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Long-term exposure to wind turbine noise at night and risk for diabetes: A nationwide cohort study

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ABSTRACT

Focus on renewable energy sources and reduced unit costs has led to increased number of wind turbines (WTs). WT noise (WTN) is reported to be highly annoying at levels from 30 to 35 dB and up, whereas for traffic noise people report to be highly annoyed from 40 to 45 dB and up. This has raised concerns as to whether WTN may increase risk for major diseases, as exposure to traffic noise has consistently been associated with increased risk of cardiovascular disease and diabetes. We identified all Danish dwellings within a radius of 20 WT heights and 25% of all dwellings within 20–40 WT heights from a WT. Using detailed data on WT type and hourly wind data at each WT position and height, we estimated hourly outdoor and low frequency indoor WTN for all dwellings, aggregated as nighttime 1- and 5-year running means. Using nationwide registries, we identified a study population of 614,731 persons living in these dwellings in the period from 1996 to 2012, of whom 25,148 developed diabetes. Data were analysed using Poisson regression with adjustment for individual and area-levels covariates. We found no associations between long-term exposure to WTN during night and diabetes risk, with incidence rate ratios (IRRs) of 0.90 (95% confidence intervals (CI): 0.79–1.02) and 0.92 (95% CI: 0.68–1.24) for 5-year mean nighttime outdoor WTN of 36–42 and ≥ 42 dB, respectively, compared to < 24 dB. For 5-year mean nighttime indoor low frequency WTN of 10–15 and ≥ 15 dB we found IRRs of 0.90 (0.78–1.04) and 0.74 (95% CI: 0.41–1.34), respectively, when compared to and < 5 dB. The lack of association was consistent across strata of sex, distance to major road, validity of noise estimate and WT height. The present study does not support an association between nighttime WTN and higher risk of diabetes. However, there were only few cases in the highest exposure groups and findings need reproduction.

1. Introduction

Focus on renewable energy sources has increased globally during the last decades, which together with reduced costs has led to an increased number of wind turbines (WTs). WT noise (WTN) has consistently been associated with annoyance among people living by. Schmidt and Klokker (2014), Michaud et al. (2016a), Janssen et al. (2011), Michaud et al. (2016b). Also, reviews and meta-analyses have found WTN to be associated with self-reported disturbance of sleep, (Schmidt and Klokker, 2014; Onakpoya et al., 2015) although recent studies using objective measures of sleep have failed to find an association (Michaud et al., 2016; Jalali et al., 2016). This has raised concern as to whether WTN may increase risk for major diseases.

Recent studies have found exposure to road traffic and aircraft noise to be significantly associated with higher risk of diabetes, (Sorensen et al., 2013; Eze et al., 2017a; Clark et al., 2017) whereas no association was found for railway noise (Roswall et al., 2018). In support of this, traffic noise has been associated with major risk factors for diabetes, including fasting blood glucose, (Cai et al., 2017) glycosylated hemoglobin, (Eze et al., 2017b) obesity (Eriksson et al., 2014; Pyko et al., 2015, 2017; Christensen et al., 2016) and physical inactivity (Roswall et al., 2017; Foraster et al., 2016). The believed pathophysiologic pathways behind noise as a metabolic risk factor are activation of a general stress response and disturbance of sleep, which may lead to reduced insulin secretion and sensitivity, reduced glucose tolerance and altered levels of appetite-regulating hormones (Spiegel et al., 2004; Taheri et al., 2004; Mazziotti et al., 2011; McHill and Wright, 2017). Also, reduced sleep quality and quantity have both consistently been

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shown to increase risk of diabetes (Cappuccio et al., 2010).

Findings on traffic noise and diabetes are not readily applicable to WTN. Levels of WTN are generally much lower than noise from traffic in urban settings. However, WTN has been associated with a higher proportion of annoyed residents than traffic noise at comparable sound levels (Janssen et al., 2011). While people start reporting WTN to be highly annoying at levels from 30 to 35 dB and up, traffic noise is generally not reported as highly annoying at levels below 40–45 dB (Michaud et al., 2016). A potential explanation is that WTN depends on wind speed and direction making it less predictable than traffic noise, where the latter e.g. often abates at night. Also, amplitude modulation may give WTN a rhythmic quality different from e.g. road traffic noise. It has therefore been suggested that the characteristics of WTN relevant for annoyance may be better captured by metrics focusing on amplitude modulation or low frequency (LF) noise, rather than the full spectrum A-weighted noise as typically used in studies of traffic noise (Jeffery et al., 2014). A review from 2016 on LF noise (from various sources) indicated that LF noise was associated with annoyance and potentially sleep disturbance, although it was added that research in this area was scarce and with methodological short-comings (Baliatsas et al., 2016). Lastly, WTs are often placed in rural areas, where the auditory impact of WTs may be more pronounced as compared to more densely populated areas, due to less background noise from traffic, industry and others.

