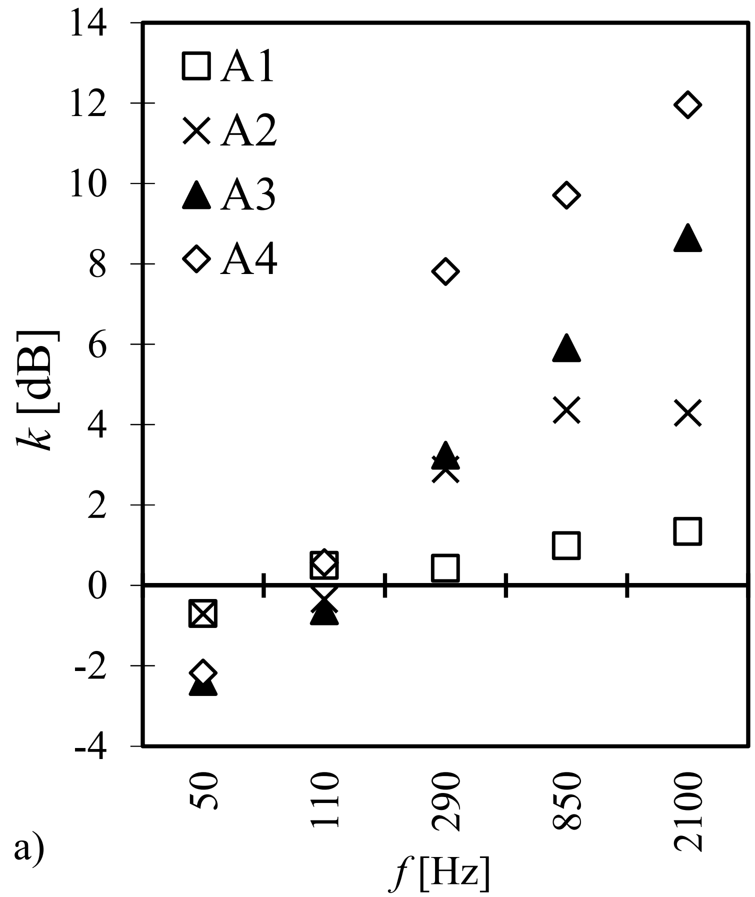
Tonality in wind turbine noise

- Yokoyama et al. observed tonality both in emission distances (200 m or closer) and immision distances (200–1000 m).
- Important tonality was found within 50–800 Hz.
- Oliva et al. found that annoyance penalty k depends on frequency and tonal audibility



Yokoyama et al. (2016) *Internoise*

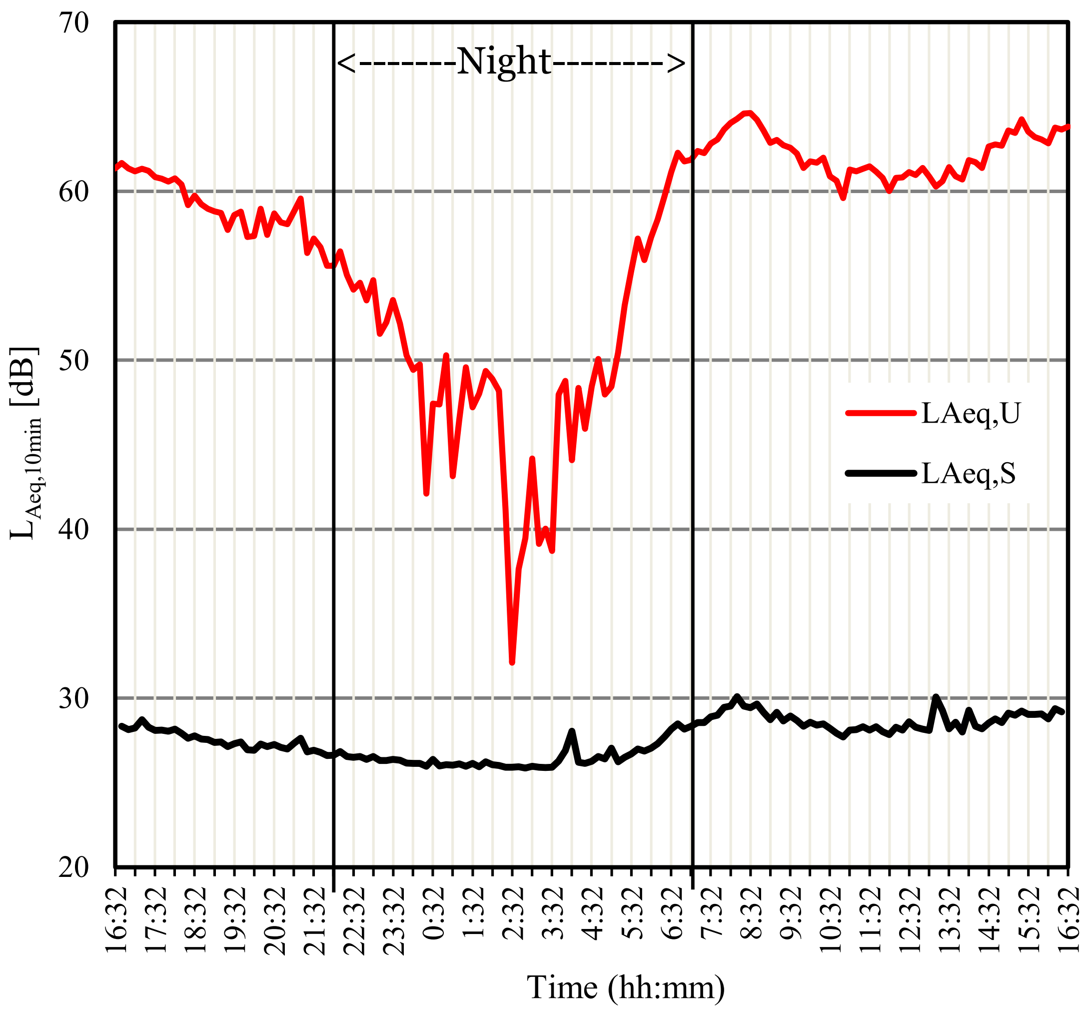
A1 - Tonal audibility 5 dB (weak)
A2 - Tonal audibility 10 dB
A3 - Tonal audibility 17 dB
A4 - Tonal audibility 25 dB (strong)



Oliva et al. (2017) *Build Environ*

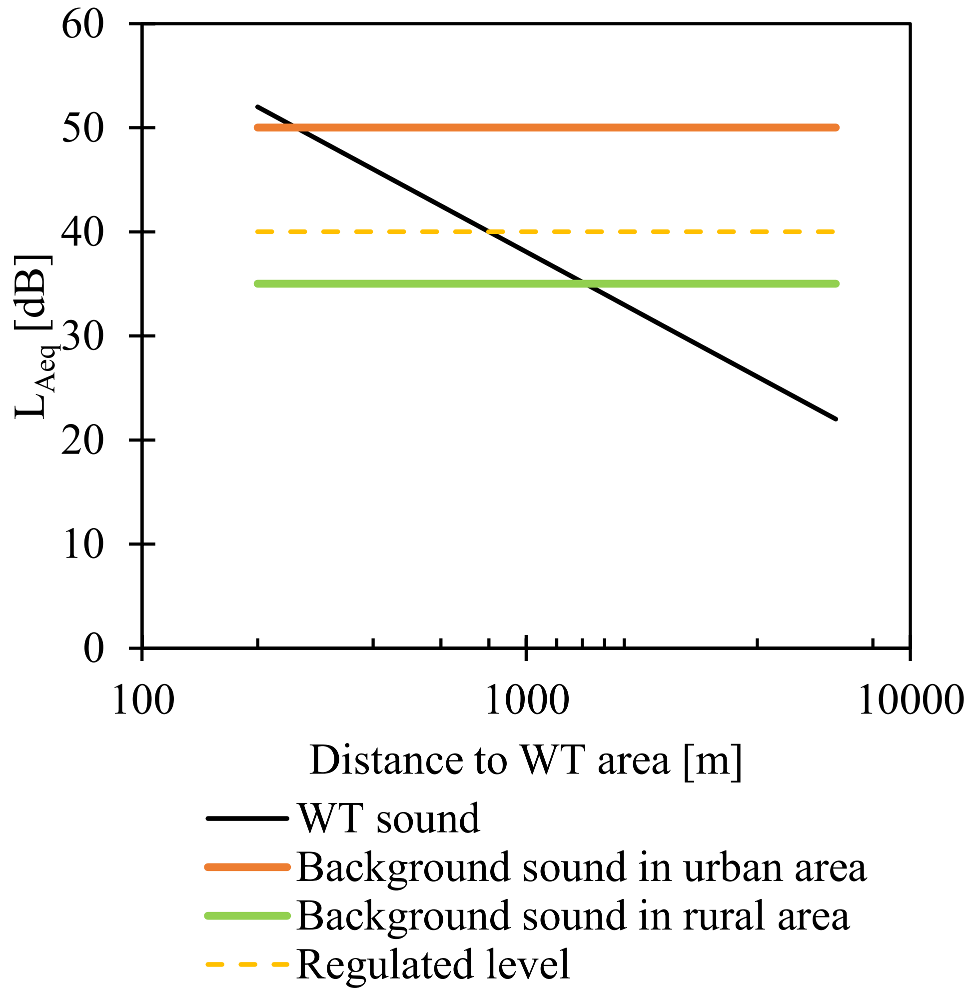
Lack of night-time noise control

- Many environmental sounds, such as road traffic noise (figure), get fainter during night time.
  - Figure depicts $L_{\mathrm{Aeq,10min}}$ of road traffic noise as a function of time during one week day outdoors (U) and indoors (S)
- However, WTs do not care about the time of the day.



Audibility in urban areas vs. silent areas

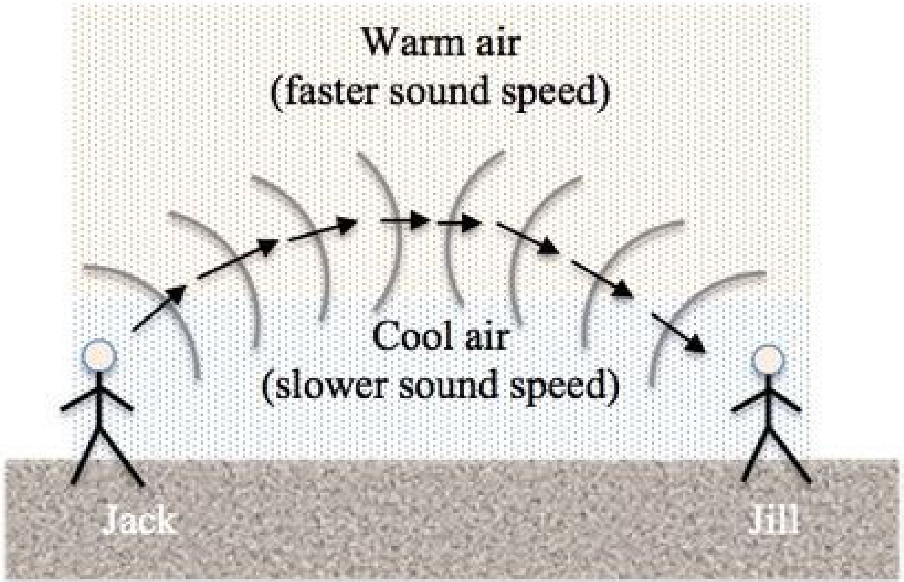
- Signal-to-noise ratio, **SNR**, is the difference between the WT noise level and background noise level
  - WT 40 dB, background 35 dB → SNR=+5 dB
- WT sound is noticeable when SNR > -5 dB
- WT sound levels are always under 40 dB L_{Aeq} at maximum power (strong wind) in residential yards
- Typical daytime background noise level during a windy day is
  - 50 dB in urban areas: SNR is always below **-10 dB**
    - wind + road traffic noise mask the WT noise
  - 35 dB in silent areas: SNR is even **+15 dB** close to WTs
    - Only wind masks the WT noise
- Thus, SNR can be 30 dB larger in the silent area and the noticeability during night time is obvious.
- This can lead to elevated concerns, noise annoyance, and sleep disturbance if windows are open.



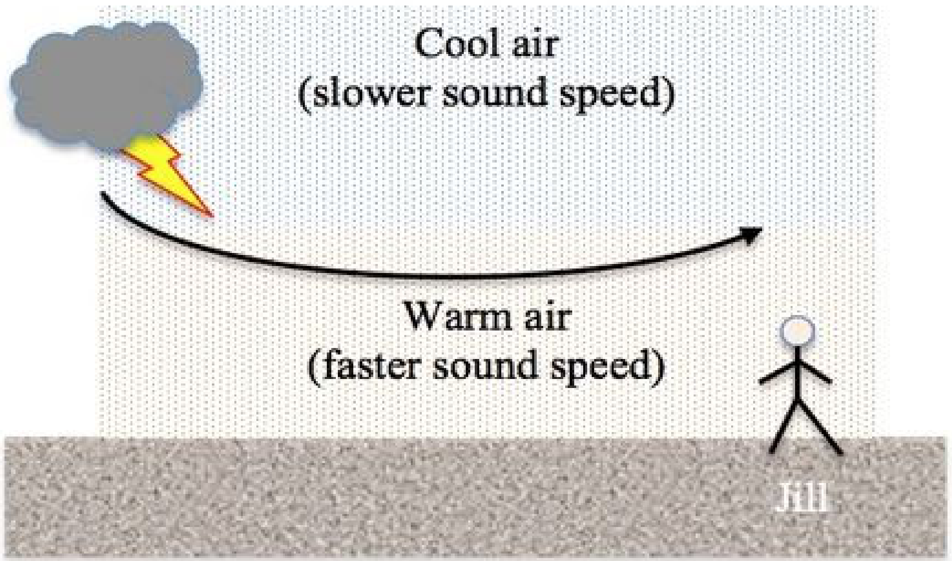
Effect of temperature layers on sound propagation

- In typical weather, temperature increases towards ground and sound attenuates is 6 dB per distance doubling (dd) according to geometric propagation law.
- In **inversion** condition, temperature increases towards sky, and attenuation is only 3-5 dB per dd
- Weaker attenuation is caused by reflection from the upper layers of the athmosphere.
- Reflection increases sound levels above 1 km from the turbines.
- Regulated levels are seldom violated due to this, since setback distance is usually under 1 km.

INVERSION CONDITION



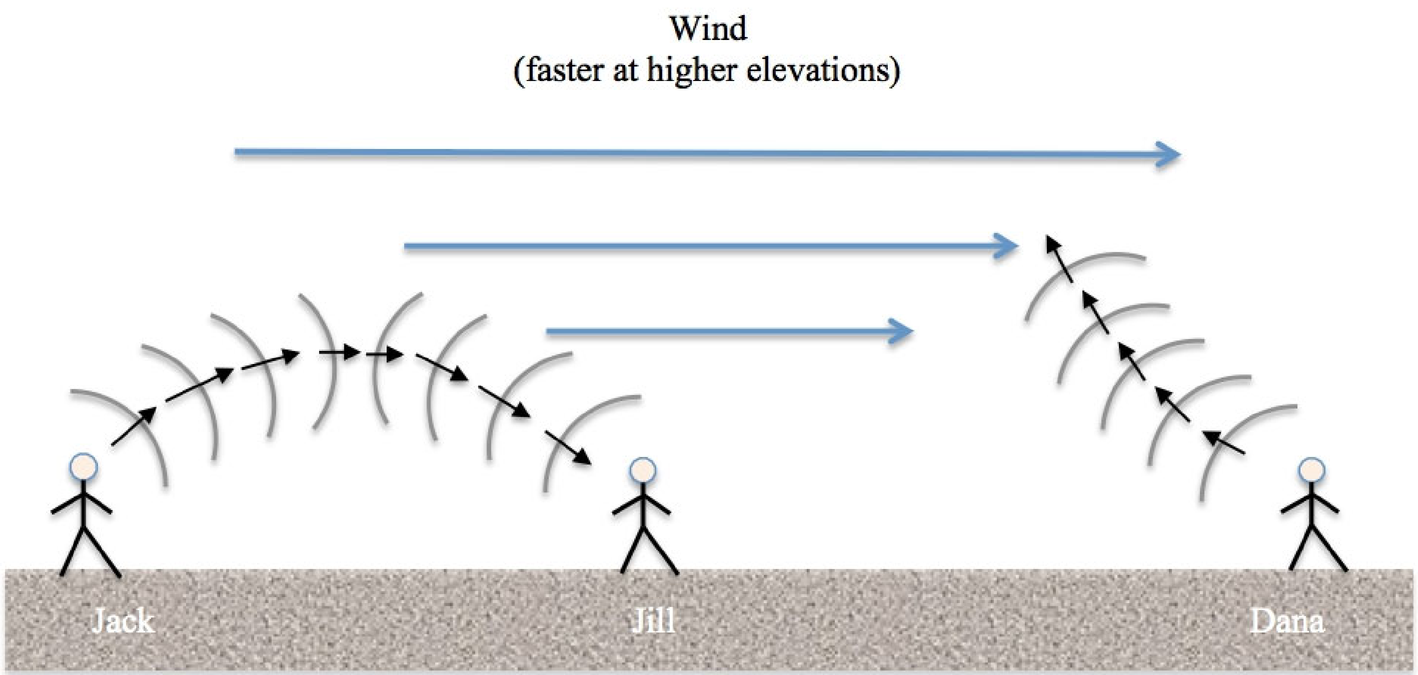
TYPICAL WEATHER



https://soundphysics.ius.edu/?page_id=788

Effect of wind speed layers on sound propagation

- Sound propagates more easily downwind than upwind
- The excessive noise occurs only downwind and opposite effect is found upwind: total noise does not increase !
- Reduced attenuation due to athmospheric phenomena seldom leads to the violation of regulated noise limits but it may result in intermittent annoyance reports in sensitive areas if the background noise is low.
  - Summer evenings
  - Cottage areas



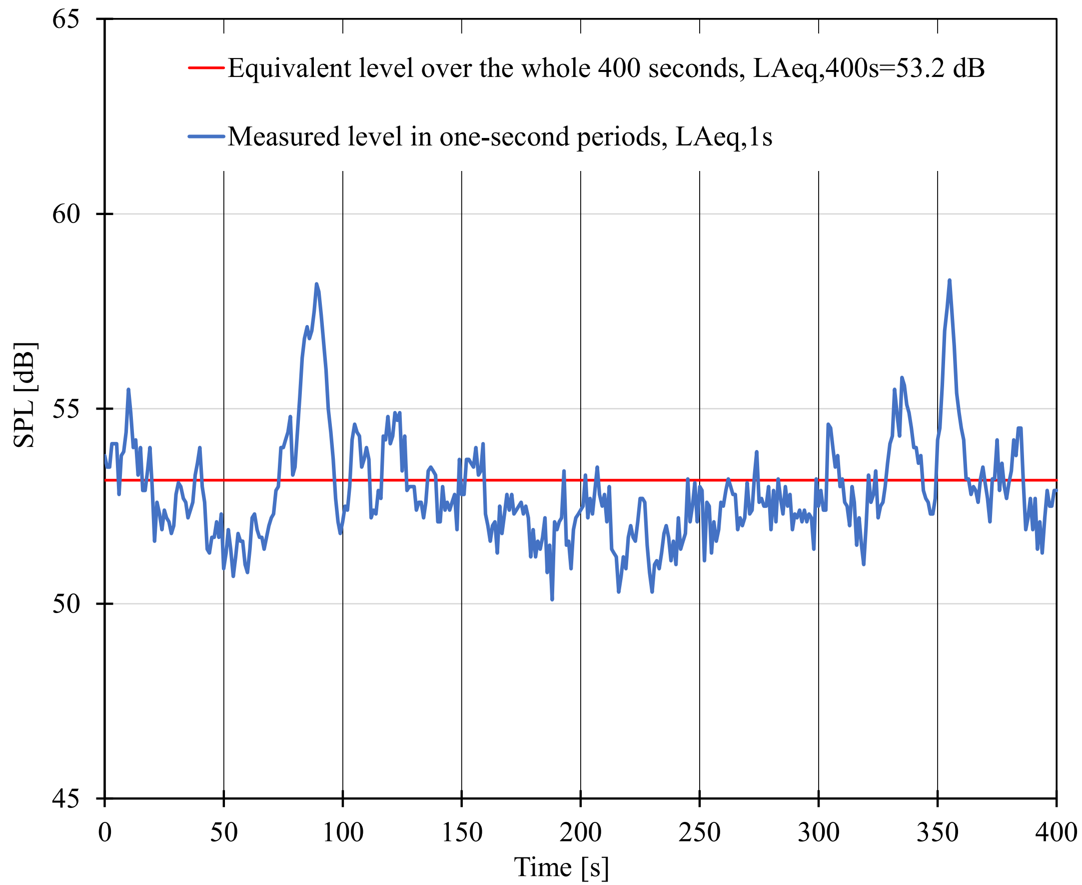
https://soundphysics.ius.edu/?page_id=788

Wind Turbine Noise:
3. Measurements

General

- Wind turbine noise measurements focus on the determination of A-weighted sound pressure level, L_{Aeq}.
- The tightest regulated value is 40 dB $L_{Aeq,\ 22\text{-}07}$, it it the equivalent level during T=9 hours, from 22 to 07 (night time).
- Since the regulated value shall not be exceeded in any condition, the measurements are made during maximum energy wind conditions
- The measurement duration of WTN does not last full 9 hours since maximum wind seldom exists that long.
- Therefore, a reasonable time period with maximum energy production is chosen for measurements.

