



# The influence of wind turbine visibility on the health of local residents: a systematic review

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## Abstract

**Purpose** The health effects of visible wind turbine features on residents were investigated. Further, it was examined, if visual annoyance has an influence on residents' health, and if wind turbine visibility impacts residents' health independently of or in combination with acoustical aspects.

**Methods** Medical databases, Google Scholar, public health institutions, and reference lists were searched systematically (PROSPERO registry number: CRD42016041737). Two independent reviewers screened titles/abstract and full texts, extracted data, and critically appraised the methodology of included studies. Study findings were analyzed qualitatively and quantitatively.

**Results** Seventeen studies from 19 publications of varying methodological quality were included (two cohort studies, fifteen cross-sectional studies). The pooled prevalence of high annoyance due to altered views and shadow flicker was 6% each. The results of other health effects were inconsistent, with some indications showing that direct wind turbine visibility increases sleep disturbance. Annoyance by direct visibility, shadow flicker, and blinking lights was significantly associated with an increased risk for sleep disorders. One study indicated reactions to visual wind turbine features may be influenced by acoustical exposures.

**Conclusions** In interpreting the results, the differing methodological quality of the included studies needs to be considered. Direct and indirect wind turbine visibility may affect residents' health, and reactions may differ in combination with noise. Further, annoyance by wind turbine visibility may interact as mediator between visual exposures and the health of local residents. To confirm the results, more high-quality research is needed.

**Keywords** Wind turbine · Visibility · Health effect · Resident · Systematic review

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## Introduction

Since the early 1990s, several international political agreements were reached, which aimed to limit global warming by decreasing the emission of greenhouse gases, e.g., the United Nations Framework Convention on Climate Change, the Kyoto Protocol, or the Paris Agreement (UN n.d.). One approach to achieve this goal is enhancing the deployment of renewables such as wind energy, photovoltaics, or bioenergy (UNFCCC 2015). According to the International Energy Agency, the global share of renewables in electricity was 23% in 2015, and will increase to 30% in 2022 (IEA 2017). The total capacity of renewable energy increases steadily globally (IRENA 2017). Equally, the global cumulative installed wind capacity is rising, with China, the USA, and Germany as the leading countries (GWEC 2018).

Onshore wind turbines are often located in the vicinity of populated areas. Several research papers issued the influence of different wind turbine features on the residents' health. In particular, the association between noise exposure and different health effects such as annoyance, sleep disorders, or quality of life has been investigated by a large number of observational studies (Bakker et al. 2012; Michaud et al. 2016d; Mroczek et al. 2015; Pedersen and Persson Waye 2007; Shepherd et al. 2011). Further, non-acoustical types of sound (i.e., infrasound or low-frequency noise), ice throw, and visual risk factors such as shadow flicker, reflections, or blinking lights are discussed as potential risk factors for humans' health (Twardella 2013). The residential health effects of wind turbines have been summarized in several systematic reviews (Arra et al. 2014; Merlin et al. 2013; Onakpoya et al. 2015; Schmidt and Klokke 2014), focusing primarily on noise exposure. Only Merlin et al. (2013) additionally examined one visual risk factor (i.e., shadow flicker). Onakpoya et al. (2015), who concentrated on wind turbine noise, pointed out that the visual perception of wind turbines is related to negative health outcomes and also to the attitude towards wind turbines. The impact of visual wind turbine features on human health has been examined in experimental settings (Maehr et al. 2015; Mausfeld et al. 2000). Further, some observational studies investigated the impact of different direct and/or indirect visual risk factors of wind turbines (Pohl et al. 2012; Voicescu et al. 2016). But to date, those studies were not systematically searched and summarized comprehensively. Thus, this systematic review was conducted to survey and summarize the evidence on the association between direct and indirect visual exposures of wind turbines and the health of residents living in their proximity.

## Goals and hypotheses

### Main goal

The main goal of this systematic review is to examine whether the direct or indirect visibility of wind turbines affects the health of residents living in their vicinity. It is assumed that wind turbine visibility influences the health of residents.

### First subgoal

It is supposed that annoyance to wind turbine visibility has an effect on the health of people living in their proximity. Thus, the first subgoal is to evaluate whether visual annoyance caused by wind turbines impacts residents' health.

### Second subgoal

A second subgoal is to investigate whether the effect of direct or indirect visibility of wind turbines on residents' health is influenced by acoustic factors. It is hypothesized that wind turbine visibility and noise may interact to impact health.

## Methods

A systematic review was conducted to achieve our goals. The PRISMA statement was applied for structuring the reporting of the paper (Moher et al. 2009). The study protocol was published on the International prospective register of systematic reviews prior to the study conduction (PROSPERO registry number: CRD42016041737) (Scheffer et al. 2016).

### Criteria for considering studies for this review

#### Population

Humans of all ages, living in the immediate vicinity of wind turbines were regarded as eligible. Animals were excluded.