Two studies have investigated associations between WTN and self-reported diabetes: (Michaud et al., 2016a; Pedersen, 2011) A Canadian study of 1238 participants living within 12 km of a WT, among whom 113 reported to have diabetes, found no associations between estimated A-weighted residential WTN and prevalent diabetes (Michaud et al., 2016a). In the second study, results from two Swedish and one Dutch study population(s) were presented. In one of the Swedish study populations (N = 744), A-weighted residential WTN was associated with an odds ratio (OR) for prevalent diabetes of 1.13 (95% confidence intervals (CI) 1.00–1.27) in analyses adjusted for age and sex. However, no association was seen for the other two study populations (N = 1011, ORs of 0.96 and 1.00) (Pedersen, 2011). Both of these studies were cross-sectional, which prevent conclusions on causality and chronological order of events, and with risk of selection and recall bias. No prospective studies have investigated associations between WTN and diabetes.

We aimed to prospectively investigate associations between long-term residential exposure to WTN and risk for diabetes in a nationwide register based study, combining data on WTN, meteorology, WT position and type, residential addresses, development of disease and socioeconomic indicators over the period 1996–2012.

2. Methods

2.1. Study base and estimation of noise

The study was based on the entire Danish population, where all citizens since 1968 can be tracked in and across all Danish health and administrative registers by means of a personal identification number (PIN) maintained by the Central Population Register (Schmidt et al., 2014).

We identified all WTs (7860) in operation in Denmark any time between 1980 and 2012 from the administrative Master Data Register of Wind Turbines maintained by the Danish Energy Agency. It is mandatory for all WT owners to report cadastral codes and geographical coordinates of their WT(s) to the registry. Furthermore, for WTs in operation at the time of data extraction, the register also contained coordinates from the Danish Geodata Agency. In case of disagreement between the recorded geographical locations, the WT location was validated against aerial photographs and historical topographic maps of Denmark. Of the 7860 WTs, we excluded 517 (6.6%) offshore WTs. Furthermore, we excluded 87 (1.1%) WTs with two (or three) different registered locations, for which we were unable to identify the correct location based on aerial photographs and historical topographic maps. Moreover, 314 (4.0%) WTs wrongly recorded in the Master Data Register were assigned new coordinates based on maps and aerial photographs, leaving 7256 WTs for investigation. On the basis of information on height, model, type and operational settings (when relevant) from the register for all WTs each WT was classified into one of 99 noise spectra classes, with detailed information on the noise spectrum from 10 to 10,000 Hz in thirds of octaves for wind speeds from 4 to 25 m/s. These noise classes were made from existing measurements of sound power for Danish WTs (Backalarz et al., 2016; Sondergaard and Backalarz, 2015).

For each WT location, we estimated the hourly wind speed and direction at hub height for the period 1982–2012, using mesoscale model simulations performed with the Weather Research and Forecasting model (Hahmann et al., 2015; Peña and Hahmann, 2017).

The WTN exposure modelling has been described in details elsewhere (Backalarz et al., 2016). In summary, using a two-step approach we first identified buildings eligible for noise modelling defined as all dwellings in Denmark that could experience at least 24 dB outdoor noise or 5 dB indoor low frequency (LF, 10–160 Hz) noise under the unrealistically extreme scenario that all WTs ever operational in Denmark were simultaneously operating at a wind speed of 8 m/s with downwind sound propagation in all directions. In the second step, we performed a detailed modelling of noise exposure for the 553,066 buildings identified in step one, calculating noise levels in 1/3 octave bands from 10 to 10,000 Hz using the Nord2000 noise propagation model (Kragh et al., 2001), taking into account the time varying weather conditions. The Nord2000 model has been successfully validated for WTs (Sondergaard et al., 2009). For each dwelling, the noise contribution from all WTs within a 6000 m radius was calculated hour by hour. These modelled values were then aggregated over the period 10 p.m. to 7 a.m. (nighttime), which we considered the most relevant time-window because people are most likely to be at home and sleep during these hours. We calculated outdoor A-weighted sound pressure level, which is the metric most commonly used in noise and health studies, (Pedersen, 2011; Michaud et al., 2016d). as well as A-weighted indoor low frequency (10–160 Hz) sound pressure level, as LFN easier penetrates buildings, and has been suggested to be an important component of WTN in relation to health (Jeffery et al., 2014).