- Typical example of WT noise emission measurement for 400 seconds made at a distance of 200 m from WT.
- One second levels vary within 50 and 58 dB because of
  - Variation in WT noise due to varying wind speed
  - Variation in vegetation noise



Measurement conditions

- The measurements are conducted at pre-defined weather conditions
  - Wind speed around 8 m/s at 10 m height (”12 m/s hub height”)
  - Measurement in downwind direction
  - No rain
  - More than -5 °C
    - equipment freeze fast in windy frost
  - During daylight
  - Background noise should be minimal in the measurement position (roads, neighbors, vegetation)
- Measurements are conducted in two conditions, since the background noise level due vegetation is always pretty high
  - Turbines OFF (vegetation only)
  - Turbines ON (vegetation + WTs)

Wind criteria

- Weather forecasts in the wind farm are followed by the nearest weather station in Windfinder.fi
- Measurements are successful if more than 25 % of SPL data is obtained in maximum energy condition.
- This success is usually achieved, when the two criteria are fulfilled in forecast:
  - Wind speed > 8 m/s
  - Wind gusts > 15 m/s
- In practice, it is sufficient to apply less stringent criteria to avoid waiting for several years
  - Wind speed > 7 m/s
  - Wind gusts > 13 m/s

Local date	Wednesday, Nov 02							
Local time	02	05	08	11	14	17	20	23
Wind direction								
Wind speed (m/s)	1	2	2	3	3	3	4	3
Wind gusts (max m/s)	1	3	3	5	8	9	9	8
Cloud cover								
Precipitation type								
Precipitation (mm / 3h)					3.2			
Air temperature (°C)	6	7	7	8	8	8	8	8
Air pressure (hPa)	1015	1015	1014	1014	1014	1014	1013	1013

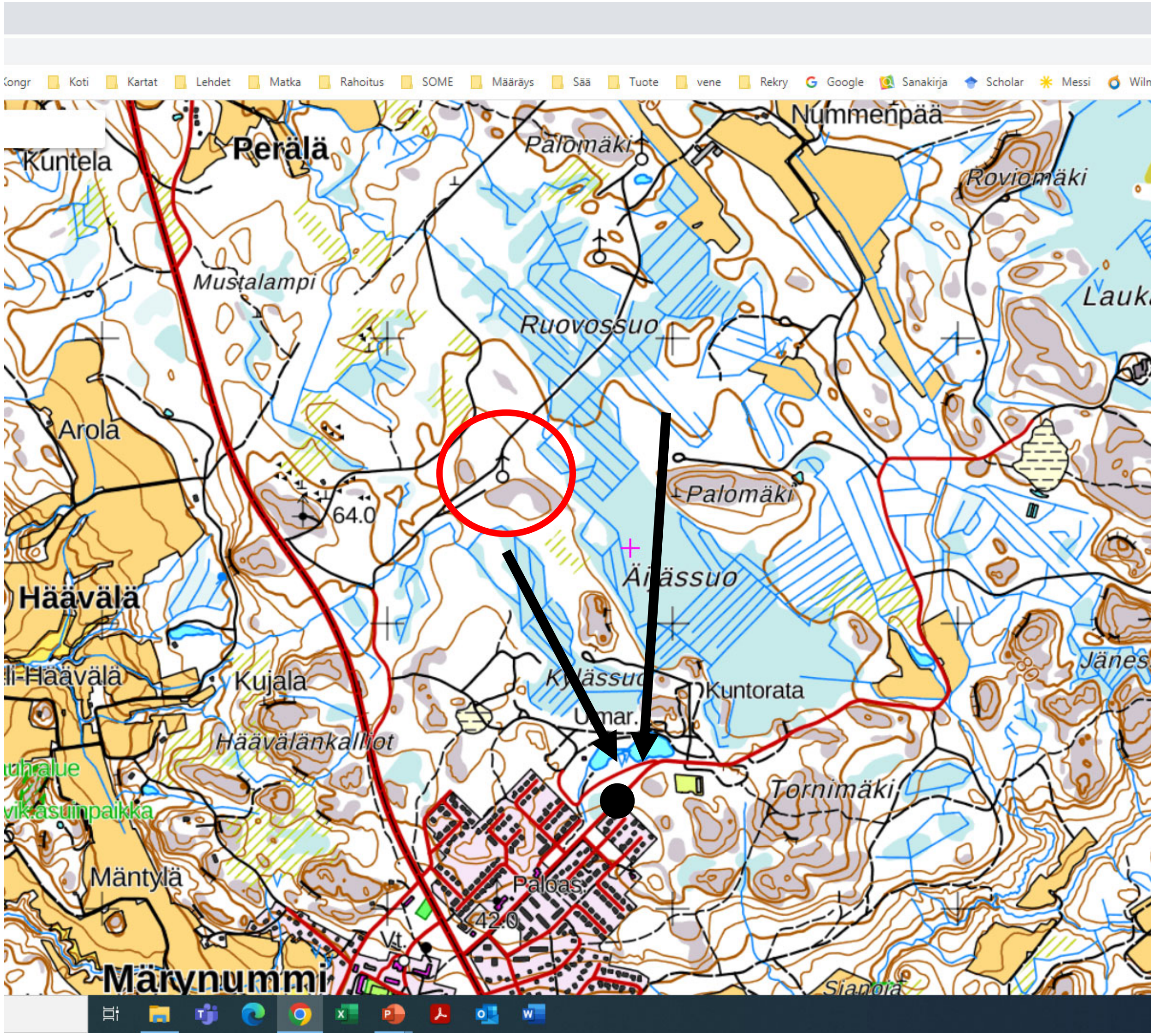
Types of measurements

Emission

- determines the sound power level of a single WT
- Generic property
- Measurement distance is around 200 m
- Usual value: 100-110 dB L_{WA}
  - SPL around 55-65 dB
- Wind direction can be anything

Immission:

- Determines the sound pressure level produced by the whole wind farm in a specific residential yard or another similar position
- Measurement distance is usually 800 to 5000 m
- Wind direction from WT area towards the yard
- Usual values under 45 dB $L_{A,eq}$



Measurement uncertainty

- Measurement uncertainty means that different operators report different dB-values for the same phenomenon.
- Also, the same operator can report different dB-values during successive days. Possible sources of that are different measurement position, wind direction, and vegetation noise.
- Measurement uncertainty can be under 1 dB only in fully controlled laboratory measurements.
- Uncertainty of WT noise measurements outdoors:
  - 1-2 dB in emission measurements (under 250 m distance),
  - > 2 dB in immission measurements (over 500 m distance)

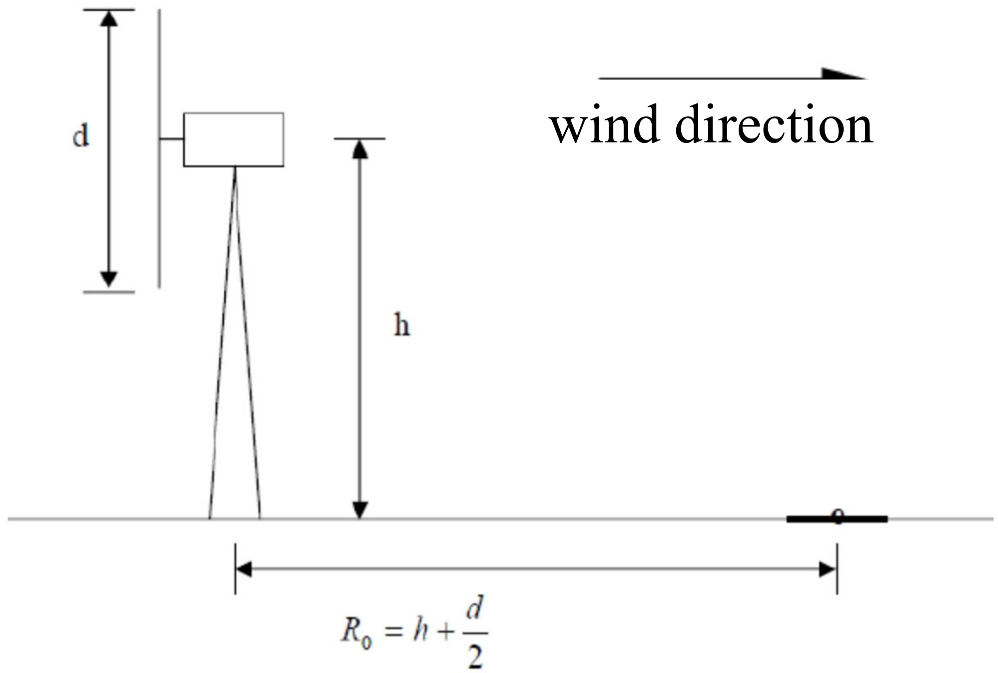
- Measurement uncertainties outdoors are caused by
  a) Measurement apparatus (microphone & analyzer)
  b) Calibrator,
  c) Background noise,
  d) Weather conditions (temperature, gradients)
  e) Location (reflections),
- Measurement uncertainties indoors are caused by
  a) Measurement apparatus (microphone & analyzer)
  b) Calibrator,
  c) Background noise,
  d) Location (room modes),

Noise emission measurement

- Emission measurement is made to determine the SWL of a **single WT**
- Emission measurements need to be made by the WT manufacturers. They use standard measurement sites, where vegetation noise is absent.
- Verification measurements can be conducted by the client or another party on any site.
- Other turbines in the area producing levels closer than 6 dB in the measurement position must be shut down during the emission measurement
- The Finnish guideline follows IEC 61400-11

Noise emission measurement

- Measurement distance is R_0
  - ±30 m or ±20% deviation is allowed
- Measurement direction downwind ±15°
- Wind speed measurement at 10 m height
- T [°C], RH [%] and p [Pa] are measured
- The target wind speed is 8 m/s at 10 m height because this wind speed produces typically the maximum energy output in the turbines.
- Typically, the measurements are conducted within 6−10 m/s to find better accuracy
- 20−20000 Hz in third octave bands
- Energy output of the wind turbine is recorded
- Noise measurement clock is synchronized with the wind farm clock afterwards.



Noise emission measurement
Microphone positioning

- Microphone is located on top of a plate of diameter 1 m or more.
- Double wind shield is preferred to avoid wind-generated false noise in the microphone
  - Normal primary wind shield
  - Large secondary wind shield
- The effect of secondary wind shield must be corrected.
- Ground location is beneficial since the wind generated noise in the microphone is smaller
- SPL close to ground is amplified by 6 dB due to the standing wave effect.
- Therefore 6 dB is reduced from the result before reporting.

IEC 64100-11

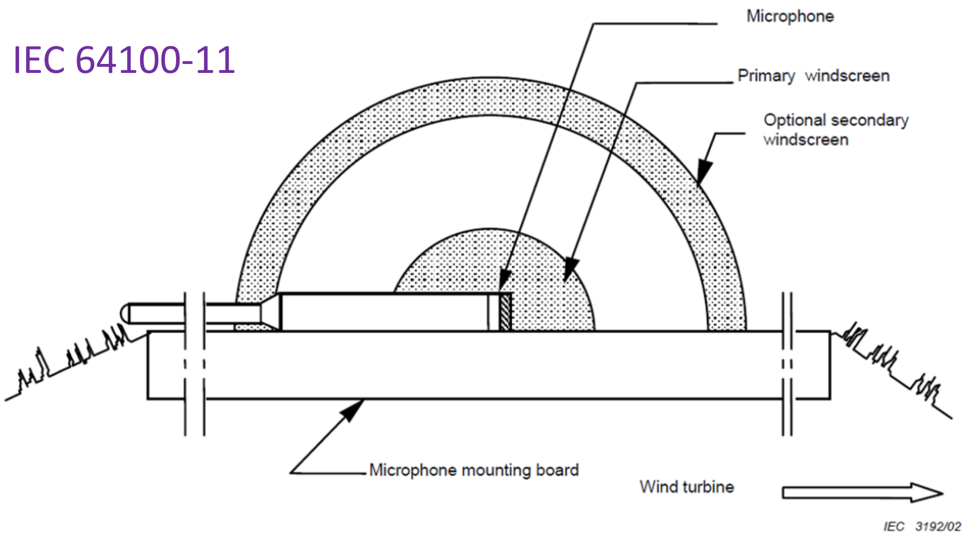


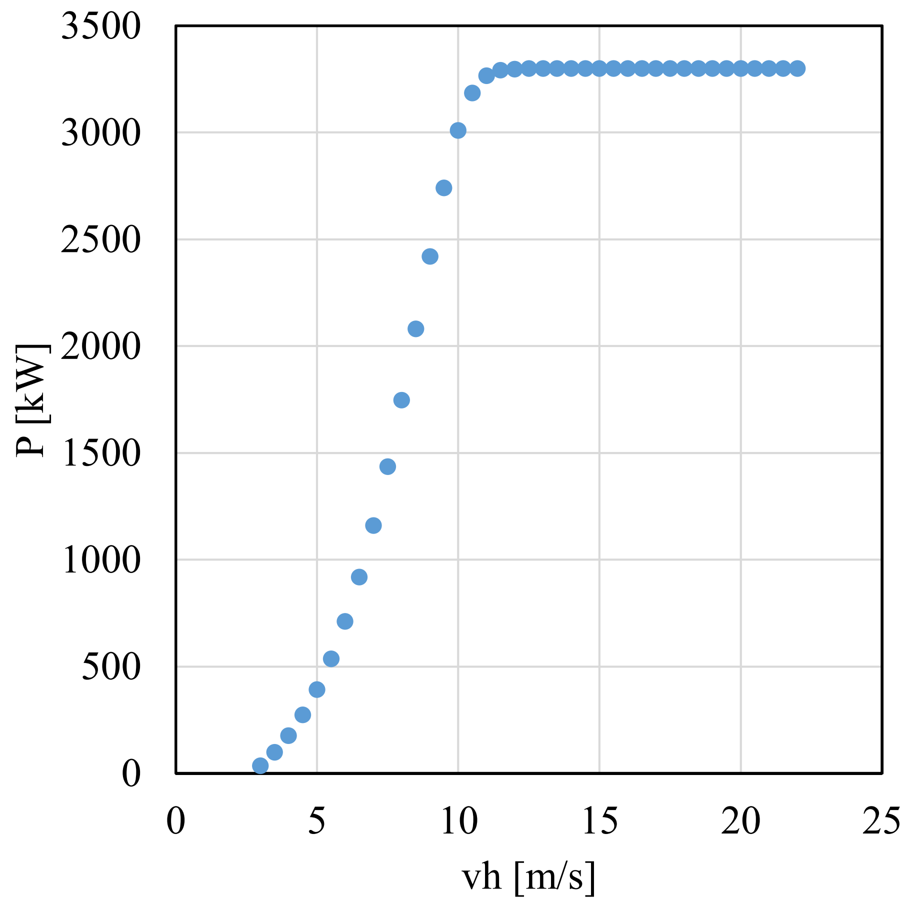
Figure 1b – Mounting of the microphone – vertical cross-section

Hongisto ja Oliva, 2017

Noise emission measurement
Wind speed

- v_h [m/s] is the wind speed at **h**ub height
- v_{ref} [m/s] is the wind speed at 10 m height
- Wind speed is determined from the power value given by operator and by using the power curve
- The speed is transformed to v_{ref} (10 m height) using a logarithmic transformation which takes the ground roughness into account

An example of a power curve determined by the manufacturer (nominal power 3300 kW)

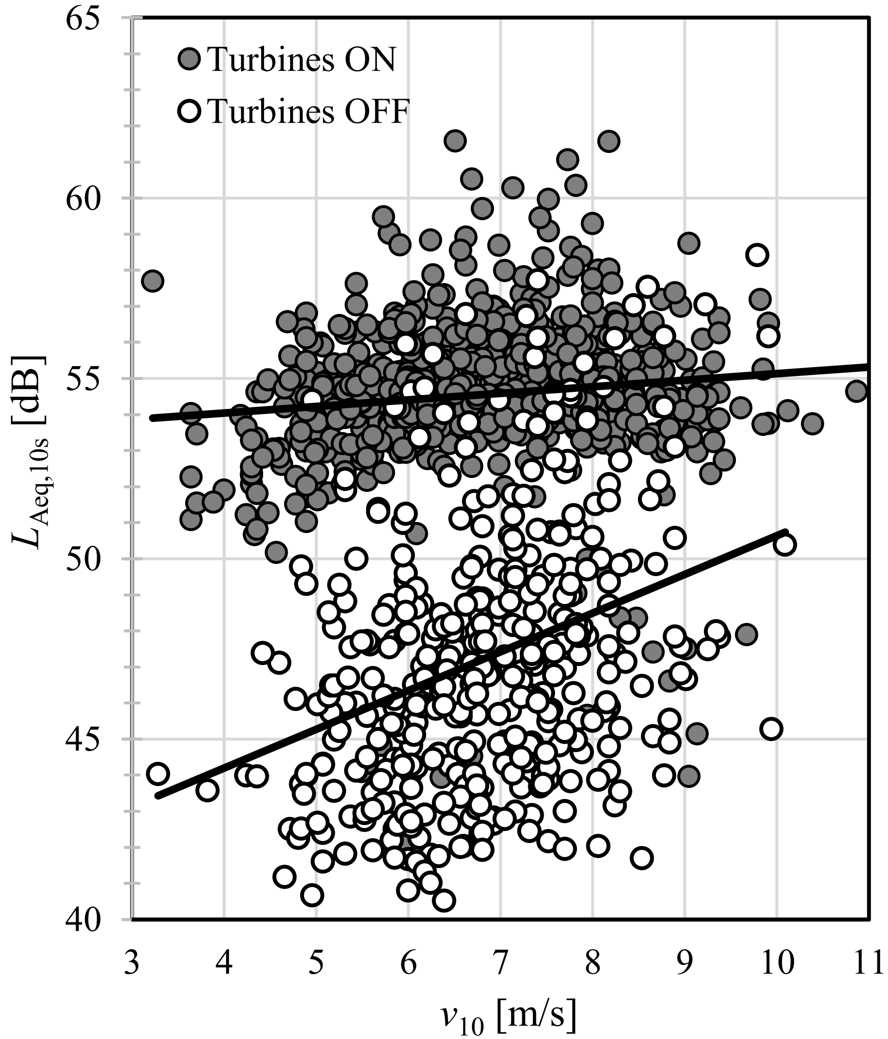


Noise emission measurement Example

- The clock of the weather mast and sound level meter are synchronized
- Sound level measurements are conducted in 10 periods on the ground.
- Equivalent A-weighted SPL, $L_{Aeq,10s}$, is plotted as a function of 10-second mean wind speed at 10 m height, v_{10}.
- Wind speed at hub height, v_h, is obtained from the wind speed versus power curve of that specific WT type.
- v_{10} is obtained from v_h using equation

$$v_{10} = v_h \cdot \left[\ln\left(10/z_0\right)/\ln\left(h/z_0\right)\right]$$

v_{10}	Wind speed at hub height normalized to 10 m height [m/s].
v_h	Wind speed at hub height [m/s].
h	Hub height [m].
z0	Roughness of ground [m]. Value 0.20 m used.



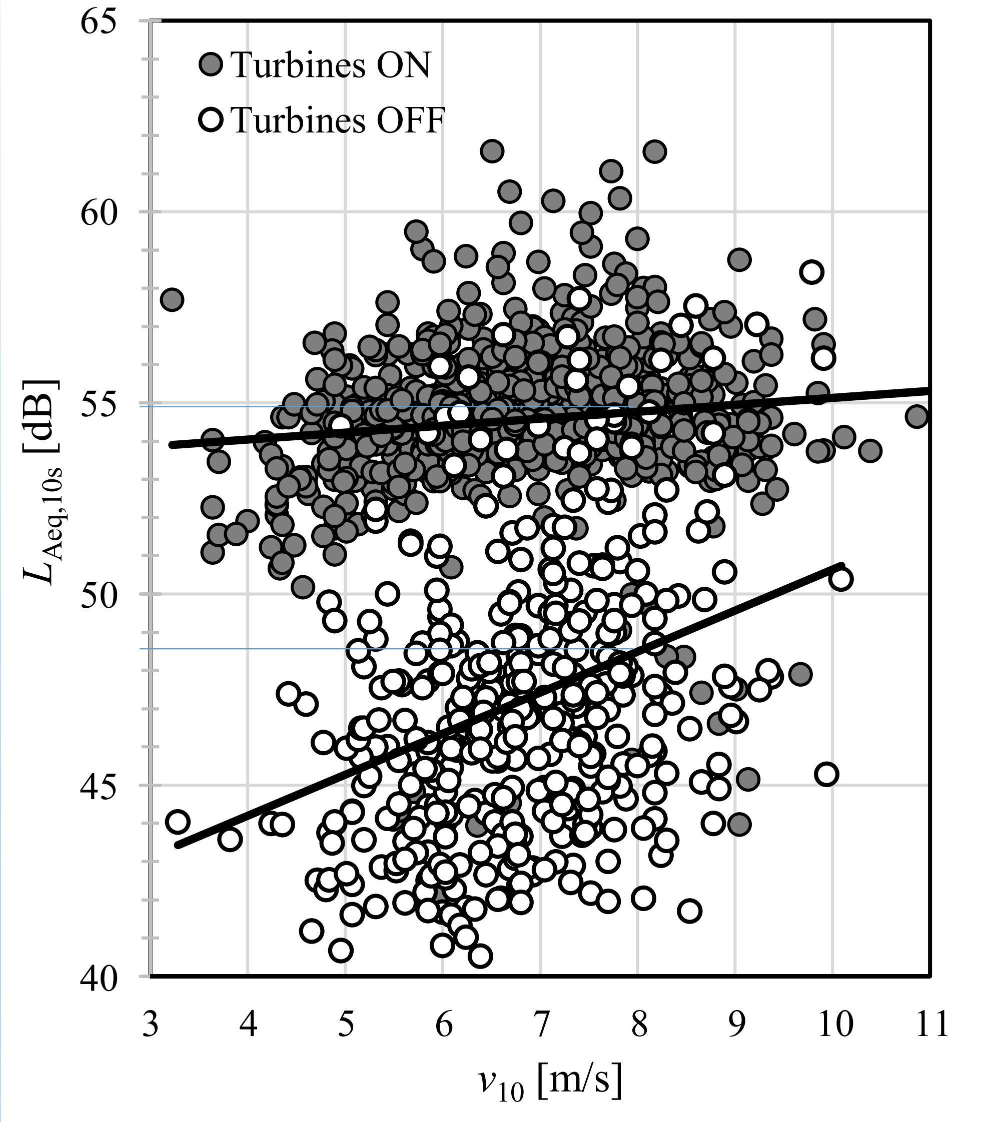
Exercise 24

Sound emission measurement was conducted at a distance of 250 meters from the tower. The microphone was located on the ground over a reflecting plate.