#### Exposure

For the main goal, the visibility of a wind turbine from a residence was the exposure of interest. Thereby, visibility can be direct (e.g., seeing a wind turbine, blinking lights) or indirect (e.g., shadow flicker, reflections). For the first subgoal, the relevant exposure was annoyance by direct or indirect wind turbine visibility. For the second subgoal, direct or indirect visibility in combination with audible or non-audible noises of wind turbines was included. Generally, onshore as well as offshore wind turbine settings were of interest. Studies exclusively investigating risk factors other than visual wind turbine exposures (e.g., audible noise, low-frequency noise, infrasound, or ice throw) were excluded.

#### Outcome

All possible health effects were included (e.g., sleep disorders, annoyance to visual wind turbine features), irrespective whether these were measured subjectively or objectively. Further, physiological parameters and surrogate markers were eligible. Non-health related outcome parameters were

irrelevant. Annoyance to non-visual wind turbine features such as noise or vibration was not considered.

## Study design

Epidemiological observational studies, and more precisely prospective and retrospective cohort studies, case-control studies, cross-sectional studies, and ecological studies, as well as intervention studies—randomized and non-randomized controlled trials and before-after studies—were of relevance. Cohort studies were of particular interest due to their possibility to investigate causality, and cross-sectional studies to evaluate associations and prevalences. No language restrictions were set. Clinical observational studies (case reports, case series, diagnostic studies, or prognostic studies), experimental studies, monitoring studies, exposure studies, reviews, subjective papers (e.g., editorials, commentaries, or expert opinions), and animal studies were excluded. Abstracts only were not considered eligible.

## Search methods for identification of studies

The search strategy was developed sensitively and the search results were managed with the literature management program Endnote.

### Electronic searches

The electronic databases MEDLINE and EMBASE (via Ovid), and CINAHL (via EBSCOhost) were searched on

September 12th, 2017. No time restriction was applied. The search strings were created sensitively by only comprising search terms of the exposure and outcome. The search strings were adapted to the requirements of each database. Its accuracy was verified by determining if a priori identified relevant studies were found. Table 1 illustrates exemplarily the search string for MEDLINE.

Furthermore, internet searches were executed. Google Scholar was searched with the same terms as used for the database searches. As Google Scholar only displays the first 1000 hits, these were screened. In addition, the websites of the following public health relevant institutions were searched up to October 12th, 2017: World Health Organization (WHO); (German) Federal Ministry of Health; (German) Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety; German Environment Agency; and US Environmental Protection Agency.

### Searching other sources

The reference lists of all included studies and of topic-related articles were hand searched up to October 8th, 2017.

## Data collection and analysis

### Selection of studies

Titles, abstracts, and full texts retrieved via the database searches were screened independently by two reviewers (AF, CS). All other searches (Google Scholar, websites of

**Table 1** Search string MEDLINE (via Ovid)

Step	Search terms
1	(Exp wind/ OR wind.mp.)
2	(Exp engineering/ OR engineering.mp. OR exp industry/ OR industry.mp. OR industries.mp. OR exp technology/ OR technology.mp. OR technologies.mp. OR exp power plants/ OR power plant.mp. OR power plants.mp. OR pow-er.mp. OR electric power.mp. OR exp renewable energy/ OR renewable energy.mp. OR energy.mp. OR exp energy-generating resources/ OR energy-generating resources.mp.)
3	1 and 2
4	((wind adj5 (facility OR facilities OR farm OR farms OR mill OR mills OR park OR parks OR plant OR plants OR station OR stations OR turbine OR turbines OR generator OR generators)).mp.)
5	3 or 4
6	((health adj5 (mental OR psychic OR psychological OR physical OR somatic OR social OR societal)).mp.)
7	(exp health/ OR health.mp. OR exp mental health/ OR well-being.mp. OR wellbeing.mp. OR well being.mp. OR exp quality of life/ OR quality of life.mp. OR social interaction.mp. OR social relationship.mp. OR social relationships.mp. OR exp perception/ OR perception.mp. OR perceiv*.mp. OR annoyance.mp. OR annoy*.mp. OR exp personal satisfaction/ OR satisfaction.mp. OR dissatisfaction.mp. OR exp anxiety/ OR anxiety.mp. OR exp anxiety disorders/ OR exp catastrophization/ OR catastrophization.mp. OR catastrophisation.mp. OR exp depression/ OR depression.mp. OR exp sleep/ OR sleep.mp. OR exp sleep wake disorders/ OR exp stress, psychological/ OR stress.mp. OR exp burnout, professional/ OR burnout.mp. OR burn out.mp. OR burn-out.mp. OR complaint.mp. OR complaints.mp. OR symptom.mp. OR symptoms.mp. OR exp syndrome/ OR syndrome.mp. OR exp disease/ OR disease.mp. OR diseases.mp. OR exp chronic disease/ OR exp acute disease/ OR disorder.mp. OR disorders.mp.)
8	6 or 7
9	5 and 8

institutions, hand searches in reference lists) were carried out by one reviewer (CS) and if a reference seemed to be eligible, a second reviewer (AF) screened the appropriate full text. In case of any disagreement between the two reviewers, consensus was sought by discussion. If a disagreement could not be resolved by this procedure, a third reviewer was consulted (JH or AS).