The quality of noise spectra available for different wind turbine models differed and these spectra were typically only described at certain wind speeds. We therefore determined a validity score that for each night and dwelling summed up information for all contributing WTs on the number of measurements used to determine the WTN spectra class, and how closely the simulated meteorological conditions of each night resembled the conditions under which the relevant WTN spectra were measured.

For the calculation of indoor LFN, all dwellings were classified into one of six sound insulation classes based on building attributes in the Building and Housing register (Christensen, 2011): "1½-story houses" (residents assumed to sleep on the second floor), "light façade" (e.g. wood), "aerated concrete" (and similar materials including timber framing), "farm houses" (remaining buildings in the registry classified as farms), "brick buildings" and "unknown" (assigned the mean attenuation value of the five previous classes). The frequency-specific attenuation values for each of the six classes are shown in (Backalarz et al., 2016).

2.2. Study population

When defining the study population, we identified all dwellings ever situated within a radius of 20 WT heights of a WT as well as a random selection of 25% of all dwellings situated between 20 and 40 WT heights from a WT, thus including all living close to WTs as well as a large population living in the same areas, but with little or no exposure.

We excluded hospitals, residential institutions- and dwellings situated within 100 m of areas classified as "town centre" (using GIS data from the Danish Geodata Agency), as type of dwelling, traffic conditions and lifestyle in town centres may differ substantially compared to the main study population. We subsequently identified all adults aged 25–84 years of age living at least one year in these "inclusion dwellings" from five years before erection of a WT until end of 2012, using the Danish Civil Registration System (Schmidt et al., 2014). This extended timeframe ensured inclusion of subjects living in exactly the same dwellings before erection (or after decommissioning) of a WT. People entered the study population after living one year in the dwelling. For this population, we then established complete migration histories from five years before study entry and until five years after moving from the inclusion dwelling. Subjects without complete address history for the period five years before entry were excluded.

The study was approved by the Danish Data Protection Agency (J.nr: 2014-41-2671). By Danish Law, ethical approval and informed consent are not required for entirely register-based studies.

2.3. Covariates

Selection of potential confounders was done *a priori*. From Statistic Denmark, we obtained information on age and sex, highest attained educational level, personal income, marital status, occupation and areal level (10,000 m^2) mean household income. Information on type of dwelling was obtained from the building and housing register (Christensen, 2011) As proxies for local road traffic noise and air pollution we identified the distance from each dwelling to the nearest road with an average daily traffic count of ≥ 5000 vehicles (in 2005) as well as total amount of kilometres driven by vehicles within 500 m of the residence each day as the product of street length and traffic density.

2.4. Identification of outcome

Diabetes cases were identified by linking the PIN of each member of the study population to the nationwide Danish National Diabetes Registry (Carstensen et al., 2011), applying the following inclusions criteria: a hospital discharge diagnosis of diabetes in the National Patient Register (International Classification of Diseases, 10th Revision: E10–14, H36.0 and O24); National Health Insurance Registry information indicating podiatry (chiropody) for diabetic patients, and/or > 1 purchase of insulin or oral glucose-lowering drugs within 6 months registered in the Register of Medicinal Product Statistics. The register has been found reliable from January 1995 (Carstensen et al., 2011). As patients diagnosed upon start of the register could include prevalent cases from before register start, we excluded all cases of diabetes diagnosed before 1996.