What is the sound power level at 8 m/s?

$$L_{p,1} = 10\lg\left(10^{L_{p,tot}/10} - 10^{L_{p,2}/10}\right)$$

Variable	unit	value	
$L_{p,tot}$	[dB]	55.0	background + WT
$L_{p,2}$	[dB]	48.5	background
$L_{p,1}$	[dB]	53.9	WT only



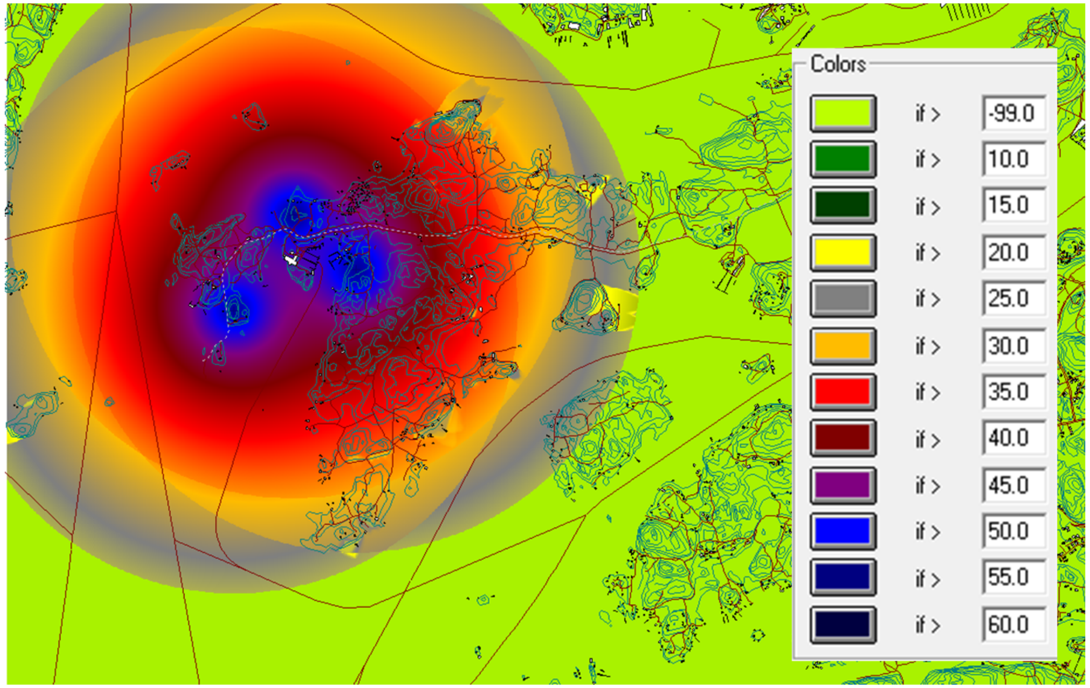
Noise immission measurement

- Immission level means the level caused by the whole wind farm in a residential yard
- Short-term measurement: usually
  - 1 hour turbines ON and
  - 1 hour turbines OFF
- Immission measurements are basically similar than emission measurements
- Since the distance to the tower is nearly always larger than 500 m, the background noise becomes a major challenge.
- The measurement uncertainties are very large, even 7 dB beyond 1 km.
- Reliable measurements are very difficult beyond 1.5 km.

Wind Turbine Noise:
4. Sound propagation modeling

Prediction of wind turbine sound propagation outdoors

- Source type and SWL (emission)
  - Point source
  - Octave band SWL values from 31.5 to 8000 Hz
- In addition:
  - Topography (maps)
  - Athmospheric absorption (T and RH)
  - Ground absorption (0 … 1)
  - Barriers (buildings) close to receivers
  - Vegetation zones (they play very small role)
- Neglegted factors:
  - Temperature gradient
  - Wind gradient
  - Turbulence
- Prediction is usually done with ISO 9613

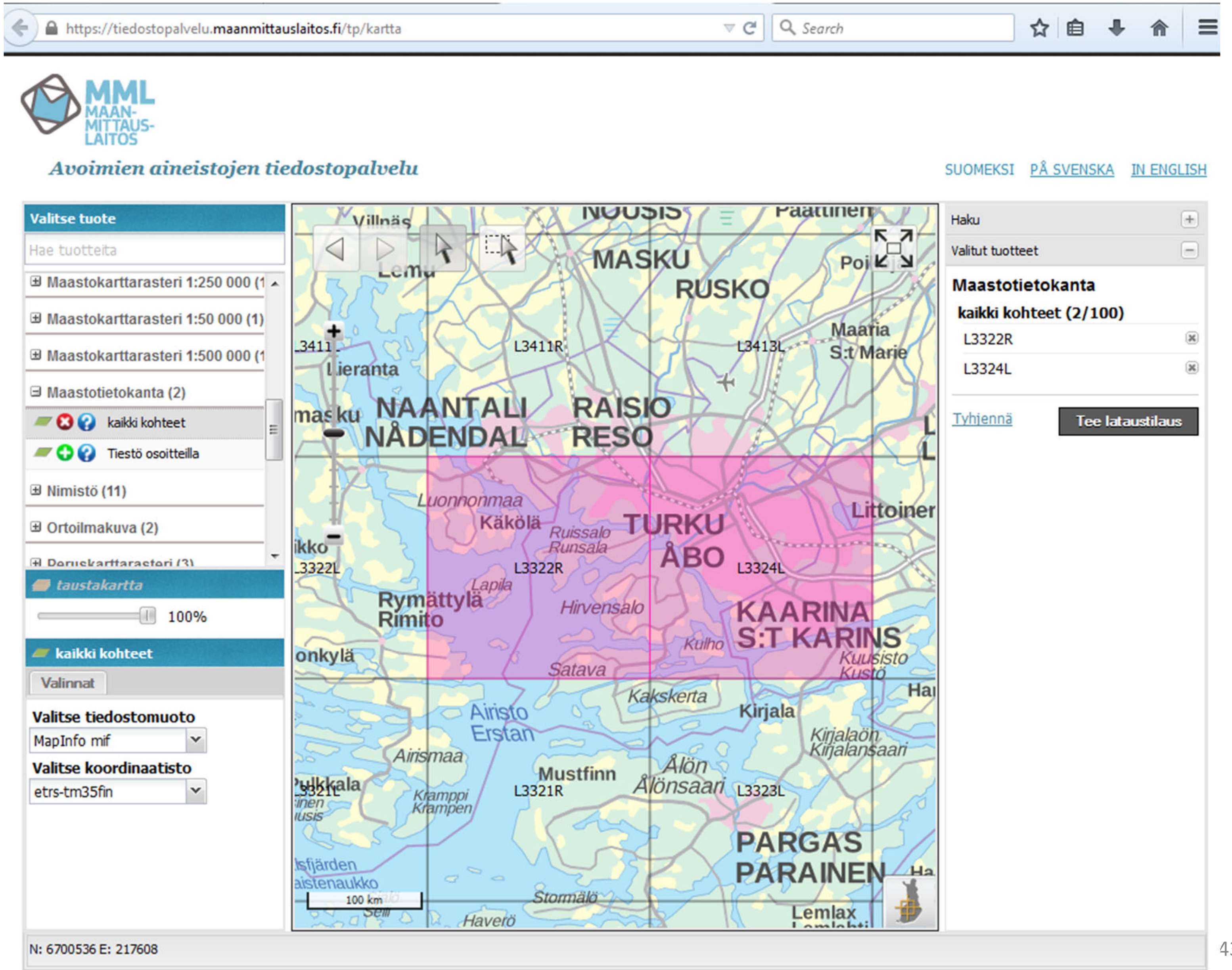


CadnaA working

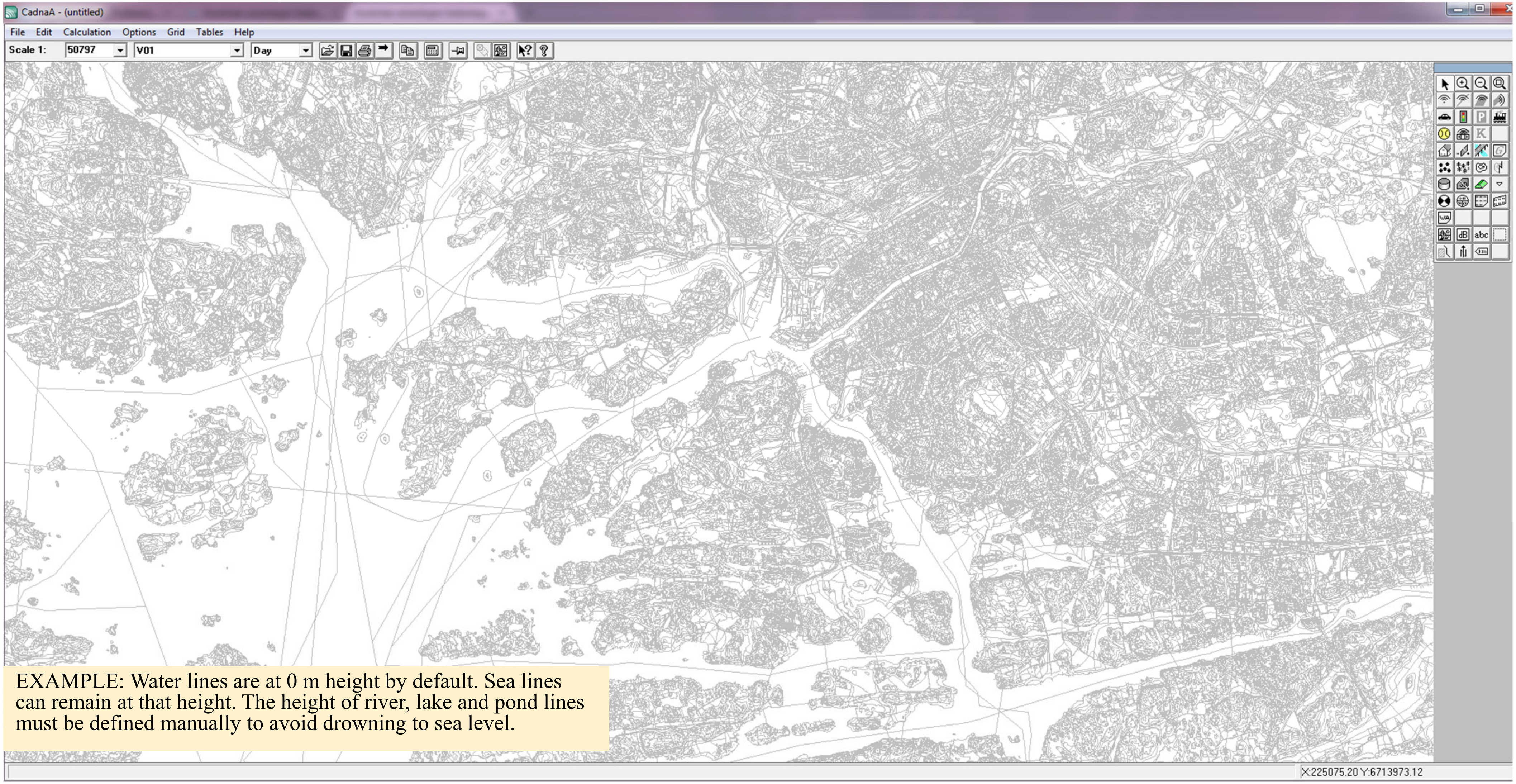
- **Download the map file from Maanmittauslaitos by email request**
  - https://tiedostopalvelu.maanmittauslaitos.fi/tp/kartta
- **Importing the map to CadnaA**
  - Cadna uses different variables names for the map items that must be transformed
- **Finalization of the imported map**
  - Contours, roads, road ground heights, buildings, building ground heights, building heights, water lines, sea, lakes, rivers.
- **Choosing the calculation method**
  - Various methods are available and the correct one (ISO 9613) is chosen
- **Sound source definitions**
  - coordinate point, source height, octave band sound power levels, diurnal variation
- **Ground absorption definitions**
  - Default: 1.0; Water: 0.0; Other grounds: 0.4.
- **Setting the noise map**
  - grid size, overall size, grid height over ground, noise category, color ID.
- **Double-checking and adjustments needed for the reporting**

Import map

- This demo deals with a hypothetic idea of placing three wind turbines to Saaroniemi, Ruissalo island.

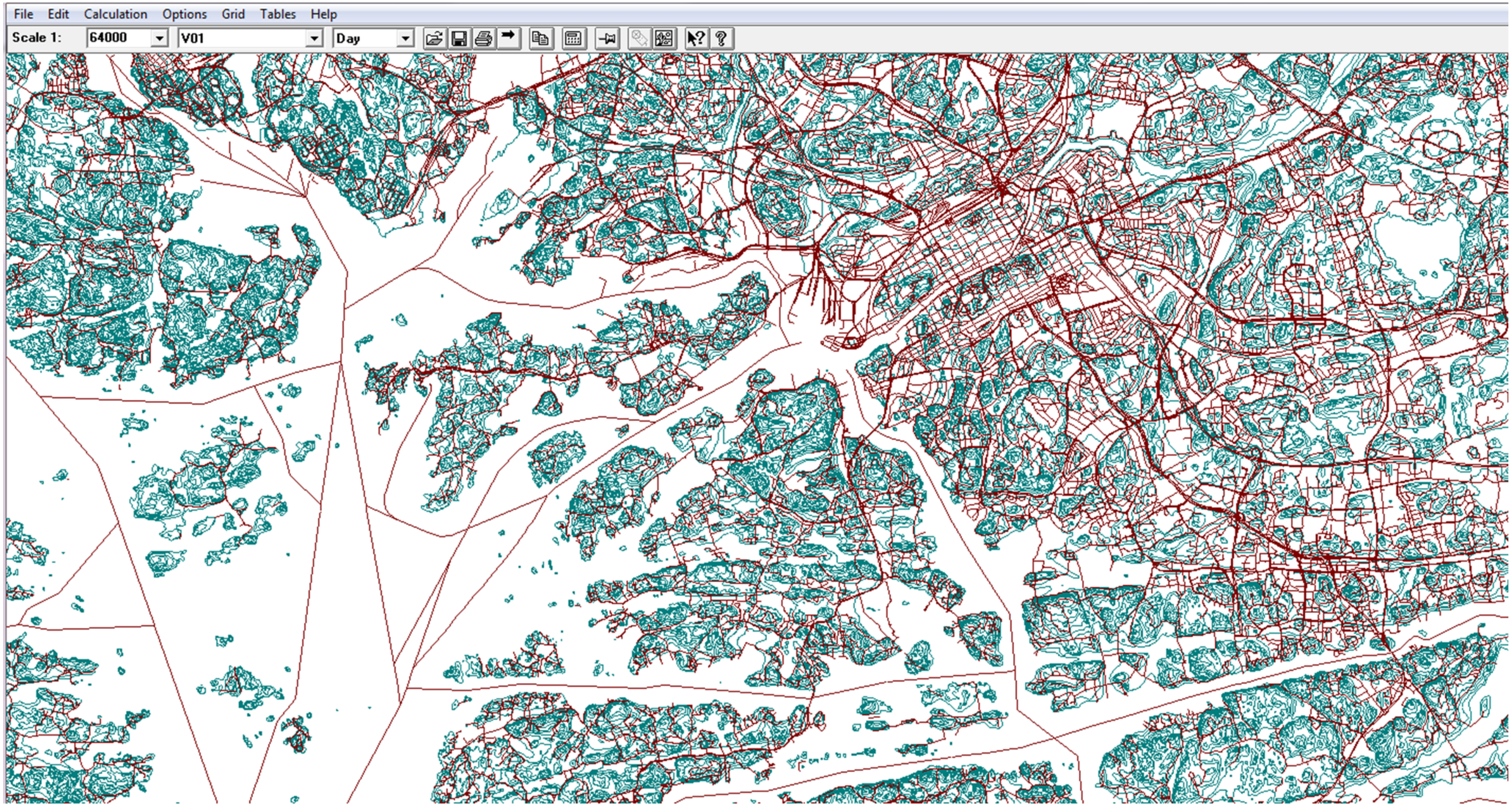


Imported map – full of lines that Cadna does not understand



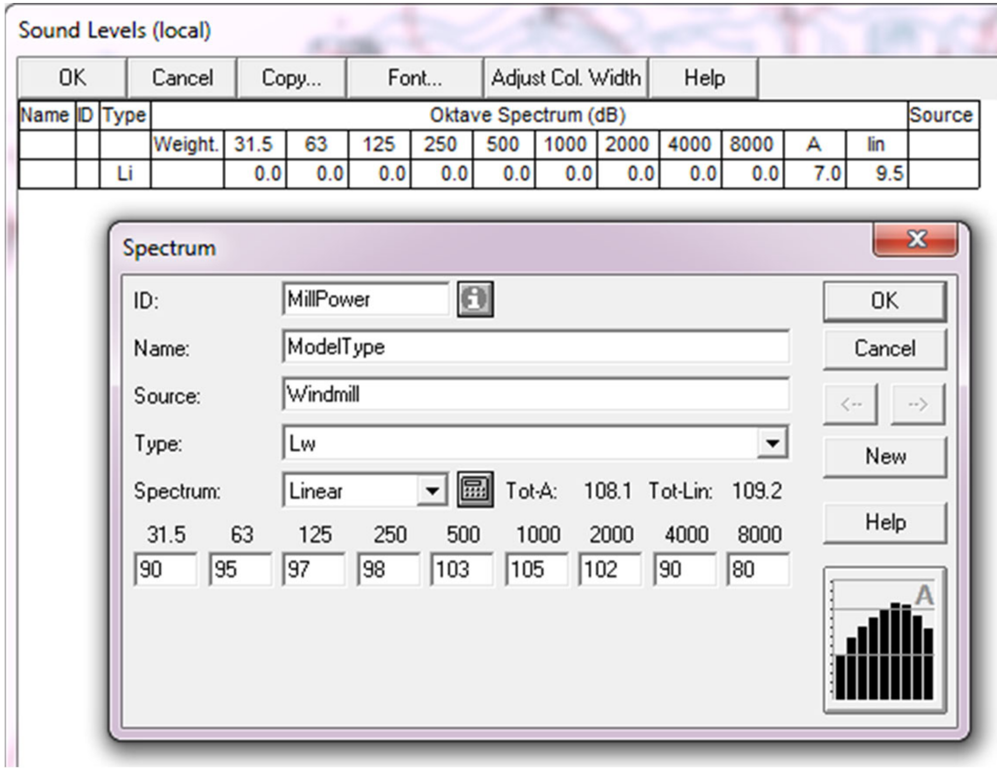
EXAMPLE: Water lines are at 0 m height by default. Sea lines can remain at that height. The height of river, lake and pond lines must be defined manually to avoid drowning to sea level.

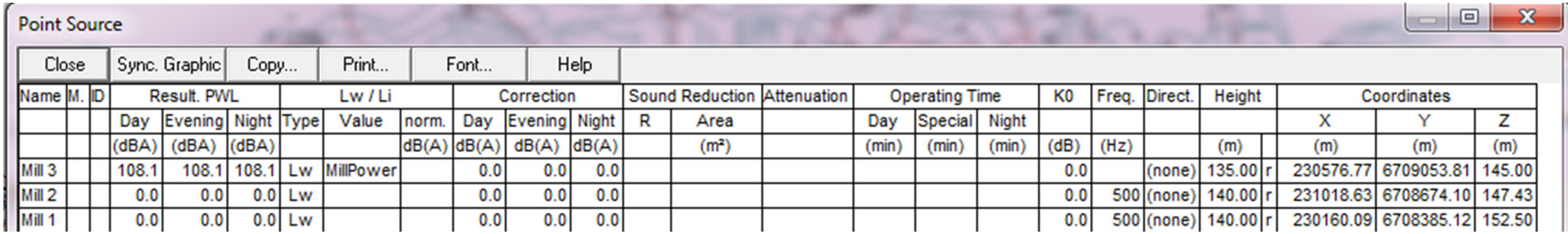
Finalized map in Cadna



Sound source definition

- XYZ-Positions
- Hourly operation (noise modes)
- Sound power levels in 31.5-8000 Hz





Name	M.	ID	Result. PWL			Lw / Li			Correction			Sound Reduction		Attenuation	Operating Time			K0	Freq.	Direct.	Height		Coordinates		
			Day	Evening	Night	Type	Value	norm.	Day	Evening	Night	R	Area		Day	Special	Night						X	Y	Z
			(dBA)	(dBA)	(dBA)			dB(A)	dB(A)	dB(A)	dB(A)		(m²)		(min)	(min)	(min)	(dB)	(Hz)		(m)		(m)	(m)	(m)
Mill 3			108.1	108.1	108.1	Lw	MillPower		0.0	0.0	0.0							0.0		(none)	135.00	r	230576.77	6709053.81	145.00
Mill 2			0.0	0.0	0.0	Lw			0.0	0.0	0.0							0.0	500	(none)	140.00	r	231018.63	6708674.10	147.43
Mill 1			0.0	0.0	0.0	Lw			0.0	0.0	0.0							0.0	500	(none)	140.00	r	230160.09	6708385.12	152.50