2.5. Statistical methods

Log-linear Poisson regression analysis was used to compute incidence rate ratios (IRRs) for diabetes according to outdoor (< 24, 24– < 30, 30– < 36, 36– < 42, and ≥42 dB) and indoor LF WTN (< 5, 5– < 10, 10– < 15, and ≥15 dB) exposure calculated as running means over the past 1- and 5-years. For dwellings so far from WTs as to never have WTN above 24 dB outdoor or 5 dB indoor, or when WTs were not operating due to wind conditions, a value of − 20 dB was used in calculating the average. Follow-up was started after living one year in the recruitment dwelling, turning 25 years or Jan 1st 1996, whichever came last, and ended at time of diabetes, death, age 85 years, disappearance or having no recorded address for more than seven days, Dec 31st 2012 or five years after moving from inclusion dwelling, whichever came first.

All analyses were adjusted for sex, calendar year (1996–1999, 2000–2004, 2005–2009, and 2010–2012) and age (25–84 years, in five-year categories). Additionally, we adjusted for marital status (married/registered partnership and other), education (basic or high school, vocational, higher and unknown), occupation (employed, retired and other), personal income (20 equal sized annual categories and unknown), area level average disposable income (20 equal sized categories and unknown), dwelling classification (farm, single-family detached house and other), distance to road with ≥ 5000 vehicles per day (< 500 m, 500- < 1000 m, 1,000- < 2000 m and ≥2000 m), and traffic load within 500 m radius of dwelling (1st and 2nd quartile and above median). Subjects were allowed to change between categories of covariates and exposure variables over time.

We used Poisson models including an interaction term and stratified analyses, to investigate the following potential effect-modifiers: sex, validity of cumulated noise estimate (above or below the median validity score among those exposed to indoor WTN ≥ 10 dB or outdoor WTN ≥ 36 dB), tree coverage (above or below 5% of area within 500 m of dwelling covered by forest, thicket, groves, single trees and hedgerows according to GIS data from the Danish Geodata Agency; we hypothesize that there is less noise from vegetation among people living with low tree coverage and that a potential association thus would be more conspicuous in this group), distance to major road (above or below 2000 m to nearest road with > 5000 vehicles/day; we hypothesize that there is less background noise among people living > 2000 m from a major road and that a potential association thus would be stronger in this group), dwelling classified as farm (yes or no; a large proportion of the highly exposed lives on farms, and we hypothesize that there is less variation in lifestyle and other exposures among this sub-population compared to the whole population, potentially reducing susceptibility to residual confounding in this group) and total height of closest WT (above or below 35 m; higher WTs have been suggested to emit relatively more LF noise than smaller WTs (Moller and Pedersen, 2011)). Data were analysed using SAS 9.3 (SAS Institute Inc. Cary, NC, USA).

3. Results

We identified 735,384 adults (age 25–84 years) living ≥ one year in the inclusion dwellings. We excluded persons who had emigrated (n = 40,190; 5.5%) or been recorded as disappeared (n = 1475; 0.2%) prior to entry, who had unknown address for eight or more consecutive days in the five years prior to entry (n = 57,668; 7.8%), who lived in hospitals or institutions at study start of follow-up (n = 1599; 0.2%) or who had diabetes before start of follow-up (n = 19.721; 2.7%). The final study population was 614,731 persons, of whom 25,148 developed diabetes during 5,213,194 person-years.

When compared to people with 1-year mean outdoor A-weighted WTN < 36 dB, person with higher exposure levels at entry were more likely to be men, below 40 years of age, working, living in a farm house, living in areas with higher average household incomes, living > 2000 m from a major road and have a low traffic load and less tree coverage within 500 m of dwelling (Table 1). Personal income and education did not show marked differences according to exposure level. Similar tendencies were seen when comparing people exposed to indoor LF WTN above and below 10 dB, except that we here observed an almost equal proportion of men and women at all exposure levels and that an even higher proportion of the highly exposed lived on farms, were younger at entry and entered the study later, as compared with outdoor WTN (Supplement Table 1).

At entry, more than 79% of the study population lived in dwellings exposed to < 24 dB outdoor WTN and 97% had indoor LF WTN < 5 dB. Among dwellings exposed to ≥ 36 dB outdoor WTN, the vast majority were located less than 500 m from a WT. With regard to height of the nearest WT, only small differences were seen when comparing the people exposed to < 36 dB with the 36–42 dB exposure group, whereas for the highest exposure group (≥ 42 dB), there was a much higher proportion of dwellings located near low WTs (Table 2). In comparison with outdoor exposure ≥ 36 dB, a larger proportion of

Table 1
Characteristics of the study population at start of follow-up according to residential A-weighted exposure to outdoor wind turbine noise calculated as mean exposure during the preceding year.