Receiver definition

- Nearest residents
- XY coordinates

ation Options Grid Tables Help

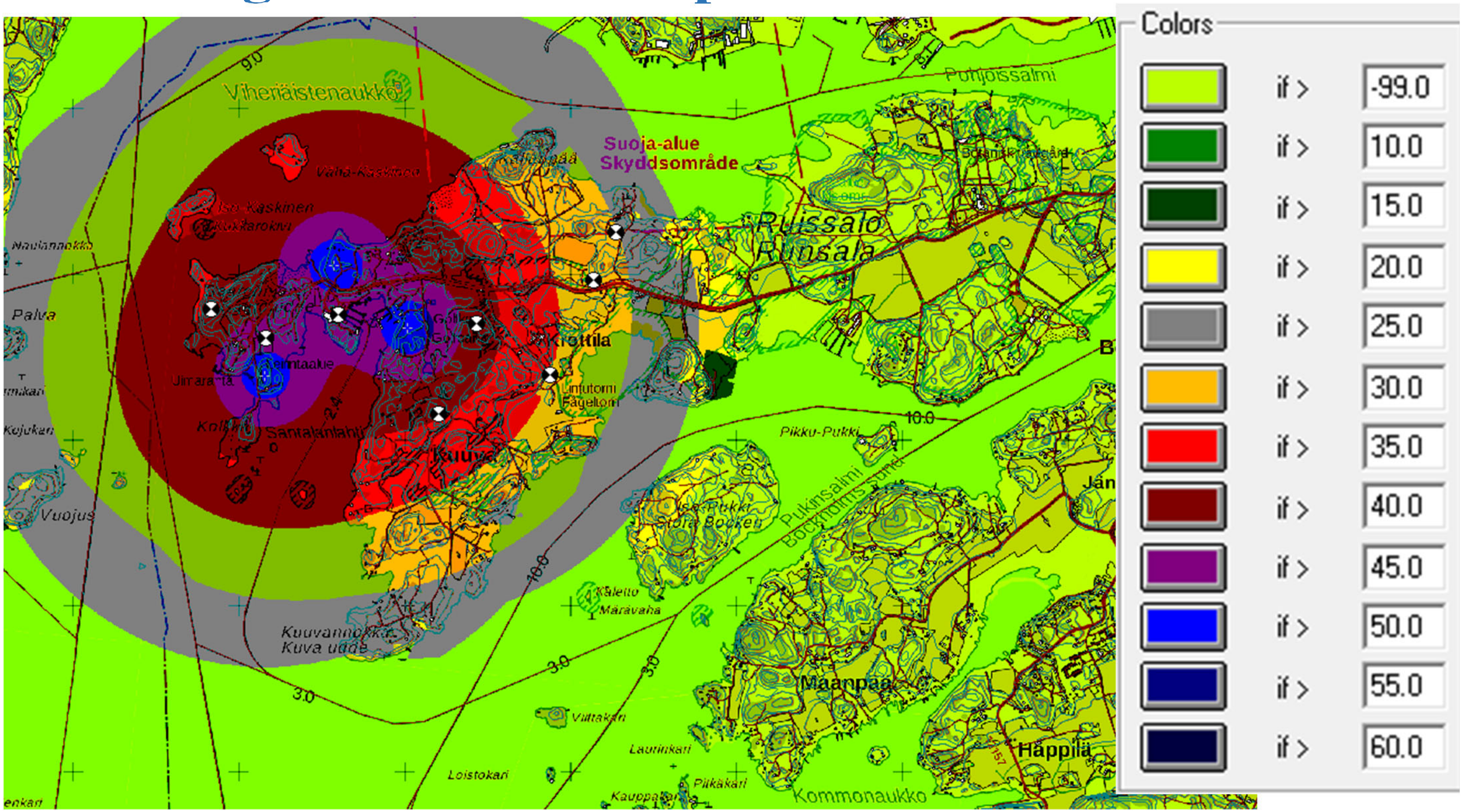
0 | V01 | Ground

Receiver

Close | Sync. Graphic | Copy... | Print... | Font... | Help

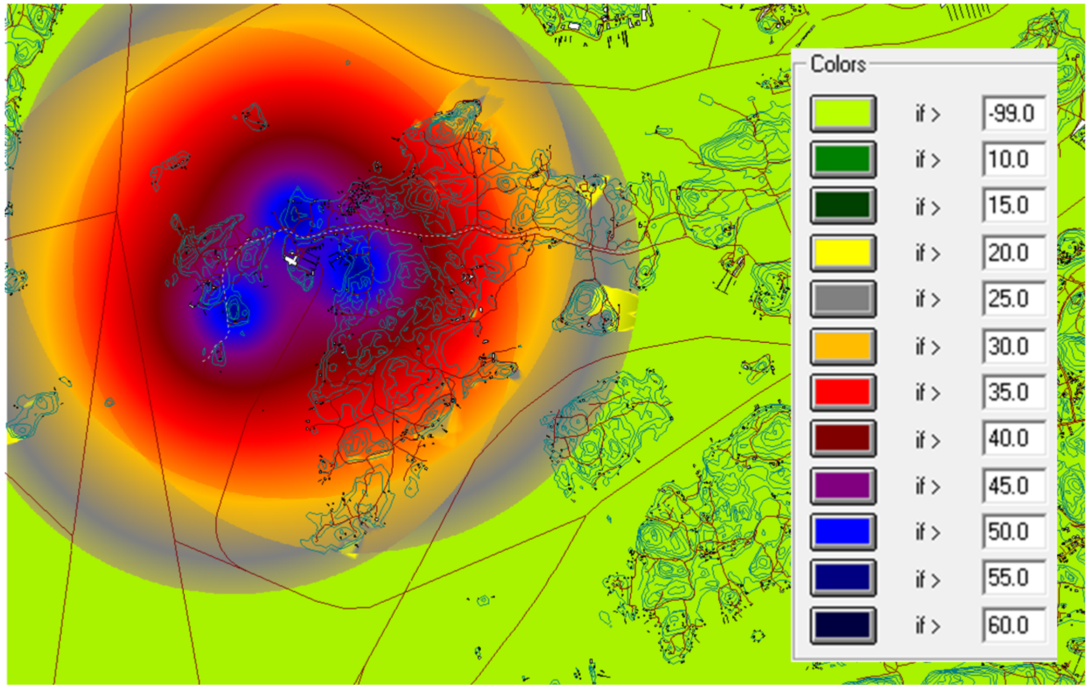
Name	M.	ID	Level Lr		Limit. Value		Land Use			Height		Coordinates		
			Day	Night	Day	Night	Type	Auto	Noise Type			X	Y	Z
			(dBA)	(dBA)	(dBA)	(dBA)				(m)		(m)	(m)	(m)
rec1			47.6	40.6	0.0	0.0		x	Total	4.00	r	230166.73	6708612.43	6.50
rec1			45.1	38.1	0.0	0.0		x	Total	4.00	r	230601.46	6708756.45	7.28
rec1			35.2	28.2	0.0	0.0		x	Total	4.00	r	231209.54	6708156.37	23.69
rec1			44.3	37.3	0.0	0.0		x	Total	4.00	r	231433.57	6708700.45	25.53
rec1			37.5	30.5	0.0	0.0		x	Total	4.00	r	231881.63	6708391.07	7.02
rec1			51.2	44.2	0.0	0.0		x	Total	4.00	r	232143.00	6708967.15	17.15
rec1			34.8	27.8	0.0	0.0		x	Total	4.00	r	232276.35	6709252.52	19.00
rec1			42.0	35.0	0.0	0.0		x	Total	4.00	r	229836.02	6708788.46	21.07

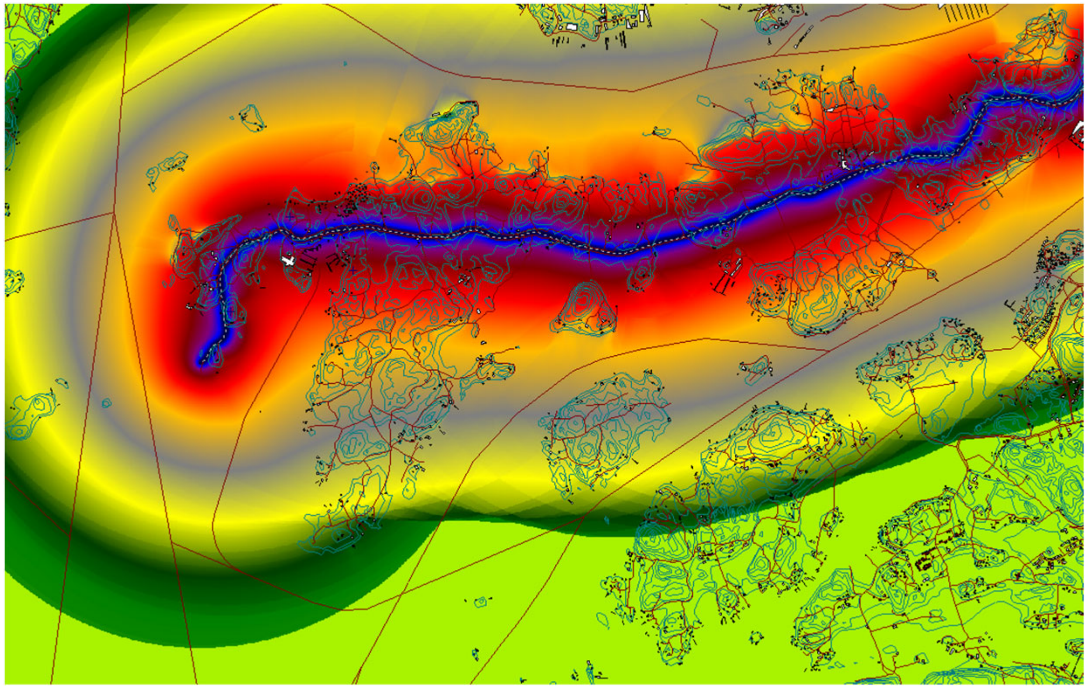
Outcoming sound level map



Road traffic vs. wind turbine sound

- It is sometimes useful to put the wind turbine noise inperspective.
- The road traffic noise in the same area is shown on the right (assumptions: 100 vehicles/hour, 50 km/h, share of heavy vehicles: 2%).



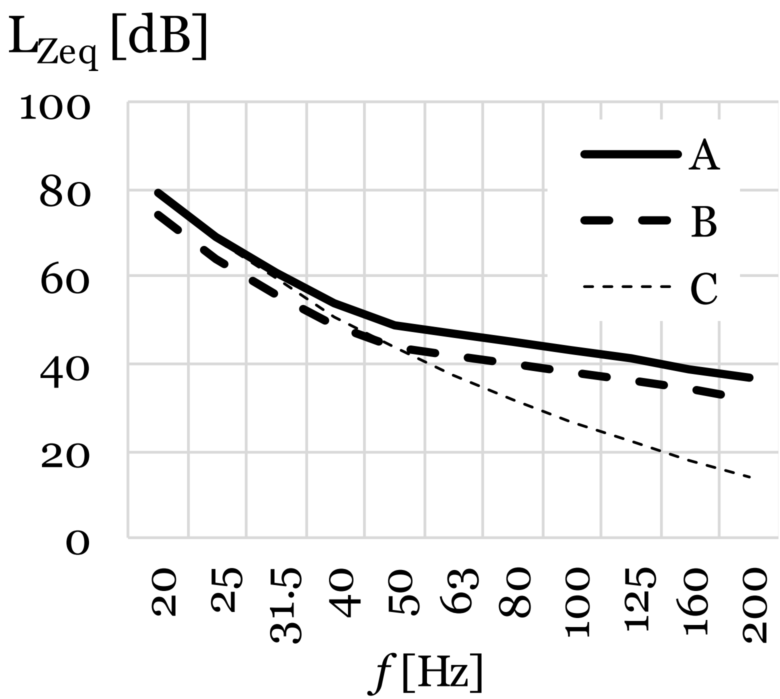


Indoor noise calculation

Action levels of Ministry of Social Affairs and Health, Finland, STM 545-2015.

- Many countries involve regulations related to the low frequency noise **indoors** in one-third octave bands.
- Knowing the indoor level requires the knowledge of the façade sound insulation
- However, the sound insulation cannot be measured for every dwelling, but estimations are used.

Band *f* [Hz]	Day 07-22 $L_{Zeq,1h}$ A	Night 22-07 $L_{Zeq,1h}$ B	Hearing threshold C
20	79	74	78.5
25	69	64	68.7
31.5	61	56	59.5
40	54	49	51
50	49	44	44
63	47	42	37.3
80	45	40	31.5
100	43	38	26.6
125	41	36	22
160	39	34	18
200	37	32	14.3

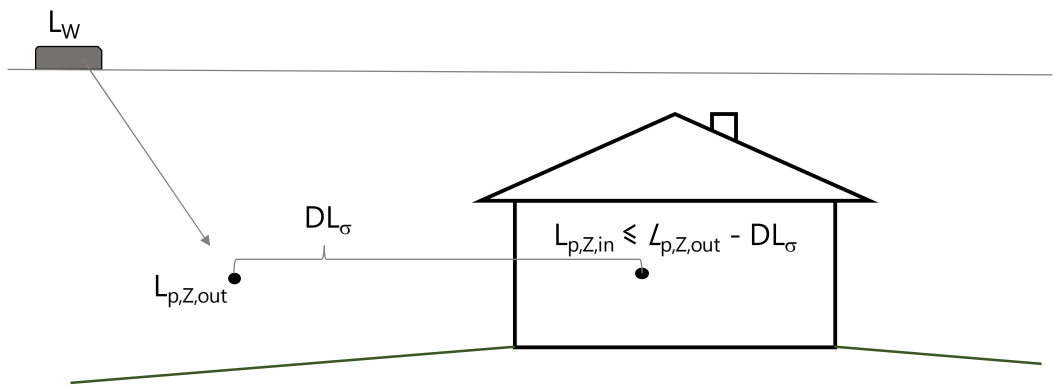


Calculation of SPL indoors

- The results of Keränen et al. (2019) are used in Finland to estimate indoor SPL of environmental noise when the façade sound insulation is unknown
- SPL of environmental noise $L_{\mathrm{p,Z,out}}$ [dB] on the yard is predicted or measured in 1/3-octave bands.
- SPL indoors $L_{\mathrm{p,Z,in}}$ [dB] is obtained by

$$L_{p,Z,in} = L_{p,Z,out} - DL_{\sigma}$$

  - where DL_{σ} [dB] represents the level difference that is exceeded in 84 % of Finnish facades (Table 4).
- SPL indoors is compared to the action levels



Keränen et al. (2019)

Table 4
The expected level difference, DL_{σ}, as a function of frequency, f. The value is based on our results from 26 façades and it is expected to be exceeded in 84% of Finnish dwellings. The second row involves the expected level difference, ΔL_{σ}, suggested by Ref. [3].

f [Hz]	5	6.3	8	10	12	16	20	25	31.5	40	50	63	80	100	125	160	200
DL_{σ} [dB]	5.5	5.7	5.9	6.2	6.6	7.1	7.6	8.3	9.2	10.3	11.5	13.0	14.8	16.8	18.8	21.1	22.8
ΔL_{σ} [dB]				4.9	5.9	4.6	6.6	8.4	10.8	11.4	13.0	16.6	19.7	21.2	20.2	21.2	

Accuracy of prediction models

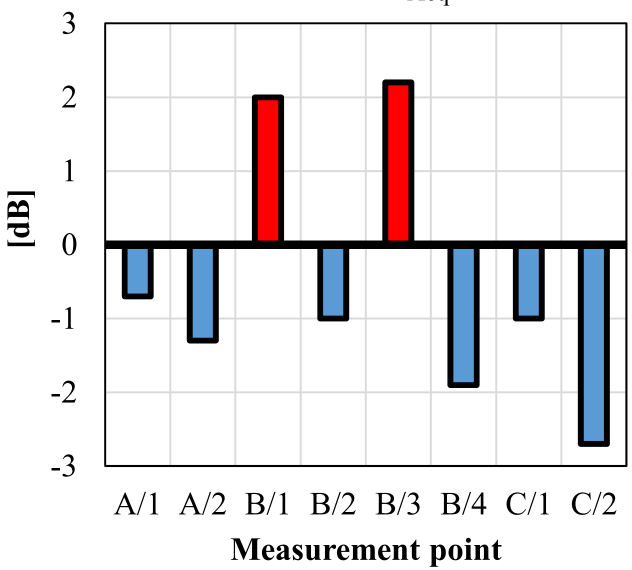
- Prediction accuracy of ISO 9613 was studied in 8 points located in 3 WT areas.
- The predicted and measured sound levels, L_{Aeq}, were in very good agreement
- The differences were within the measurement uncertainty (±3 dB) in each point.

Point	d [m]	$L_{Aeq,M}$ [dB]	$L_{Aeq,P}$ [dB]
A/M1	660	44.8	44.1
A/K1	630	45.9	44.6
B/M1	447	41.0	43.0
B/K1	244	47.6	46.6
B/K2	600	39.1	41.3
B/K3	383	46.6	44.7
C/M1	772	44.2	43.2
C/K1	889	44.7	42.0

M = Measured

P = Predicted

Difference of predicted and measured L_{Aeq}



Hongisto et al. (2017): http://dx.doi.org/10.1121/1.5006903.

Wind turbine noise.
5. Health effects.

Contains 4 sub-studies

Noise annoyance

- WHO (1948) definition of health:
  - ”*Health is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity*”.
- Definition suggests that health means *well-being* not just absence of diseases.
- Responding to a sound by noise annoyance, is an adverse effect that should be avoided in order to retain well-being.

Definition of noise

- *Sound which has adverse effects on hearing or is annoying.*
- *Any sound which is unpleasant, loud or disturbs the current activity.*
- *Unwanted sound.*

- Judgment depends on the environment.

Environments

- Home
- Home yard
- Nature, forest
- School
- Office
- Factory
- Theatre
- Gym

Activity

- Sleep
- Relaxing
- Studying, working
- Relaxed reading
- Communication
- Listening
- Sport

Non-auditory effects of noise

- **Annoyance**
- Disordered body function: **sleep disturbance**

- Deterioration of cognitive functions
  - Concentration
  - Attention
  - Short-term memory performance
  - Long-term memory performance
  - Learning
- Communication
  - hearing
  - speaking
- Stress-induced body responses
  - Cardiovascular functions (heart rate, heart rate variation)
  - Endocrine system (stress hormones)
  - Metabolism
  - Immune system
- Vocal disorders

Increment of morbidity

- Cardiovascular diseases
- Infections
- Psyche

NOTE: A sound can be beneficial in one context and detrimental in another.

Jauhiainen et al, (2007)

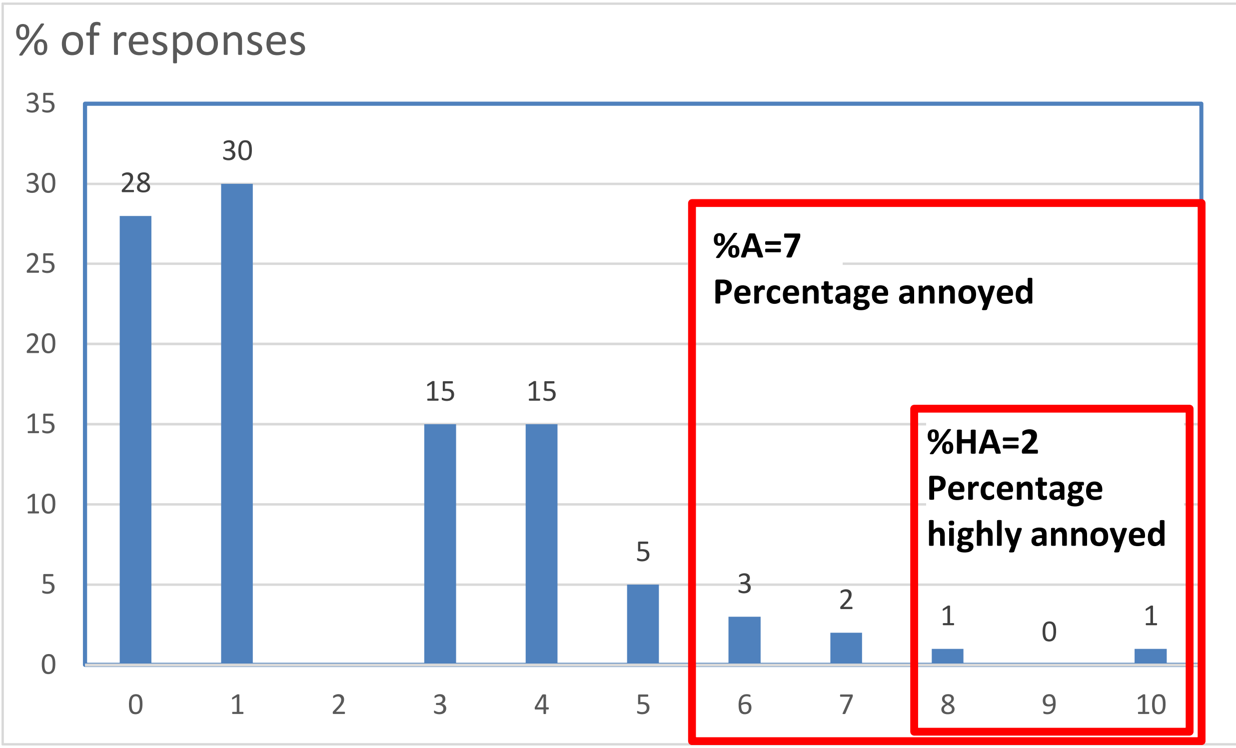
Measurement of noise annoyance (ISO/TS 15666)

How much the noise of source X has bothered, disturbed or annoyed you?

0	1	2	3	4	5	6	7	8	9	10
Not at all										Extremely

- %A : the share of those responding 6 or more.
- %HA: the share of those responding 8 or more.