Characteristics at entry	Outdoor wind turbine noise		
	< 36 dB (N = 606,275)	36–42 dB (N = 7010)	≥ 42 dB (N = 1446)
Men	50%	53%	53%
Age			
< 40 years	42%	49%	44%
40–50 years	19%	20%	23%
50–60 years	16%	15%	19%
≥ 60 years	22%	15%	15%
Year of entry			
1996–2000	55%	55%	73%
2000–2005	15%	20%	17%
2005–2010	22%	17%	8%
2010–2012	8%	8%	2%
Personal income			
Quartile 1 (low)	20%	21%	21%
Quartile 2	24%	26%	21%
Quartile 3	26%	25%	23%
Quartile 4 (high)	25%	22%	29%
Unknown	6%	6%	5%
Highest attained education			
Basic or high school	35%	36%	37%
Vocational	41%	44%	38%
High	17%	16%	21%
Unknown	7%	4%	4%
Marital status			
Married	55%	52%	62%
Divorced/widow(er)	15%	13%	12%
Never married	29%	35%	26%
Occupation			
Working	67%	73%	75%
Retired	21%	14%	13%
Other	13%	13%	12%
Area-level income[a]			
Quartile 1 (low)	23%	12%	14%
Quartile 2	28%	28%	21%
Quartile 3	28%	34%	36%
Quartile 4 (high)	19%	20%	23%
Unknown	2%	7%	6%
Type of dwelling			
Farm	13%	39%	40%
Single-family detached house	61%	51%	51%
Others	25%	10%	9%
Distance to major road[b]			
< 500 m	35%	17%	17%
500–2000 m	27%	26%	25%
≥ 2000 m	37%	57%	58%
Traffic load within 500 m (10^3 vehicle km/day)			
< 2.5	33%	68%	67%
2.5–5.3	25%	13%	15%
5.3–9.7	19%	13%	10%
> 9.7	23%	6%	8%
Tree coverage within 500 m			
< 5%	13%	29%	29%
5–20%	63%	63%	63%
> 20%	24%	7%	9%

[a] Average disposable household income among all households in 100 × 100 m grid cell.

[b] Major road defined as ≥ 5,000 vehicles per day.

those exposed to indoor LF WTN ≥ 10 dB lived ≥ 500 m from a WT at entry (especially in the 10–15 dB group) and a much lower proportion of people exposed to LF WTN ≥ 10 dB lived near a WT < 35 m (Table 2). Median exposure levels for all exposure categories are provided in supplement Table 2,

We found no overall association between long-term exposure to outdoor WTN or indoor LF WTN and risk of diabetes, for any of the exposure time-windows (Tables 3 and 4). In the crude analyses, we found all IRRs to be below one; some with confidence limits below unity. Adjustment for potential confounders resulted in estimates markedly closer to unity. For outdoor WTN, the risk estimate among people exposed to 36–42 dB remained borderline significant (IRR: 0.87; 95% CI: 0.77–0.99). However, there was no indication of an exposure-response relationship, with IRRs of 1.01 and 1.02 in the 24–30 dB and 30–36 dB exposure groups, respectively, and of 1.06 in the highest exposure group (≥ 42 dB, Table 3). For indoor LF WTN ≥ 15 dB, the IRRs in adjusted analyses remained below unity, although not statistically significant and based on only few cases (Table 4). We found no indications of positive dose-response relationship in any analyses.

For outdoor WTN, we found no effect-modification of the risk estimates in analyses stratified by sex, type of dwelling, distance to major road, validity of noise estimate, tree coverage or WT height, with no estimate substantially above unity and all p-values for interaction exceeding 0.3 (Supplement Table 3). Similarly, we found no statistically significant effect-modification of the indoor LF WTN and diabetes association (all P-values > 0.1; Supplement Table 4).

4. Discussion and conclusion

We did not find long-term nighttime exposure to outdoor or indoor LF WTN to be associated with increased risk of diabetes in a large prospective study based on the full Danish population ever exposed to WTN. The lack of association between WTN and diabetes was consistent across various strata, including sex, distance to a major road, validity of the noise estimate and total height of the nearest WT.

A major strength of the present study is the prospective nationwide design with information on potential socioeconomic and environmental confounders, the large number of incident cases identified through a high-quality nationwide register (Carstensen et al., 2011), and access to complete residential address history for the entire exposure and follow-up period. Also, we estimated long-term exposure to WTN using high quality input data (hourly wind speed and direction at each WT position, combined with detailed WTN spectra for all WT types) and state-of-the art exposure models, allowing us to estimate noise levels specifically for nighttime, when people are most likely to be at home sleeping. Additionally, we estimated exposure to the potentially more biologically relevant indoor noise, accounting for different housing sound insulation properties, although it is important to note that we could only differentiate into few insulation categories, based on relatively crude information. Further strengths were estimation of WTN for all dwellings in Denmark that might experience WTN, and that our design ensured that all members of the study population where recruited from similar geographical areas. Furthermore, we had access to a number of individual and area-level socioeconomic variables revealing almost no differences in income and educational level between people exposed to high (≥ 36 dB) versus lower (< 36 dB) levels of WTN, which indicates low risk for residual confounding from individual SES. Also, we accounted for living on a farm, which is conceivably associated with many differences in lifestyle and environment. Due to the register-based nature of the study, we did not have information to adjust for potential lifestyle confounders, such as dietary habits, obesity and physical activity. This may have biased the results, although it is not clear in which direction. Fewell et al. (2007) It is, however, important to note that adjusting for lifestyle in studies of noise is not straight-forward, as traffic noise has been associated with e.g. obesity and physical activity, (Eriksson et al., 2014; Pyko et al., 2015; Roswall et al., 2017; Foraster et al., 2016; Christensen et al., 2015). suggesting that these are intermediates and not confounders on the pathway between noise and disease. Another limitation is the rather crude adjustment for local road traffic noise, using traffic load and distance to major road. However, residual confounding by traffic noise is unlikely

Table 2
Characteristics of wind turbines at the dwellings of the study participants at start of follow-up, according to residential exposure to outdoor and indoor low frequency (LF) wind turbine noise calculated as mean exposure during the preceding year.

Wind turbine characteristics at of the study population dwellings at entry	Outdoor wind turbine noise			Indoor LF wind turbine noise		
	< 36 dB (N = 606,275)	36–42 dB (N = 7010)	≥ 42 dB (N = 1446)	< 10 dB (N = 610,429)	10–15 dB (N = 3990)	≥ 15 dB (N = 312)
Outdoor wind turbine noise (1-year mean) [a]						
< 24 dB	79%	–	–	78%	–	–
24–30 dB	16%	–	–	16%	1%	–
30–36 dB	5%	–	–	5%	45%	2%
36–42 dB	–	100%	–	1%	38%	47%
≥ 42 dB	–	–	100%	0%	16%	51%
Indoor LF wind turbine noise (1-year mean) [a]						
< 5 dB	97%	28%	7%	97%	–	–
5–10 dB	3%	48%	37%	3%	–	–
10–15 dB	0%	22%	45%	–	100%	–
≥ 15 dB	0%	2%	11%	–	–	100%
Distance to nearest wind turbine						
< 500 m	7%	94%	97%	8%	67%	93%
500–2000 m	57%	5%	2%	56%	32%	6%
≥ 2000 m	36%	1%	1%	36%	1%	1%
Total height, nearest wind turbine						
< 35 m	31%	33%	66%	31%	12%	20%
35–70 m	56%	58%	33%	56%	58%	62%
70–100 m	11%	8%	1%	11%	28%	16%
≥ 100 m	1%	1%	0%	1%	3%	2%

Table 3
Associations between mean 1- and 5-year exposure to residential A-weighted outdoor wind turbine noise and risk of diabetes.