- Figure shows exemplary data of 100 respondents exposed to environmental noise within 30-35 dB



Non-acoustic factors and noise annoyance

Guski 1999

- One-third of noise annoyance is explained by noise level.
- One-third of noise annoyance is explained by non-acoustic factors.
- One-third of noise annoyance is explained by measurement errors

Important non-acoustic factors

Individual (person)

- Noise sensitivity
- Neuroticm
- Extraversion
- Attitudes towards source
  - Fears
  - Benefiting from source
- Coping-ability
- Home ownership
- Visibility of source

Social (area/group)

- Attitudes
- Trust towards authorities
- History of area
- Expectations
- Participation in land use design
- Benefiting from the source

Flindell & Stallen 1999

Health effects: Study 1: Perception of wind turbine noise

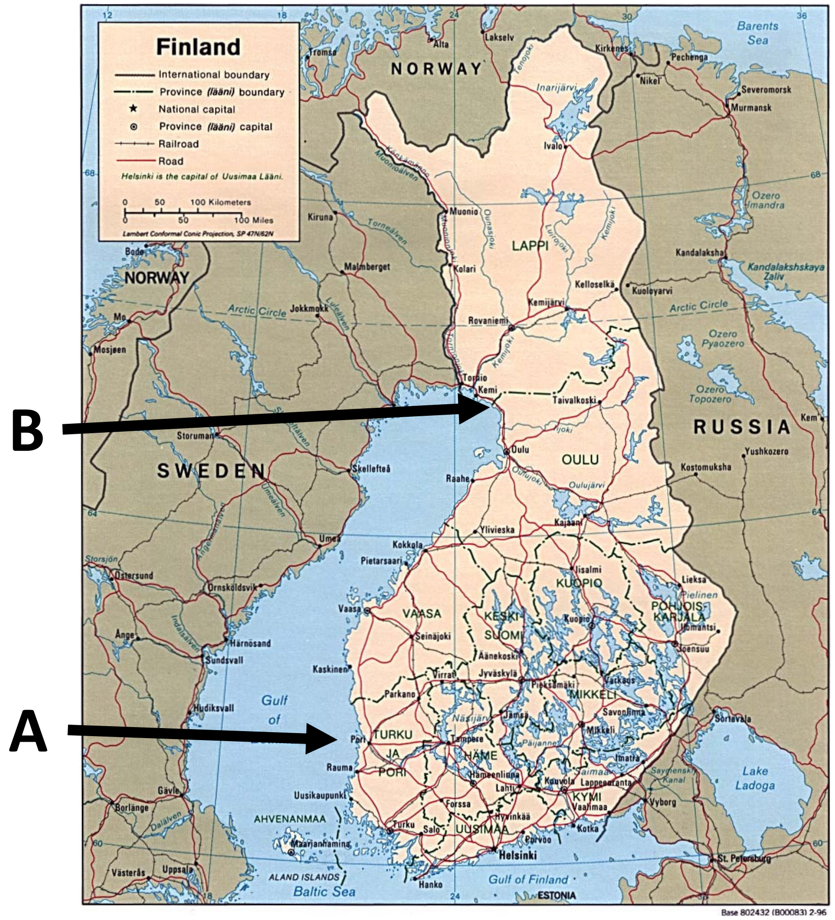
Hongisto, V., Suokas, M., Varjo, J., Yli-Kätkä, V.-M. (2015). Tuulivoimalamelun häiritsevyys kahdella tuulivoima-alueella, Ympäristö ja Terveys -lehti, 6 2015 54-59. Available at: https://tuulivoimayhdistys.fi/media/794-hongisto_ym_2015_ymparisto_ja_terveys.pdf

Purpose of the study

- The purpose was to
  - compare the perception of WT noise in two WT areas A and B which are quite similar from objective point of view
  - Determine which variables are associated with annoyance inside
- The scope was on annoyance and factors which the literature review showed that might be associated with annoyance

METHODS - Survey

- Households within 2 km from WTs
- Two WT areas: A and B
- Addresses from municipalities
- Response alternatives
  - Full interview at home
  - Full questionnaire by mail
  - Short interview by phone
    - Three main questions
- One response per household
- 20 euro compensation for full response
- Sound pressure levels L_{Aeq} were predicted to households' yards according to the **Ministry of Environment**



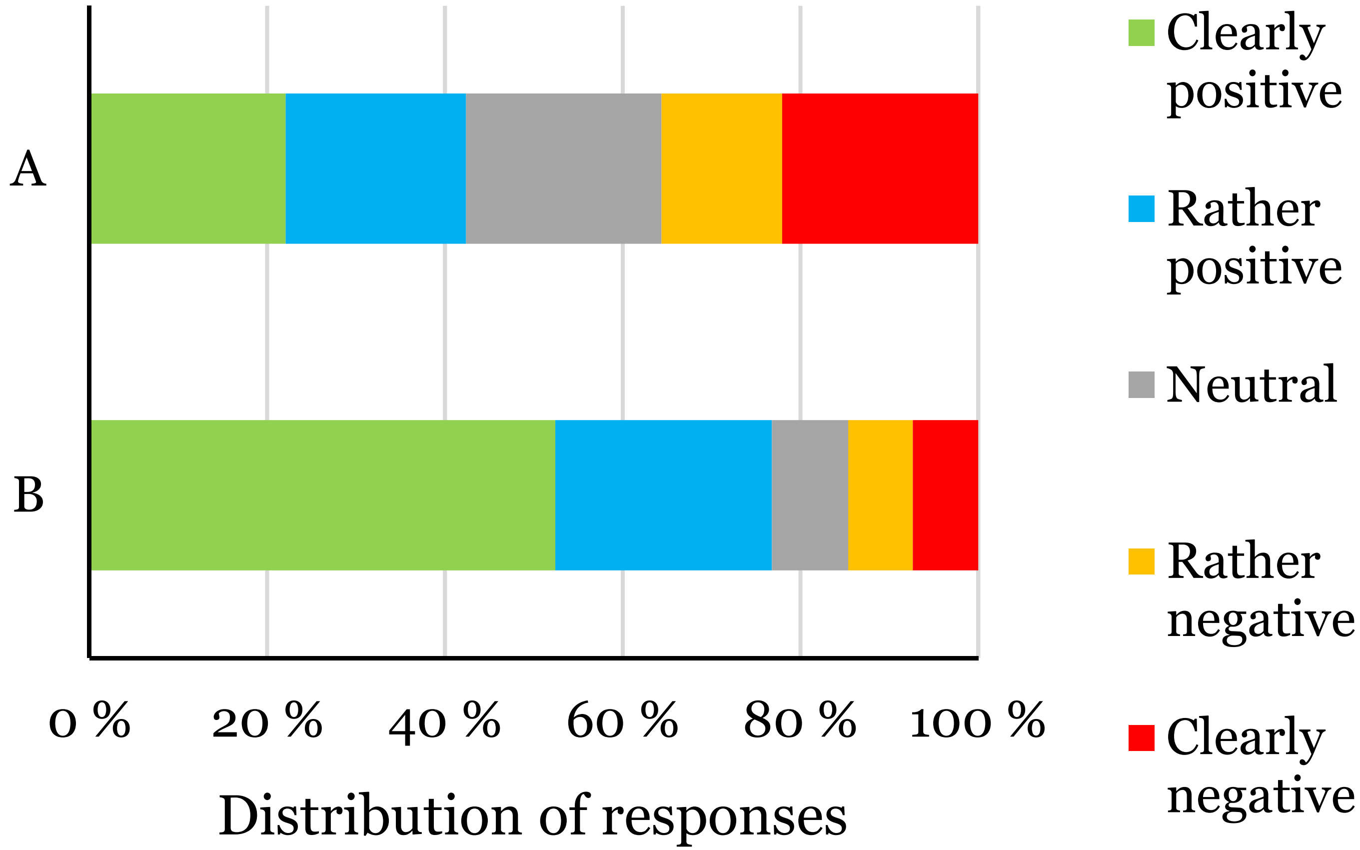
RESULTS - Descriptive

	WT area	
	A	B
Nr of housholds within 2 km from turbine	107	189
Number of households responding	62	91
Response rate [%]	57.9	48.1
Share of cottages/leisure time households [%]	52	59
Share of male respondents [%]	50	63
Mean age of respondents (standard dev)	61 (13)	58 (15)
Number of wind turbines in the WT area	12	11
Electric power of turbines [MW]	4.5	3.0-3.3
Deployment of WT area	12-2013	12-2012
Time of this survey	1-2015	5-2015

RESULTS – Attitude towards wind energy

”What is your opinion towards electric energy produced by wind turbines?”

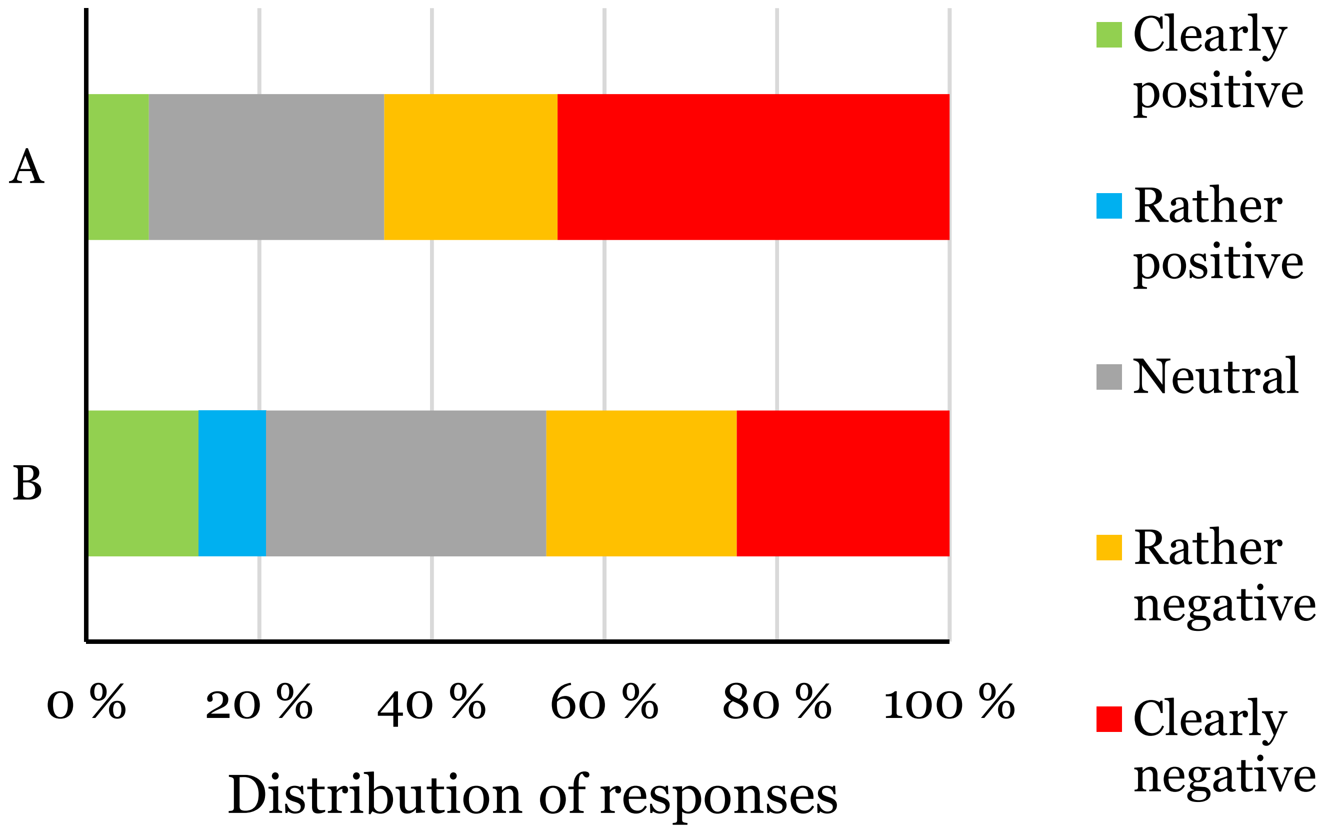
(p<0.001)



RESULTS – Attitude towards landscape effects

”My opinion towards the effects of wind turbines on landscape is …”

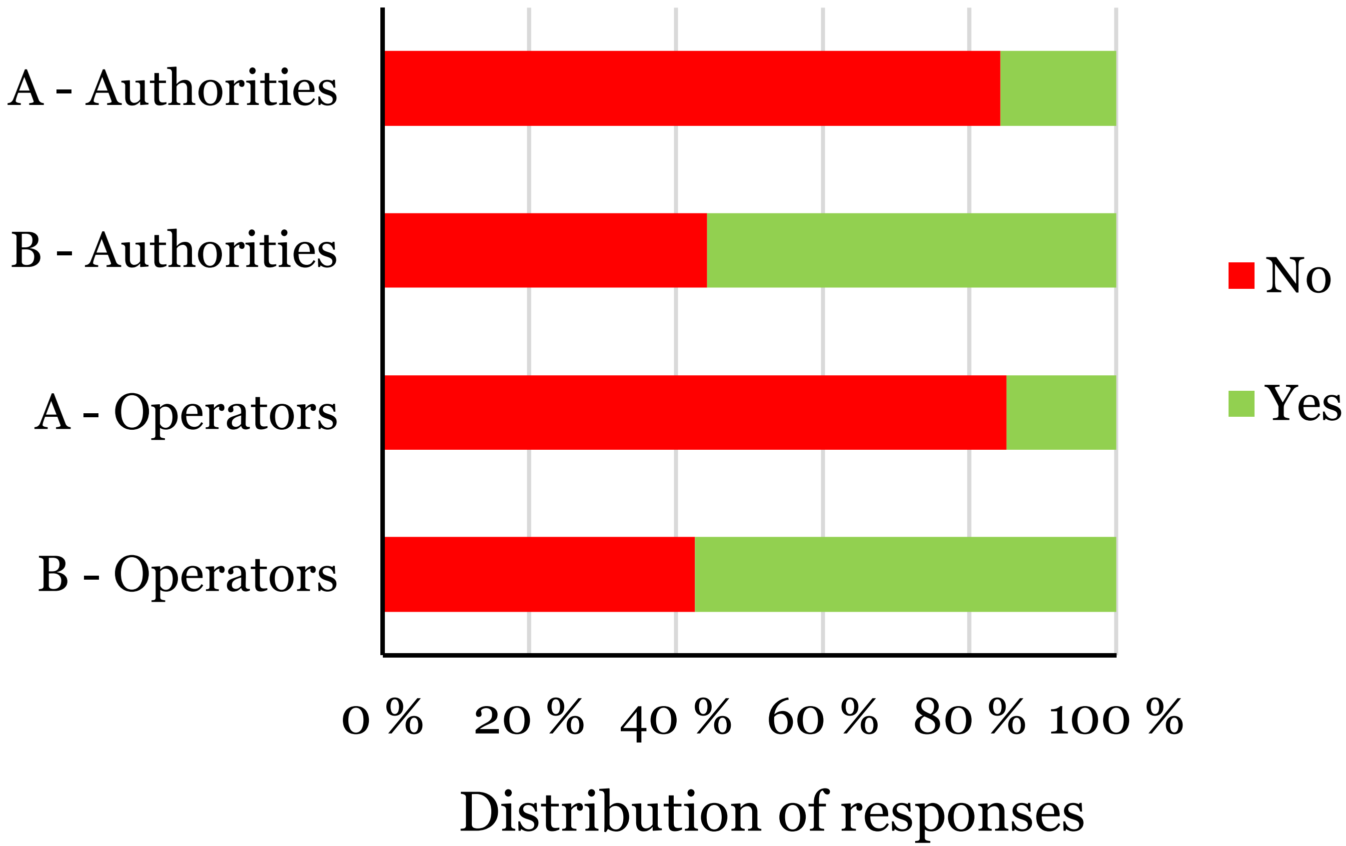
(p<0.01)



RESULTS – Trust towards authorities/operators

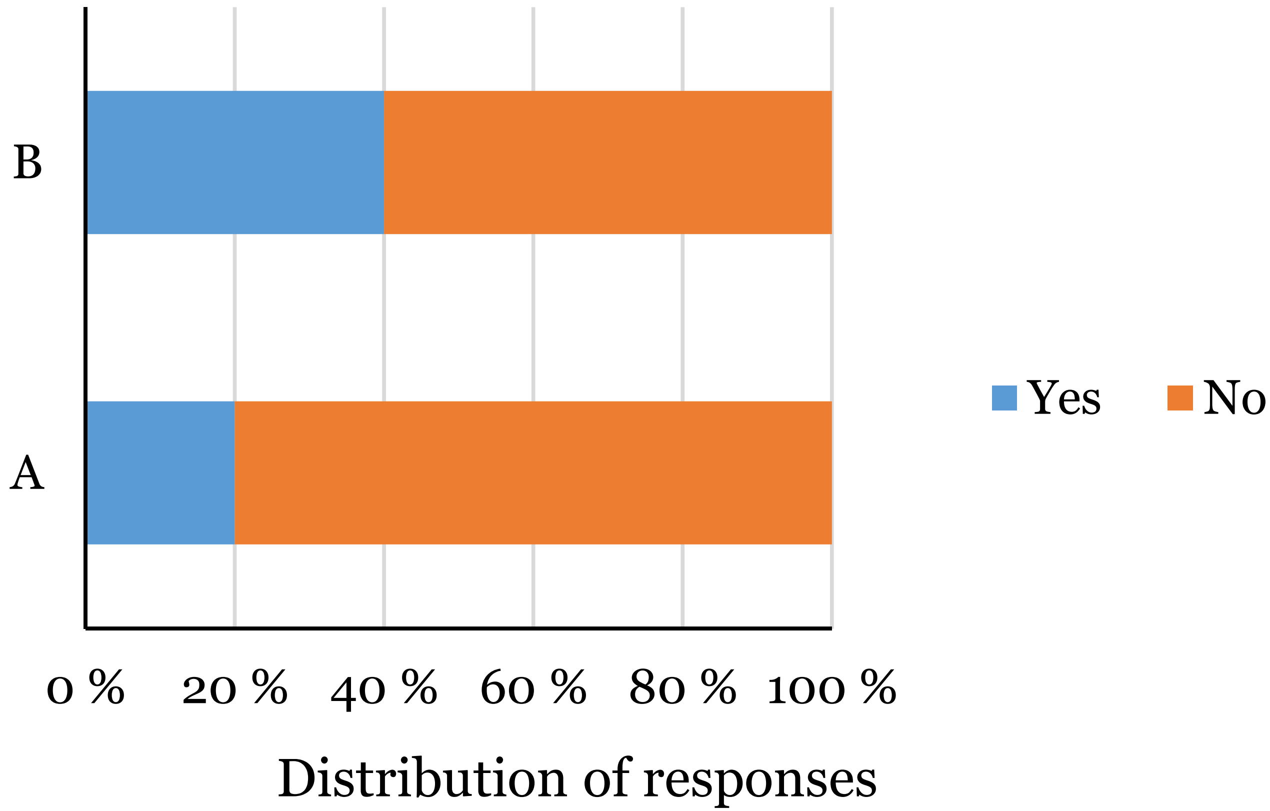
”Do you believe that the authorities or operators have acted sufficiently to exclude possible disadvantages?”

(p<0.001)



RESULTS – Benefits to the village/community

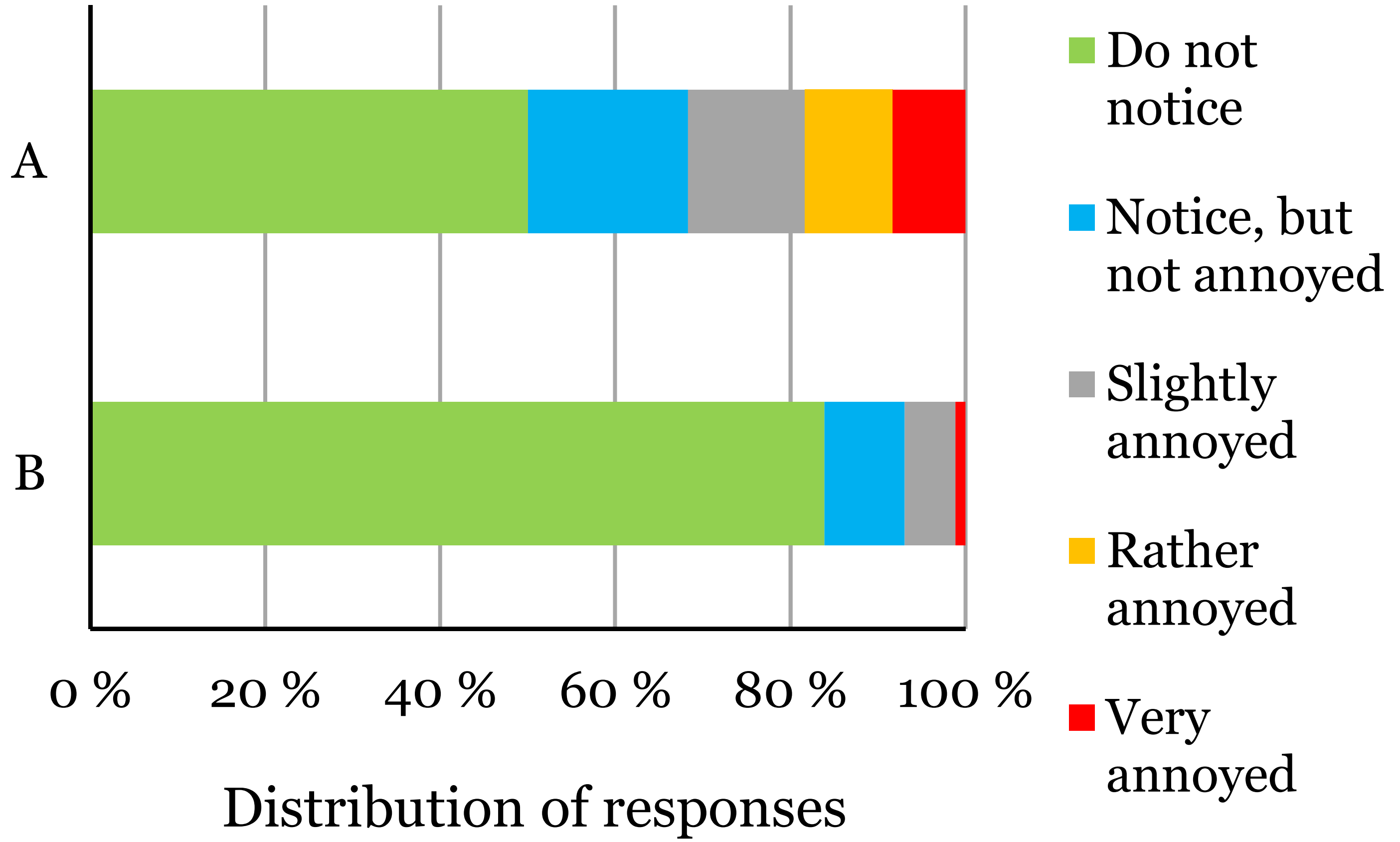
- ”Do the wind turbines benefit your village somehow?”



RESULTS – Annoyance of WT noise inside

”How annoying are the sounds of wind turbines inside your apartment?”

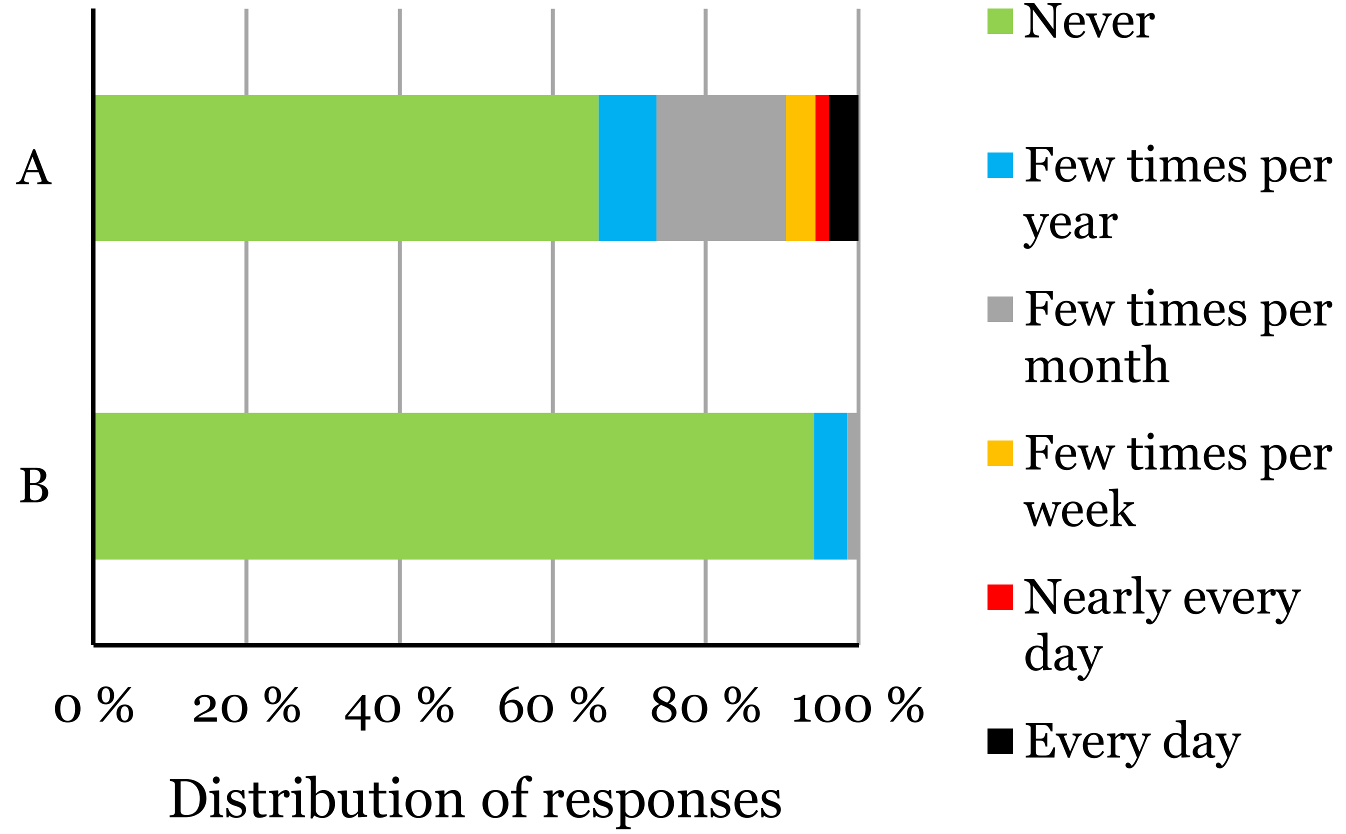
(p<0.001)



RESULTS – Effects of WT noise on sleep

”Have you waked up or stayed awake at night because of WT noise?”

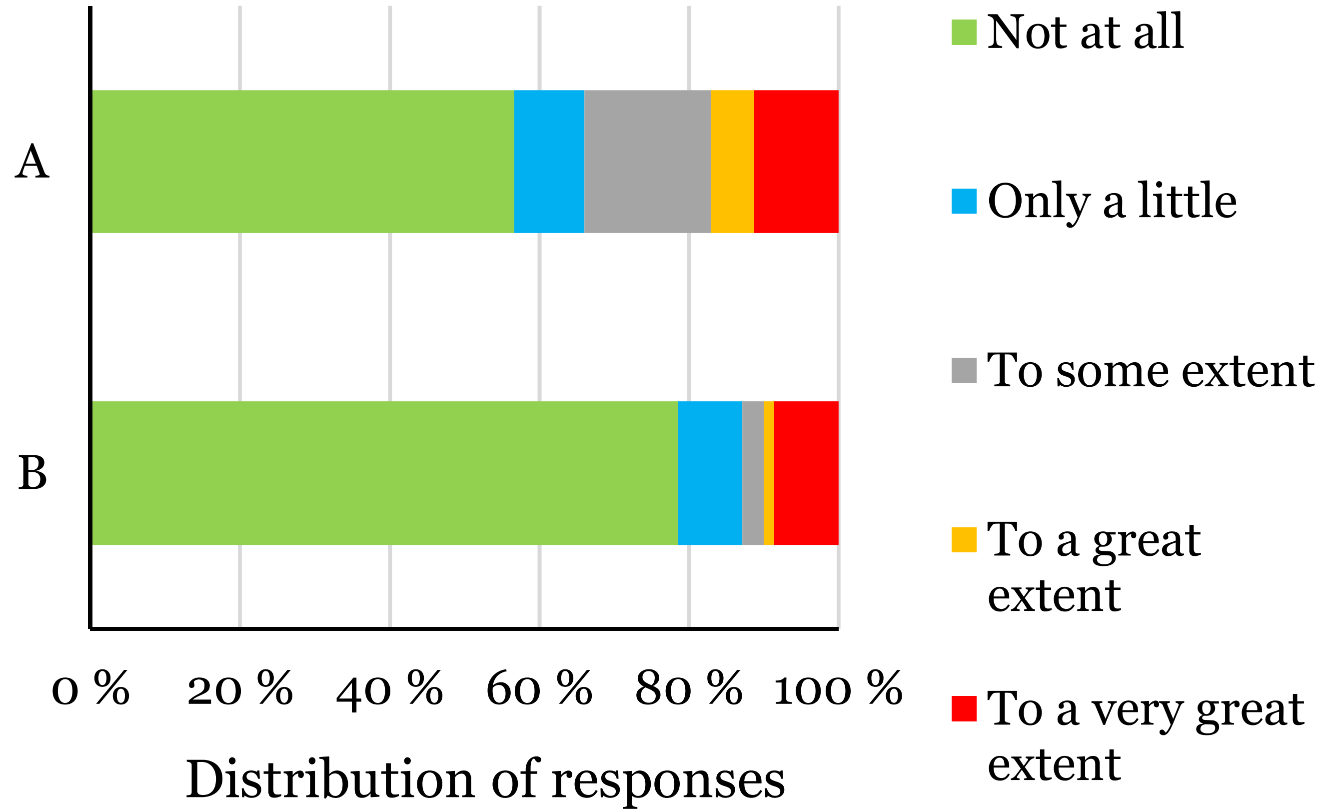
(p<0.001)



RESULTS – Concern about health effects of WT noise

”Are you concerned about possible effects of wind turbine noise on your health?”

(p=0.005)



RESULTS – Factors associated with noise annoyance inside

- Analysis for aggregate data A+B
- r_S is Spearman's linear correlation coefficient.
- Large r_S represents strong association.
- **Noise annoyance is larger inside if,**
  - The person is concerned about health effects of WT noise,*
  - The person does not trust on authorities and/or operators,*
  - Person is more sensitive to noise (individual feature);
  - Noise level outside gets larger;
  - Attitude towards landscape effects is negative;*
  - Attitude towards wind energy is negative.*

* Causality relationship is unknown.

	r_S	p
Distance to the nearest WT (200 m categories)	-0.22	*
Sound level outside L_{Aeq} (continuous variable)	0.32	**
Respondents age	-0.16	n.s.
Individual noise sensitivity	0.34	**
Visibility of a WT on the yard	0.13	n.s.
Attitude towards wind energy	0.27	*
Attitude towards landscape effects	0.33	**
Trust towards authorities	-0.44	**
Trust towards operators	-0.46	**
Concern about health effects of WT noise	0.50	**

n.s. Non-significant relationship, p>0.01
* Statistically significant relationship, p<0.01
** Statistically very significant relationship, p<0.001

CONCLUSION

- Significant differences were found between two nearly identical WT areas.
- The history of land use may explain the differences.
- Experiences from individual WT areas shall never be generalized.

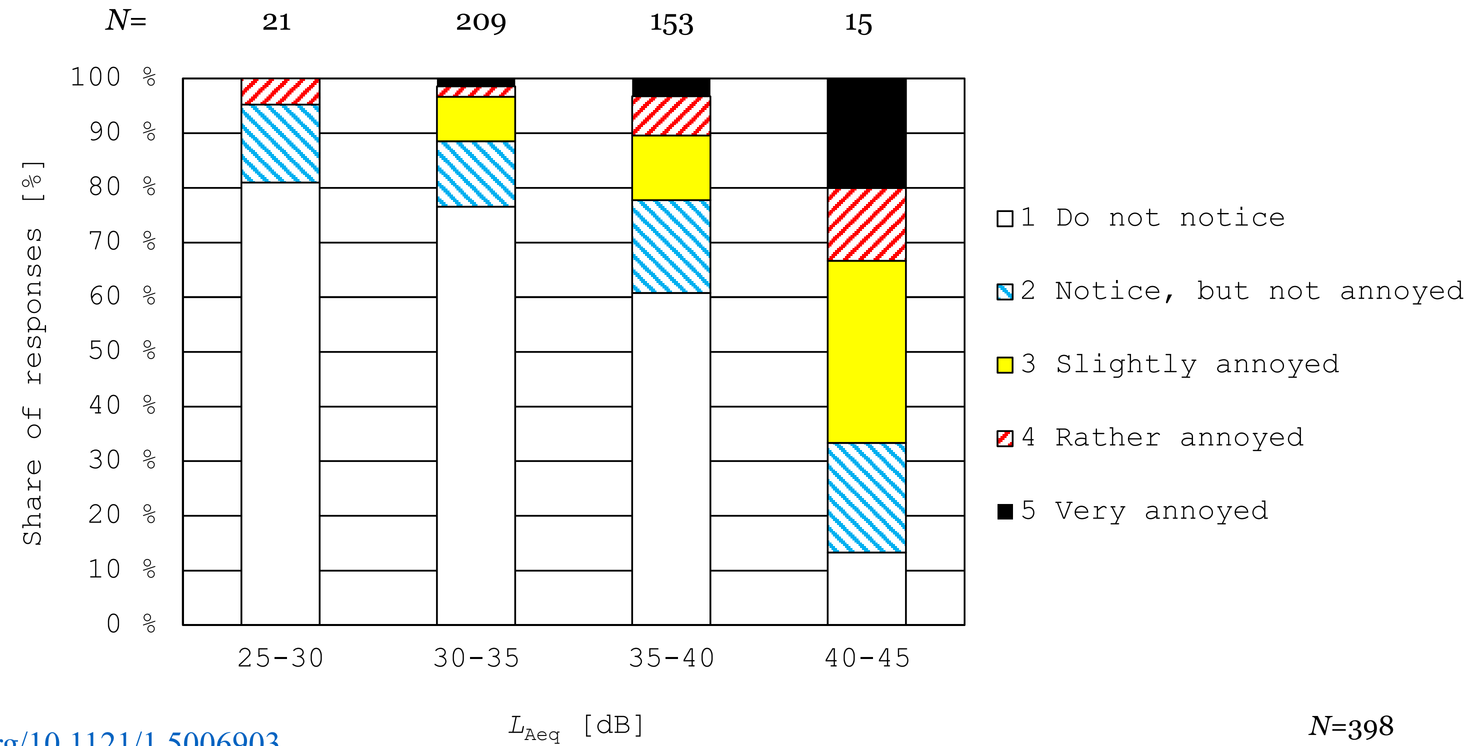
Health effects: Study 2: Dose-response relationship of wind turbine noise

Source: Hongisto, V., Keränen, J., Oliva, D. (2017). Indoor noise annoyance due to 3-5 MW wind turbines - an exposure-response relationship, **The Journal of the Acoustical Society of America** 142(4) 2185-2196. Open access at: http://dx.doi.org/10.1121/1.5006903.

Finnish dose-response relationship of WT noise annoyance

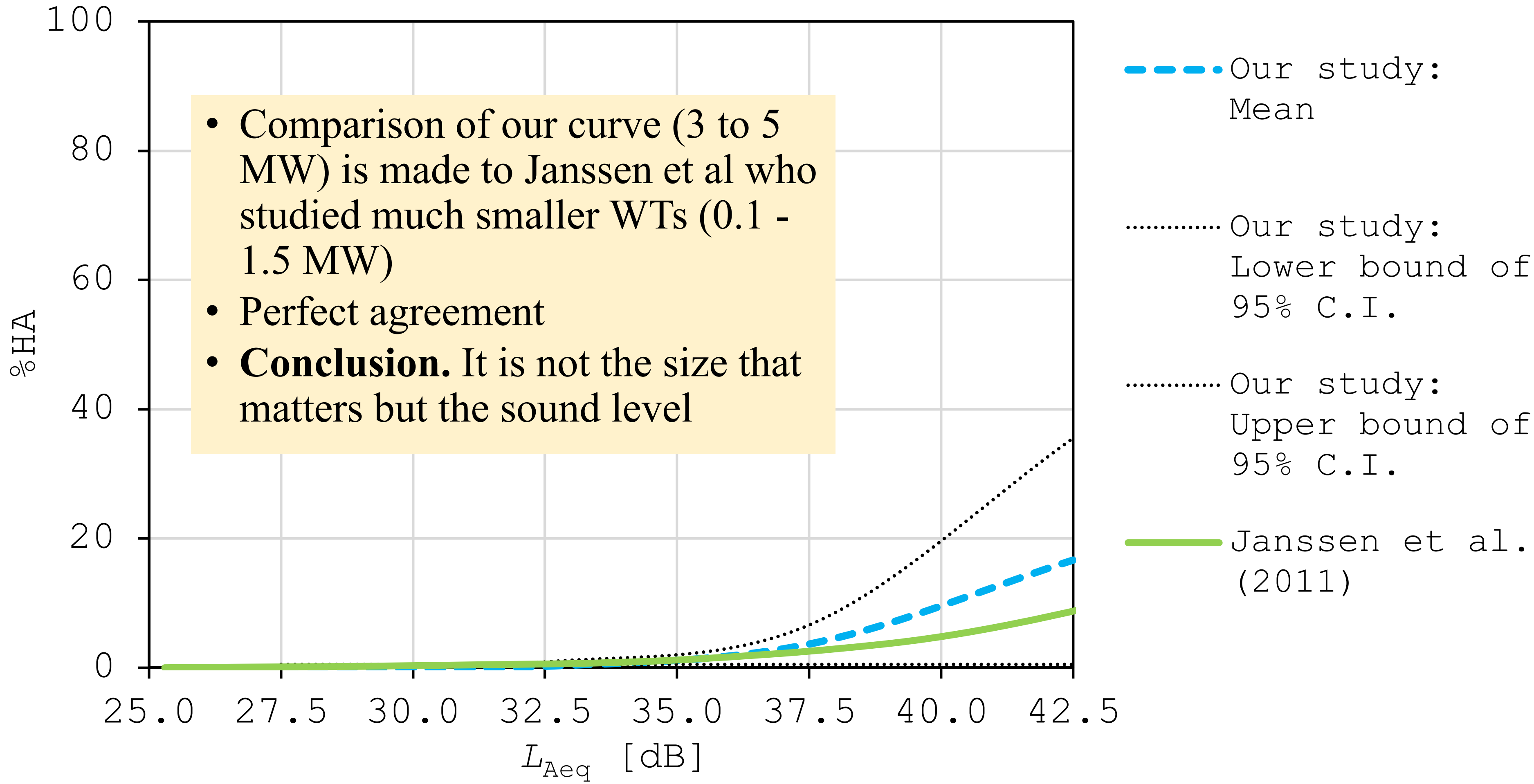
- We studied how the sound level explains %HA.
- All households living under 2 km from WTs were invited to survey in three WT areas.
- 398 responses were received.
- Direct merged annoyance responses are given in Figure.
- %HA means here those who responded 5.

	Wind power area		
	A	**B**	**C**
Number of wind turbines in the area	12	11	3
Nominal electric power of the turbines	4.5	3.0 / 3.3	5.0
Sound power level of the turbines, L_{WA} [dB]	108.8	106.7 / 107.6	109.6
Time of deployment	Dec 2013	Dec 2012	Dec 2014
Time of the survey	Jan 2015	May 2015	Sept 2015
Location	Pori, Peittoo	Ii, Olhava	Salo, Märynummi
Nr of households within 2 km	107	189	457
Nr of responding households	70	91	268
Nr of respondents reporting annoyance	64	78	258



Hongisto et al. 2017 J Acoust Soc Am. At: http://dx.doi.org/10.1121/1.5006903.

Finnish dose-response relationship of WT noise annoyance



- Comparison of our curve (3 to 5 MW) is made to Janssen et al who studied much smaller WTs (0.1 - 1.5 MW)
- Perfect agreement
- **Conclusion.** It is not the size that matters but the sound level

Health effects - Study 3: Health effects of wind turbine noise (WTN) and road traffic noise (RTN) on people living near wind turbines

Purpose

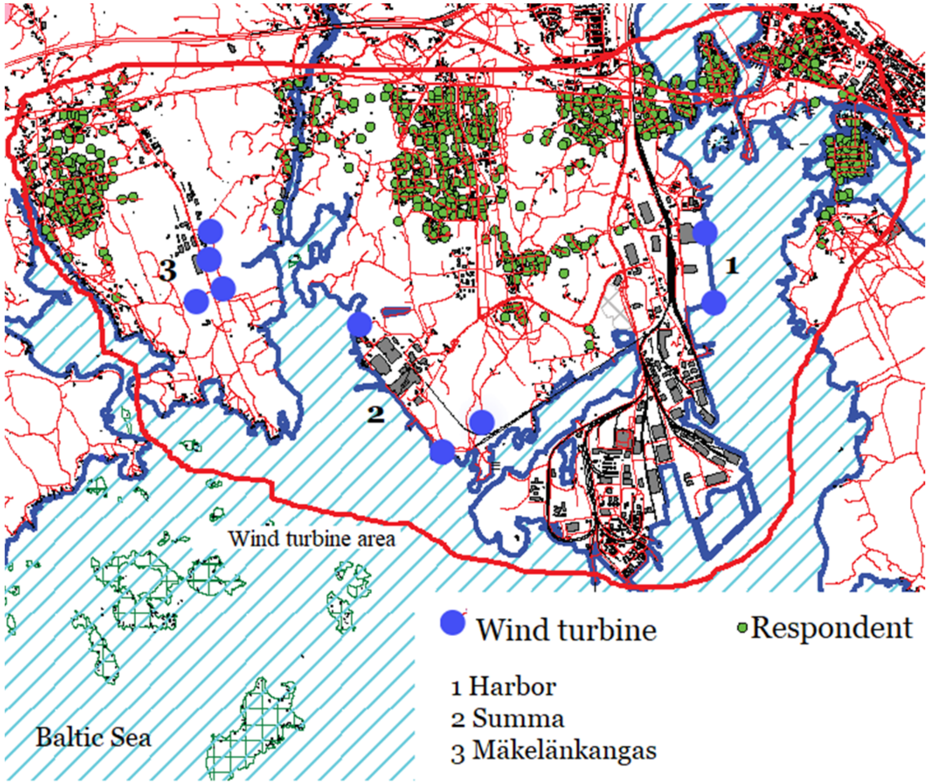
- Our purpose was to determine, using a case-control study, how RT (road traffic) and WT (wind turbine) sound level are associated with noise annoyance, symptoms, stress, and diseases close to WT areas, where the new WT noise regulations are fulfilled.
    - Selection of a WT area where regulations are violated in some residences cannot be chosen since their opinion could bias the responses of other residents.

- The full version of the study is published in an open-access journal:
- Radun, J., Maula, H., Saarinen, P., Keränen, J., Alakoivu, R., Hongisto, V. (2022). *Health effects of wind turbine and road traffic noise on people living near wind turbines.* **Renewable & Sustainable Energy Reviews** 157 (2022) 112040 (13 pp).
- **Open Access**: https://www.sciencedirect.com/science/article/pii/S1364032121013022

Methods - WT areas

- Case-control study requires two groups:
  - Group with exposure
  - Group without exposure.
- Since the sound power level of WTs had to be measured (time-consuming) to guarantee proper sound level predictions, and the number of responses needed to be large to reach high statistical power, we had to choose such areas which are highly populated and close to each other. This place in Finland is **Hamina**.
- Control group: a suburb of eastern **Kotka** and 6.8 km west from Hamina WT areas
  - Similar types of residences.
  - Both places are close to coast.
  - Socioeconomic status was similar

Methods - WT areas

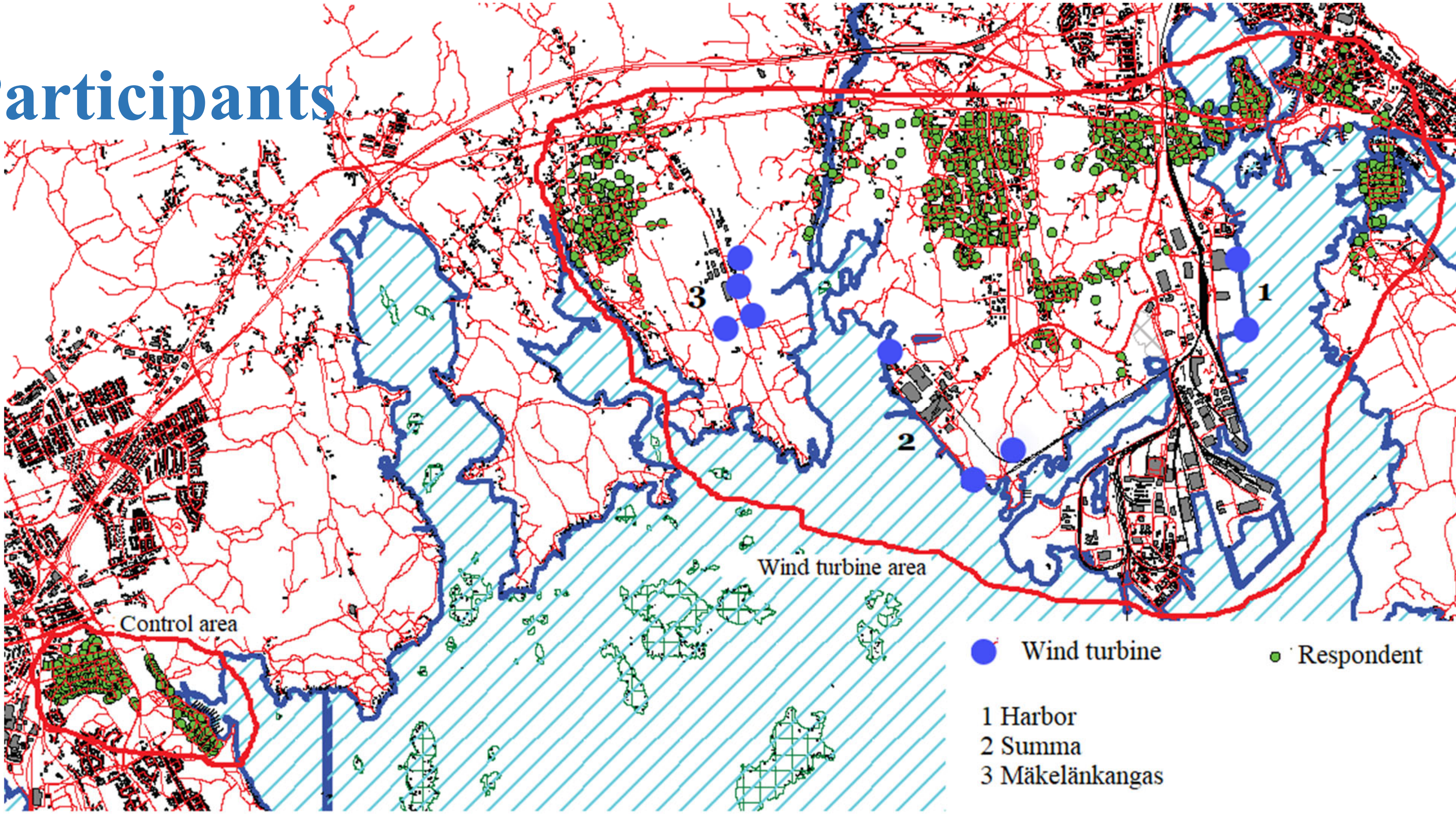


Three nearby WT areas in Hamina:

- Mäkelankangas: 4 pcs 2.0 MW
- Summa: 3 pcs 3.0 MW
- Satama 2 pcs 3.0 MW

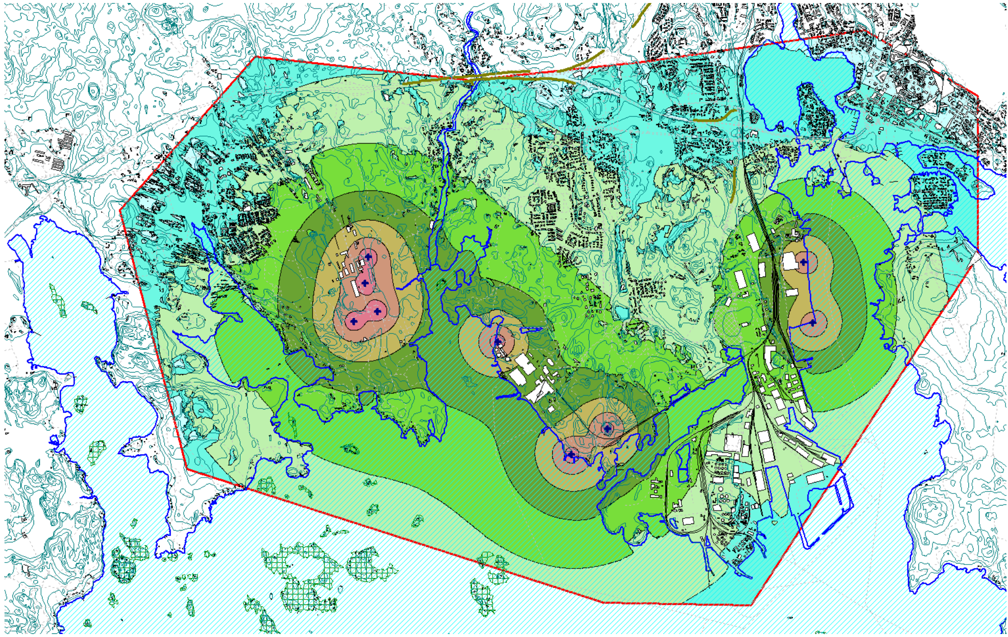
Methods – Participants

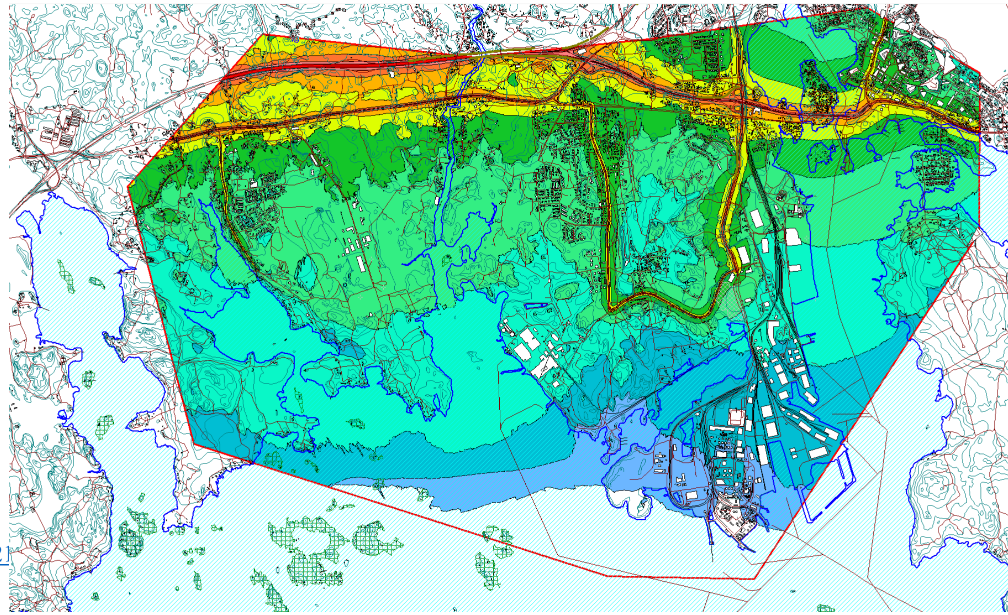
- 3058 questionnaires were mailed.
- 684 responded
  - WT area: 563
  - Control area: 121
- Response rate 22.4 %



Methods – Determination of WT sound levels in residents' yards

- **WT sound level** $L_{\mathrm{Aeq,WT}}$ were modeled according to national proceduce which has shown to have high precision [1]. The sound levels correspond to the condition, where all WTs produce maximum electric power
  - This occurs <10% of time during year.
- Sound power level of WTs was determined by IEC 61400-11 measurements in each three areas
- **RT sound level** $L_{\mathrm{Aeq07\text{-}22,RT}}$ was determined using Nordic model
- Cadna A software.





1. Hongisto, V., Keränen, J., Oliva, D. (2017). J. Acoust. Soc. Am. 142(4) 2185–2196. Online at: http://dx.doi.org/10.112

Methods – Living environment questionnaire

- Paper questionnaire (10 pp)
- Reminder to everyone
- Gift card.
- Purpose was masked: it was not possible to deduce that WT effects are under main interest.
- Non-response analysis.
- Questionnaire is available in the original paper.
- In this study, we focus on health effects and stress.

Prevalence of non-specific symptoms during last 12 months:

- migraine or headache including nausea,
- vomiting,
- sensitivity to light and sound;
- dizziness;
- ringing,
- whistling or other sounds in your ears that have no actual source, e.g., tinnitus;
- impaired hearing;
- blocked ears or a sense of pressure in your ears; r
- ash or itchy skin;
- back pain or backache;
- regular stomach problems;
- blurred vision;
- tachycardia or heart palpitations;
- problems in concentrating or remembering things;
- panic attacks or similar sensations.

Scale: 1 Never, 2 A few times, 3 Every month or almost every month, 4 Every weeks or almost every week, 5 Every day or almost every day.

Responses 3, 4, 5 denote that symptoms exist.

Annoyance of WT and RT noise.

- 11-step response scale (0 Not at all, 10 Extremely).
- People responding 5-10 were rated to be annoyed (%A).

Prevalence of diseases during last 12 months (YES or NO:

- chronic pain;
- asthma;
- joint inflammation;
- cancer;
- depression;
- elevated blood pressure;
- bronchitis, pulmonary emphysema, or chronic obstructive pulmonary disease;
- diabetes;
- heart disease;
- sleep problems, including sleep apnea and insomnia;
- restless legs syndrome.

Stress

- Cohen's stress questionnaire

Results – Sound levels

WT area:

- $L_{Aeq,WT}$ was within 17 – 39 dB
- Respondents were divided into three categories: 17–25 dB, 25–30 dB, or 30–40 dB
- $L_{Aeq07\text{-}22,RT}$ was within 32–63 dB
- Distance to WTs varied within 900–2700 m

Control group (>7 km from WTs):

- $L_{Aeq,WT}$ was inaudible, mean was 15 dB
- $L_{Aeq07\text{-}22,RT}$ was within 36 – 54 dB

Finnish environmental noise regulations, L_{AeqT}

WT noise
Government decree 1107/2015

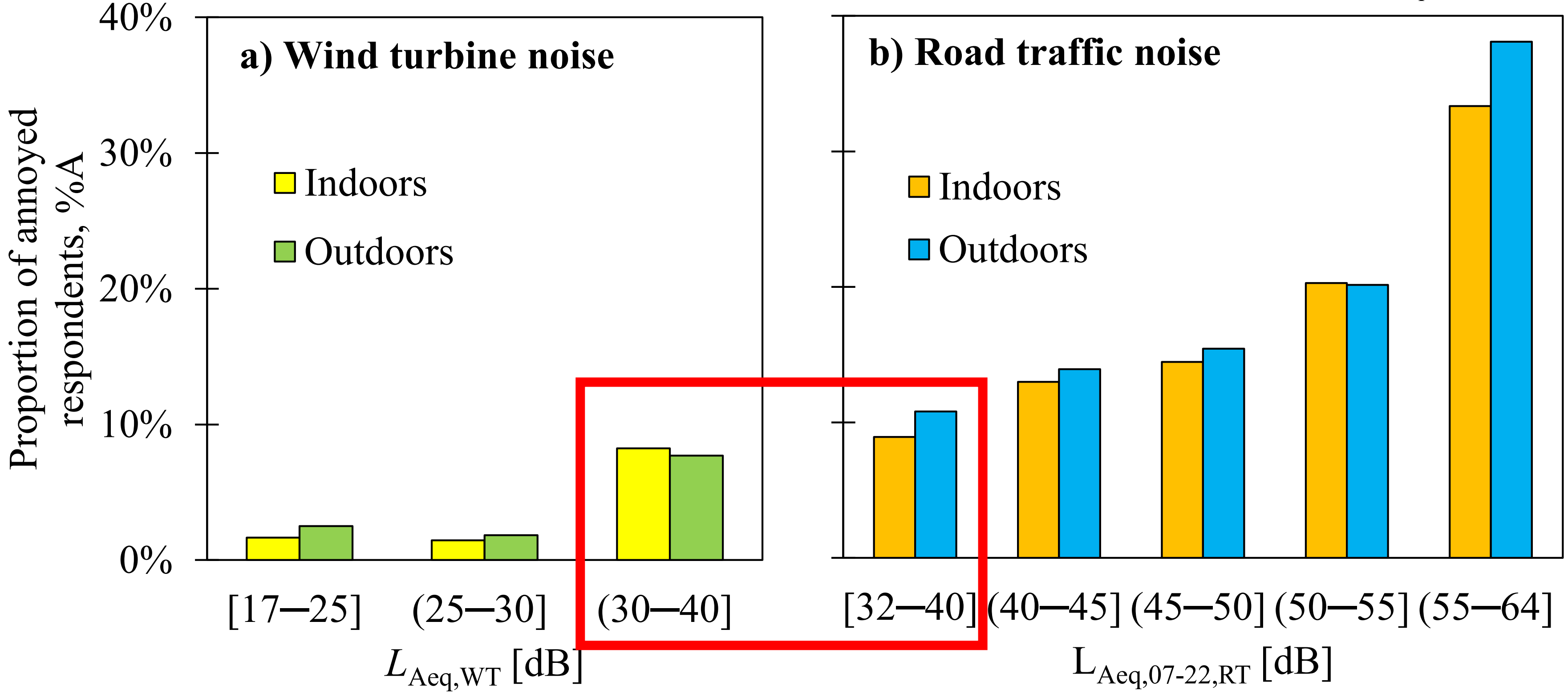
- Day 07-22: 45 dB
- Night 22-07: 40 dB

Other environmental sources, such as RT
Government decree 993/1992

- Day 07-22: 55 dB
- Night 22-07: 45 dB

Results – Noise annoyance

- %A increased with increasing sound level
- NEW1: RT noise annoyed more than WT noise
- NEW2: Within 30–40 dB, **there is no difference between noise types**.
  - This disagrees with the general belief that WT noise is more annoying than RT noise, when L_{Aeq} is the same.



Results – Effects of WT noise

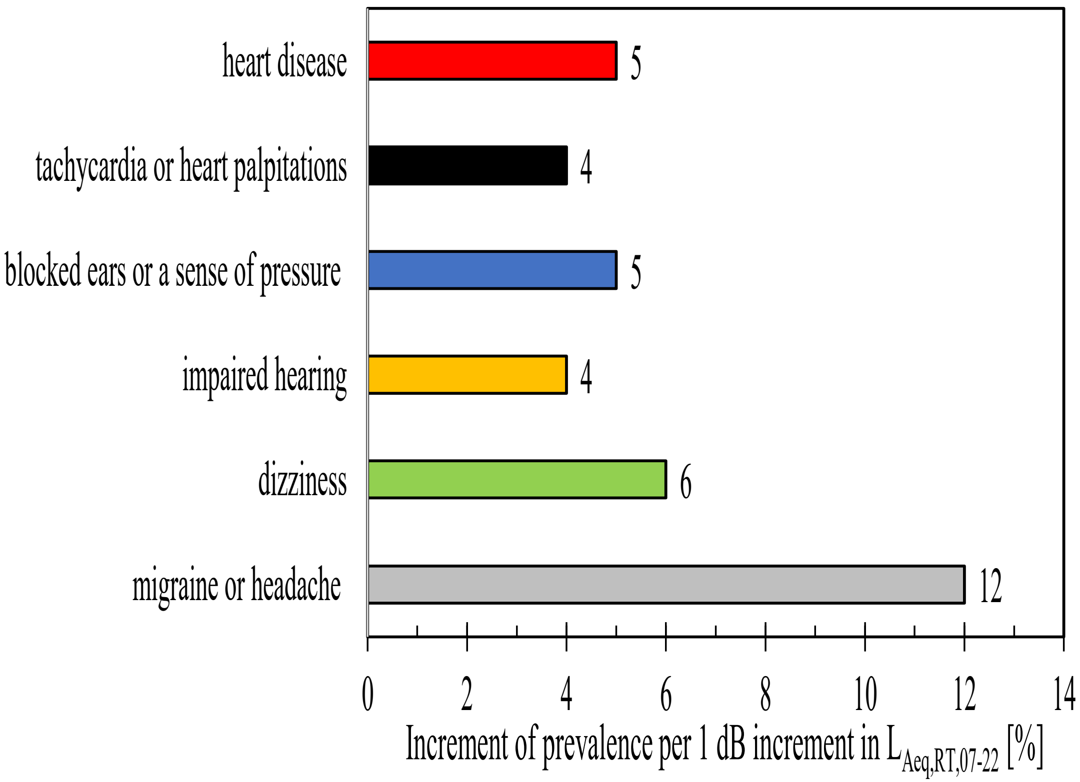
- Association of WT noise on health outcomes was evaluated by two methods:
    1. Comparison between WT sound level groups (17–25, 25–30, 30–40 dB) and control group.
    2. Analysis over continuous WT sound level in the WT area (17–39 dB)
- In both methods, binary logistic regression was applied.

RESULTS

1. There was **no** statistically significant differences between control group or any of the WT noise groups regarding symptoms, stress, or chronic diseases.
2. Within the WT area, sound level of WT noise was **not** associated with symptoms, stress, or chronic diseases.

The only health effect of WT noise was noise annoyance.

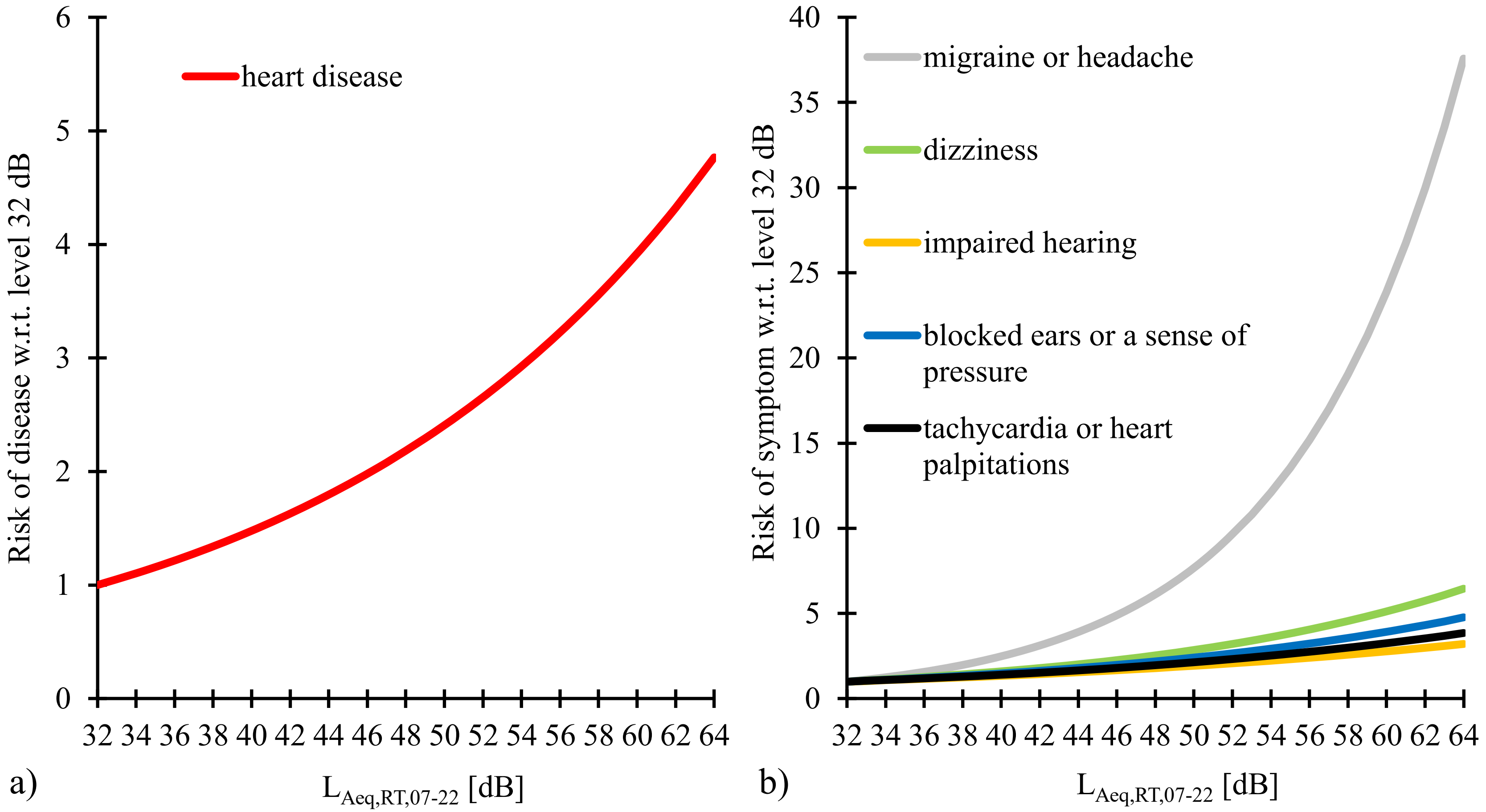
Results –Effects of RT noise



- Analysis was conducted over continuous RT sound level in the WT area (32–64 dB) using logistic regression analysis.

- Several significant findings were made.
- Higher RT sound level was associated with higher prevalence of **symptoms**:
  - Migraine or headache
  - Dizziness
  - Impaired hearing
  - Blockes ears or a sense of pressure
  - Tachycardia or heart palpitations.
- Higher RT sound level was associated with higher prevalence of one **disease**:
  - Heart disease
- RT sound level was not associated with **stress**.

Results – Meaning of risk factors



a) Prevalence of heart disease was significantly higher, when the A-weighted SPL of RT noise, $L_{Aeq,RT,07–22}$, was higher. Prevalence increased by 5 %, when the level increased by 1 dB.
b) Prevalence of five non-specific symptoms was significantly higher, when $L_{Aeq,RT,07–22}$ was higher. $L_{Aeq,07-22,RT}$ represent the value in the respondents' yard.

Discussion

- Previous studies have not found other health effects of WTs than noise annoyance. Our findings agree with that.
- RT sound level was associated with five non-specific symptoms and also one disease. Our results agree with those as well.
- Some of previous findings of RT noise could not be supported. RT sound levels were reasonably low which may limit the existence of health effects.
- Our study represents a new generation study, where WT noise is highly controlled but RT noise is not. Our study has strong political meaning, since it supports that, in Finland,
  - WT noise control is sufficient
  - RT noise control is insufficient

Conclusions

- From public health point of view, the new WT noise regulation is justified.
- It is not justified to tighten them more.
- RT noise can be a larger problem close to WT areas than WT noise: from public health point of view, noise control of RT noise is insufficient since high RT sound level is a health risk.
- Since WTs did not produce health risks in this area, infrasound from WTs does not produce health risks in this area either.

Finnish environmental noise regulations, L_{AeqT}

WT noise
Government decree 1107/2015

- Day 07-22: 45 dB
- Night 22-07: 40 dB

Other environmental sources, such as RT
Government decree 993/1992

- Day 07-22: 55 dB
- Night 22-07: 45 dB

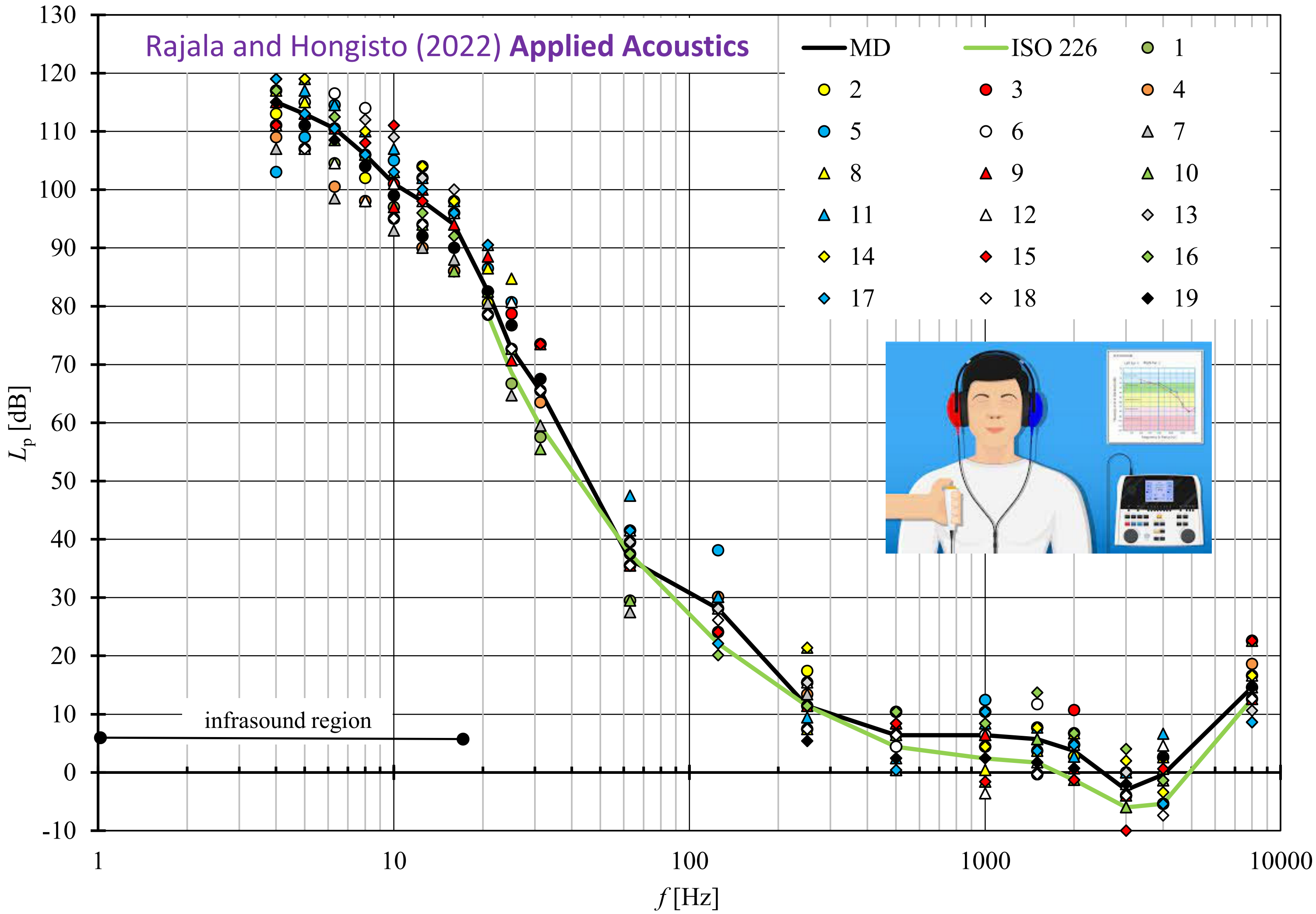
https://www.finlex.fi/fi/laki/alkup/2015/20151107

Study 4: Review: Is the infrasound of wind farms causing adverse health effects?