Outdoor wind turbine noise	**N cases**	**Crude IRR (95% CI)**[ab]	**Adjusted IRR (95% CI)**[ac]
1-year mean exposure			
< 24 dB	18,340	1 (ref)	1 (ref)
24–30 dB	4926	0.98 (0.94–1.01)	1.01 (0.98–1.04)
30–36 dB	1598	0.94 (0.89–0.99)	1.02 (0.96–1.07)
36–42 dB	241	0.76 (0.67–0.86)	0.87 (0.77–0.99)
≥ 42 dB	43	0.86 (0.64–1.16)	1.06 (0.78–1.43)
5-year mean exposure			
< 24 dB	18,419	1 (ref)	1 (ref)
24–30 dB	4913	0.98 (0.95–1.01)	1.00 (0.97–1.04)
30–36 dB	1529	0.93 (0.88–0.98)	1.00 (0.94–1.05)
36–42 dB	244	0.79 (0.69–0.89)	0.90 (0.79–1.02)
≥ 42 dB	43	0.77 (0.57–1.03)	0.92 (0.68–1.24)

[a] IRR: incidence rate ratio; CI: confidence interval.
[b] Adjusted for age, sex and calendar-year.
[c] Adjusted for age, sex, calendar-year, personal income, education, marital status, occupation, area-level socioeconomic status, type of dwelling, traffic load in 500 m radius and distance to major road.

Table 4
Associations between mean 1- and 5-year exposure to residential A-weighted indoor low frequency wind turbine noise and risk of diabetes.

Indoor low frequency wind turbine noise	**N cases**	**Crude 1. IRR (95% CI)**[ab]	**Adjusted IRR (95% CI)**[ac]
1-year mean exposure			
< 5 dB	23,692	1 (ref)	1 (ref)
5–10 dB	1197	0.89 (0.84–0.95)	0.99 (0.93–1.05)
10–15 dB	244	0.84 (0.74–0.95)	0.98 (0.86–1.11)
≥ 15 dB	15	0.64 (0.39–1.07)	0.80 (0.48–1.33)
5-year mean exposure			
< 5 dB	23,857	1 (ref)	1 (ref)
5–10 dB	1097	0.91 (0.86–0.97)	1.00 (0.94–1.07)
10–15 dB	183	0.77 (0.67–0.89)	0.90 (0.78–1.04)
≥ 15 dB	11	0.60 (0.33–1.07)	0.74 (0.41–1.34)

[a] IRR: incidence rate ratio; CI: confidence interval.
[b] Adjusted for age, sex and calendar-year.
[c] Adjusted for age, sex, calendar-year, personal income, education, marital status, occupation, area-level socioeconomic status, type of dwelling, traffic load in 500 m radius and distance to major road.

to be a major issue in the present study, as adjusting for the proxies only resulted in minor changes in estimates, and we found no effect modification by distance to major roads.

There is inevitable uncertainty in the modelled noise exposure metrics, but we expect this to be non-differential, which in most cases will influence the estimates towards the null. Although our validity score does not cover all aspects of uncertainty pertaining to the noise estimates, we find that the observed lack of marked differences in risk estimates when stratifying by this estimator, speaks against exposure misclassification as explanation for the null finding. This is further supported by the similar estimates observed in strata of environmental factors, which could influence sound reception and perception (tree coverage and major roads). Lack of information on a number of factors that may influence the personal exposure to WTN, including window opening habits, bedroom location and hearing impairment, are likely to have resulted in exposure misclassification. Such misclassification is thought non-differential and influence risk estimate towards unity. Finally, despite including all relevant cases in Denmark, statistical power was impaired by having relatively few cases with high exposure to WTN.

Overall, our results do not support the hypothesis that exposure to outdoor WTN or indoor LF WTN, or aspects of WTN directly associated with these metrics, are risk factors for diabetes. However, we observed that adjustment in our analyses consistently drew the estimates from a reduction in risk (statistical significant for many estimates) in the crude analyses towards unity in the adjusted analyses, and with regard to indoor LF WTN the point estimates among those with high exposure remained below unity even after adjustment. We can therefore not entirely rule out that residual confounding is present, which could change the results.

In support of a null-finding, we, however, found no suggestions of a positive association in any of the stratified analyses. The lack of a positive association between WTN and diabetes observed in the present study is mostly in line with the few cross-sectional studies on WTN and diabetes, which found ORs of 1.13 and 0.96 in two Swedish populations, of 1.00 in a Dutch population and an equal distribution of cases across five WTN exposure categories in a Canadian population

(Michaud et al., (2016a; Pedersen, 2011). As the present study is the first prospective study on WTN and diabetes, more studies are needed before firm conclusions can be drawn.

In conclusion, the results of the present study do not support an association between long-term nighttime exposure to WTN and higher risk of diabetes.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2018.03.040.

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