SOURCE: Hongisto V. ja Oliva D. (2017). Tuulivoimaloiden infraäänet ja niiden terveysvaikutukset. **Turun ammattikorkeakoulun raportteja 239**, Turku. ISBN 978-952-216-653-1 (pdf). Available at: http://julkaisut.turkuamk.fi/isbn9789522166531.pdf.

Infrasound term

- Hearing threshold level, HTL, is the lowest SPL that a human can hear
- It is individual but the HTL differences are small for young normal-hearing adults
- Our recent audiological experiment of 19 subjects proved that HTL exists down to 4 Hz
- ISO 226 has published HTL only to 20 Hz. Therefore, frequencies under 20 Hz are called infrasound.
- This is the reason for the apprehension that infrasound is inaudible but it is not.



- Infrasound is similarly audible as non-infrasound.
- We are not sensitive to that, it needs to be very loud to be heard.
- However, it has no applications in music.

General misconceptions related to infrasound

Infrasound is inaudible!

- **WRONG:** We can hear infrasound down to 4 Hz but it needs to be so loud that audible infrasound exists very rarely

Rajala & Hongisto (2022)

Infrasound penetrates inside any house!

- **WRONG:** Sound reduction index of facades is positive also at infrasound.

Keränen, Hakala & Hongisto (2019)

Room resonances amplify infrasound!

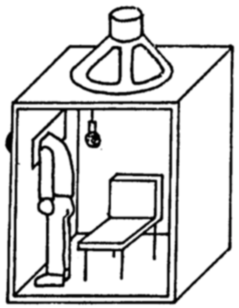
- **WRONG:** There are no room resonances under 20 Hz. Sound pressure is constant in the room.

Keränen, Hakala & Hongisto (2019)

Our body feels the infrasound although we don't hear it!

- **WRONG:** Hearing is 30 dB more sensitive than human body to airborne sound.

Yamada et al (1983)



Infrasound propagates 50 km away!

- **WRONG:** Infrasound attenuation is 6 dB per distance doubling as for any frequency of sound. Any frequency can be heard at any distance, if source level is sufficiently high.

Infrasound affects our brain functions!

- **WRONG:** There is only evidence that audible infrasound affects our brain functions, similarly as any sound frequency does.

Sources of infrasound

Inaudible (<100 dB)

- Respiration, heart beat
- Running, coughing
- Swinging
- Walking on the floor
- Sling of washing machine
- Large waterfalls
- Sea waves
- Pressure changes in the athmosphere
- Air flow of ventilation
- Fans and engines
- Traffic
- Many industrial processes, including wind turbines

Audible (>100 dB)

- Explosion
- Thunder
- Strong wind
  - up to 135 dB at 100 km/h; up to 110 dB at 25 km/h),
- Idle sound of large diesel engines in trucks, busses and vessels
- Opening the back window of the car in motorway
  - LEXUS 123 dB at 17 Hz (FFT)
- Swimming

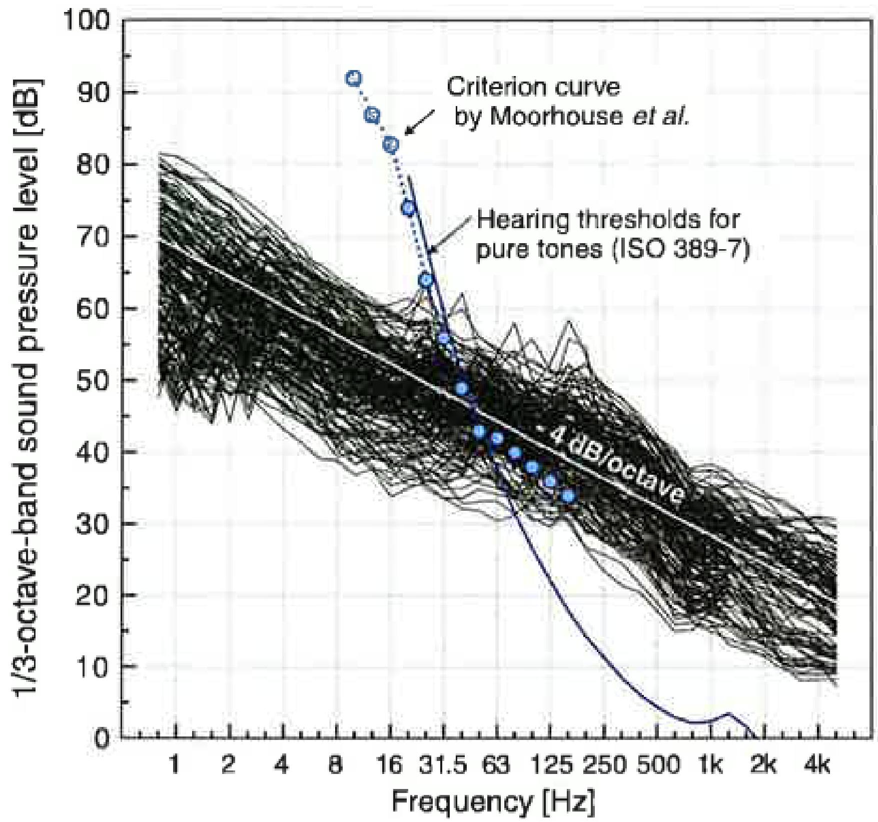
Leventhall 2007 *Progr Biophys Molecular Biol*
Crichton et al 2013 *Front Publi Health*

Infrasound levels of wind turbines, 1

- 29 wind farms were investigated
- 164 points within 100 and 1000 m were measured
- 5 days were measured in each point
- 1-3 MW turbines

Main outcomes:

- Hearing threshold level was not exceeded below 31 Hz
- Infrasound levels 20 dB below hearing threshold



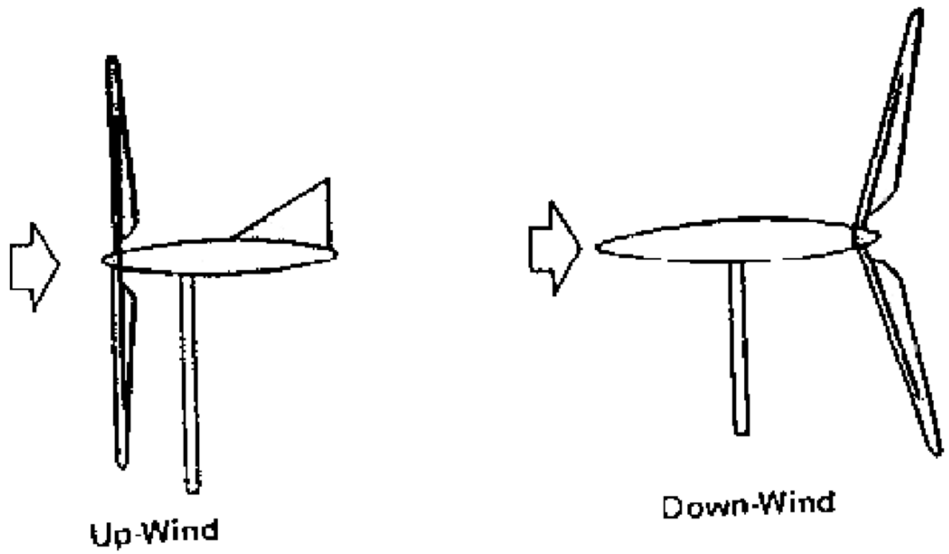
(a) Measurement results of WTN at 164 points around 29 wind farms.

JAPANESE STUDY: Tachibana et al. 2014 *Noise Con Eng J*

Infrasound levels of wind turbines, 2

- Literature survey of 18 different turbines, 0.05-4.2 MW
- Turbines with **downwind** oriented rotors produce 10-30 dB higher infrasound levels than **upwind** oriented rotors of the same output power.
- Downwind turbines are very seldom used onshore nowadays.
- **Main outcome:** Infrasound of upwind turbines could be neglegted at typical living distances because the levels are far below hearing threshold.

DANISH STUDY:
Jacobsen 2005 *J Low Freq Noise Vibr Act Con*

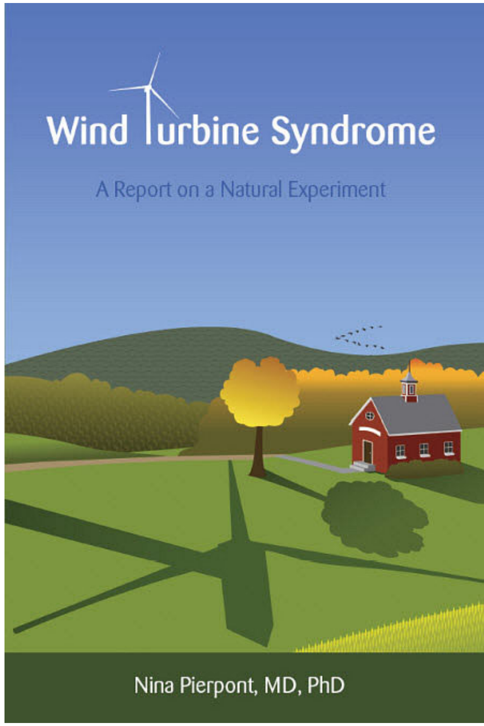


Wind turbine syndrome WTS

- Pierpont (2009) interviewed 38 persons from 10 families living nearby wind farm
- The results were published in a book by herself
  - scientifically invaluable
  - no control group living far from the farm
  - selection bias is possible
- Pierpont found similar symptoms among the persons and created the name WTS
- Infrasound of WT's was said to cause the WTS
- Scientific epidemiological evidence is lacking to prove a causal link between WT's infrasound and VAD. Therefore, CD-10 does not recognize WTS
  - *International Statistical Classification of Diseases and Related Health Problems*
- The non-specific symptoms are typical among the whole population (*non-specific symptoms*)
- Non-specific symtoms are typical to *hypochondria*.
- The WTS has become a very popular reason to oppose WT's s after 2009 at least in Australia.

Some symptoms of WTS:

- sleep disturbance,
- headache
- tinnitus (ringing in ears)
- ear pressure
- dizziness
- vertigo
- nausea
- visual blurring
- tachycardia (rapid
- heart rate)
- irritability
- problems with concentration memory
- panic episodes



Knopper & Ollson et al. 2011 ***Env Health***

Canadian study on stress effects of WTN

- 1242 people living close to wind farms participated in a cross-sectional survey at various WT noise exposure levels
  - LEVEL N
  - < 25 dB L_{Aeq}: 84
  - 25-30 dB L_{Aeq}: 95
  - 30-35 dB L_{Aeq} : 304
  - 35-40 dB L_{Aeq} : 521
  - 40-46 dB L_{Aeq} : 234
- Subjective measures (N=1242)
  - Perceived stress
  - Various other control variables
- Objective measures (N>600)
  - Blood pressures in rest
  - Heart rate in rest
  - Long-term accumulation of stress hormones (cortisol in hair)

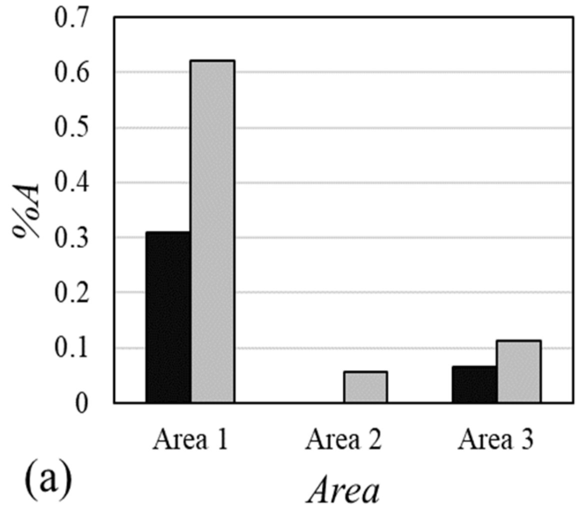
- **The findings did not support an association between noise exposure level and stress of any kind**
- Noise exposure level is strongly associated with infrasound level because the attenuation is similar for noise and infrasound.
- Because health effects were not increased closer to the turbines, infrasounds or any other factor, might not cause health effects according to this study.

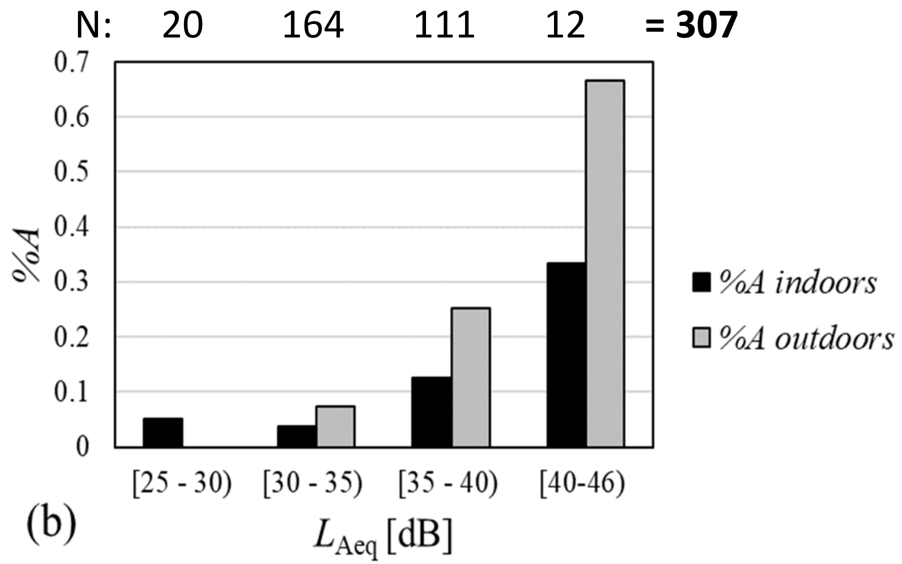
Michaud et al 2016 *J Acoust Soc Am*

Concern about health effects

- We investigated how %A was explained by sound level and non-acoustic subjective variables.
- Residents living within 2 km of wind farm were interviewed Olhava, Peittoo, and Märynummi
- Percentage of annoyed respondents, %A, involved those being rather or very annoyed
- %A increased clearly with increasing L_{Aeq}. However, most respondents were exposed to 30-40 dB and annoyance responses were scattered.
- *Concern about health effects of WT noise* were most strongly associated with %A. It explained alone 47% of %A indoors.
- Sound level was not associated with %A indoors.
- Also area explained %A. One explanation is that false information about health effects of WT noise was more distributed in Area 1.

How annoying you find WT sound indoors/outdoors?
1 Do not notice
2 Notice, not annoyed
3 Slightly annoyed
4 Rather annoyed } %A
5 Very annoyed } %A



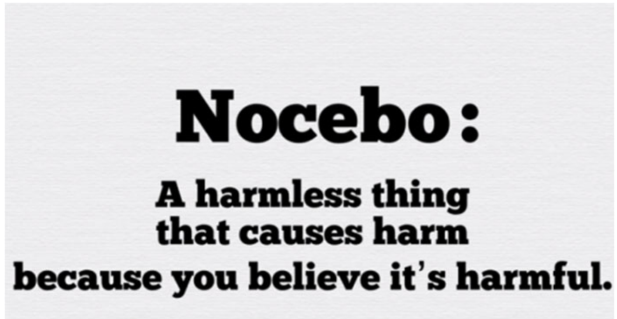


Nocebo effect

- So far, not a single scientific study provides data which indicates a causal link between infrasound of WTs and adverse health effects.
- Negative expectations and factoids related to health effects of WT's infrasound are increasingly distributed in the internet.
- Numerous high quality studies have shown that negative expectations and beliefs towards an environmental stressor can produce new symptoms or strenghten the existing ones.
  - NOCEBO effect

Placebo effect: positive expectations can result in positive outcomes.

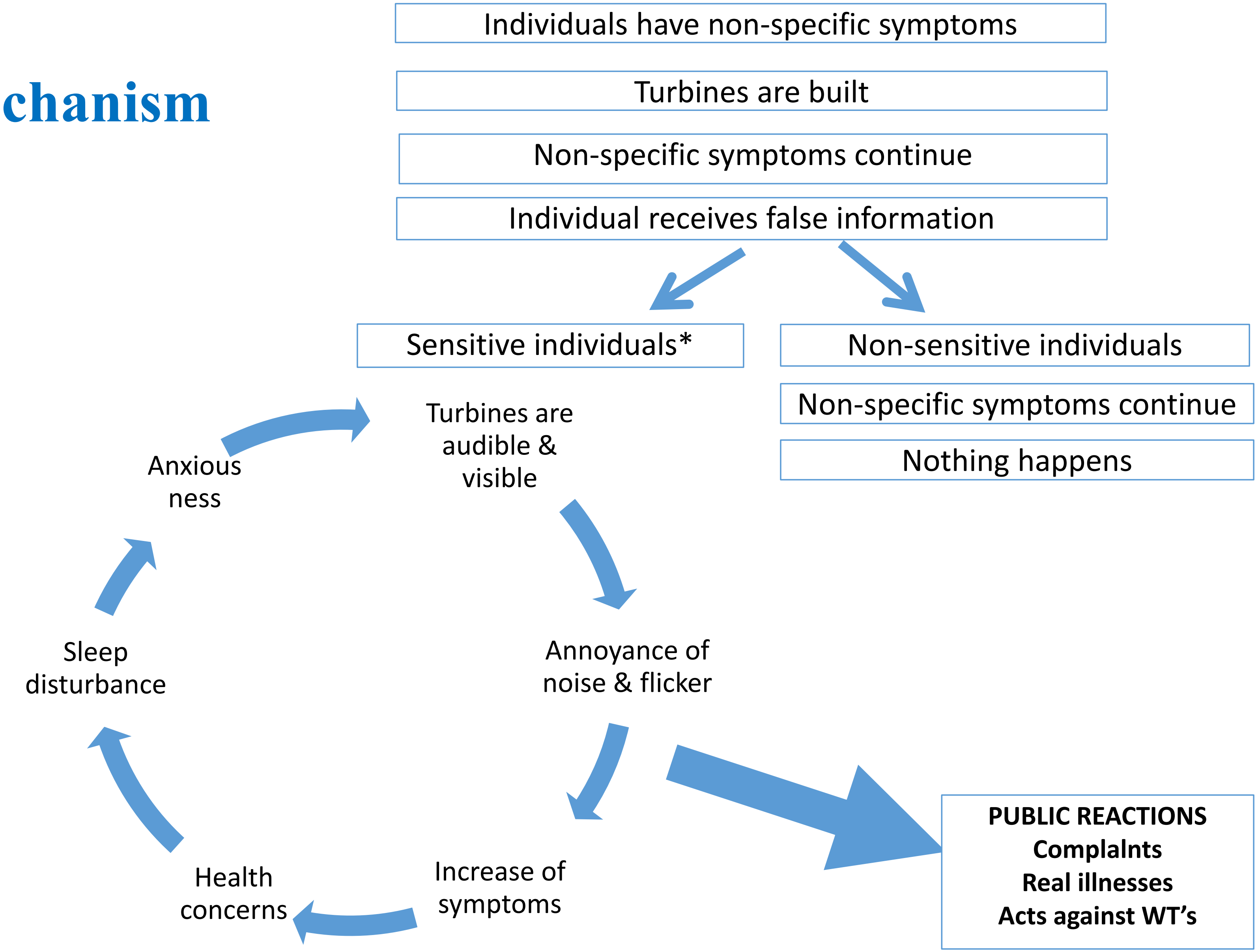
Nocebo effect: negative expectations can result in negative outcomes.



How the perceived symptoms from WTs are explained?

- **Nocebo:** expectations about adverse health effects can cause or increase symptom reporting.
- **Misattribution:** symptoms existing before WTs are attributed to WTs, although there is absolutely no justification to that.
- **Concern:** concern about health effects of environmental source can increase symptom prevalence although the source does not actually cause them.
- **Noise annoyance:** symptoms are usually more frequent among those who also report higher noise annoyance.
- **Personality traits:** certain traits are associated with higher symptom prevalence
- **Media conception:** some media are provocative and create a conception that unexplainable health effects due to WTs could exist.
- **Amplitude modulation:** periodic level variation due to blade landing at 0.7 Hz is misattributed to infrasound.
- **Environmental sensitivity:** some people who believe that WTs cause their symptoms, move away from WTs to get rid of those symptoms. This leads to permanent evasion of WTs since the knowledge that WTs are nearby causes strong stress reactions. This is a cover mechanism of central nervous system, that is hard to dismantle.

Possible mechanism



*** Factors affecting individual sensitivity**

- Higher noise sensitivity
- More sensible hearing
- Negative attitudes towards QTs
- Stress in life
- Visibility and audibility of WTs
- Low background level
- Certain personality factors (Taylor et al. 2013)

INFRASOUND CONCLUSIONS

- Human hears infrasound, i.e., sounds under 20 Hz if the level exceeds 90-120 dB.
- Infrasound level from WTs do not exceed the hearing threshold at any distance from them
- Infrasound from WT's is not higher than infrasound we are continuously exposed to.
- Present evidence supports that
  - hearing sensation precedes other health effects of noise.
  - it is very improbable that infrasound of wind turbines could have adverse health effects in living environments.
- Several scientific studies suggest that concerns and fears based on false information may produce symptoms and adverse health effects (*hypochondria*).
- Concern and stress caused by false information related to health effects of WT infrasounds can produce health symptoms although the infrasound would not.
- Popular fact-based information should be distributed in free access form in the internet by independent parties so that the amount of fact documents exceeds the amount of factoid information.