Specific guidelines with information about the inclusion and exclusion criteria and their order of prioritization supported the decision making during both screening phases. Both screening processes were piloted beforehand. During screening of titles and abstracts, the reviewers were blinded to the study's author names and the publication year. For title-abstract and full text screening of the database searches, the degree of agreement between the two reviewers was determined by calculating the proportion of agreement and Cohen's Kappa (Cohen 1960; Landis and Koch 1977).

### Data extraction

For almost all studies, data were extracted independently by two reviewers (AF, CS). Only if a second publication was retrieved that contained additional information, data of this second article were extracted by one reviewer (CS) and checked by a second one (AF). Differing results were discussed. The process was piloted beforehand with one randomly selected study.

The following types of data were extracted within a standardized data extraction sheet:

- (a) information about the reference (e.g., name of the study's author, publication year, language, country),
- (b) methodological data (e.g., study design, duration of the study, sampling of participants),
- (c) population-specific characteristics (e.g., setting, sample size, age, sex, socio-economic status, duration of residence),
- (d) study findings (e.g., exposure of interest, outcome of interest, measurement instrument, measurement variables, important study findings, statistical analysis, response rate),
- (e) further information (e.g., main conclusions, conflict of interest, funding).

### Assessment of methodological quality

The methods of all included studies were critically appraised by two independent reviewers (AF, CS), for cross-sectional studies with the Appraisal tool for Cross-Sectional Studies (AXIS) (Downes et al. 2016) and for cohort studies with a combination of the appropriate checklists of the Scottish Intercollegiate Guidelines Network (SIGN 2012) and the

Critical Appraisal Skills Programme (CASP 2017), following a publication by Seidler et al. (2012).

The AXIS -checklist was used for the first time by all authors, thus it was tested in a pilot phase utilizing the corresponding explanation paper as basis of understanding. For question 13 about the response, a cut-off of 50% was defined to assure that the majority of the residents under study participated to avoid a selection bias. An overall assessment of a study's methods is originally not intended with the AXIS -checklist. Nevertheless, it was decided to determine the overall quality of a study by summarizing the evaluations of five questions that are of particular importance according to this review's authors: question 5 (representativeness), question 6 (selection process), question 8 (validity), question 9 (reliability), and question 13 (response). A study was judged with "1" ("high quality"), if all five questions were given a positive answer; with "2" ("acceptable quality"), if four of five questions were answered positively; and with "3" ("low quality"), if at least two questions were answered in the negative or as unclear.

The combined CASP/SIGN checklist was discussed in internal meetings and adapted to the requirements of this systematic review. Further, the checklist was extended with questions from the AXIS -checklist dealing with ethical issues, funding, and conflict of interest. The overall assessment of a cohort study's methods was rated as "++" ("high quality"), "+" ("acceptable quality"), and "-" ("low quality").

### Statistical analysis and data synthesis

Most results of the studies were summarized descriptively, with regard to the review's goals and reported separately for the different visual risk factors.

If possible, prevalences of high and general annoyance were pooled for different visual exposures in meta-analyses. General annoyance comprises any degree of annoyance, whereas high annoyance refers only to higher gradings. For high annoyance, the definitions stated in the studies were used or were defined by us. It was tested, whether the included studies were homogeneous enough to be included, based on the following characteristics: population, sample size, setting, distance from the residence to a wind turbine, number and height of the wind turbines, use of the same questionnaire, and overall study quality. If a study reported a prevalence for the overall study population, instead of the exposed population, or if we could not calculate the latter from the reported values, the study was not considered for a meta-analysis. Random effects models were calculated to take the variance of the observed effects between the studies into account, and thus to consider existing heterogeneities (Kunz et al. 2009). Calculations were done with the program MetaXL

5.3 (EpiGear International 2016). The measures for heterogeneity were the Cochrane's Q statistics and the  $I^2$ -value. Sensitivity analyses for each meta-analysis were calculated to investigate if the following factors had an influence on the pooled prevalence and/or heterogeneity: study period, sample size, setting, distance to wind turbines, number and height of the wind turbines, and overall study quality.

The pooled results of high annoyance are reported in the manuscript, as annoyance reactions to environmental exposures should rather focus on high annoyance (WHO 2011). The pooled general annoyance prevalences are outlined in the Supplementary Material.

## Results

### Study selection process

Through the searches, 3299 records were identified. After the removal of duplicates, 2697 titles and abstracts were screened and 2608 of those were excluded. Finally, 89 full texts were assessed for eligibility, of which 19 articles—originating from 17 primary studies—were included in the qualitative analysis. Of the 19 articles, seven were retrieved from database searches, ten from internet searches, and two from hand searches of reference lists. Six of the included studies were analyzed quantitatively in meta-analyses. Regarding the screening of database searches, the proportion of agreement between reviewers for the title-abstract

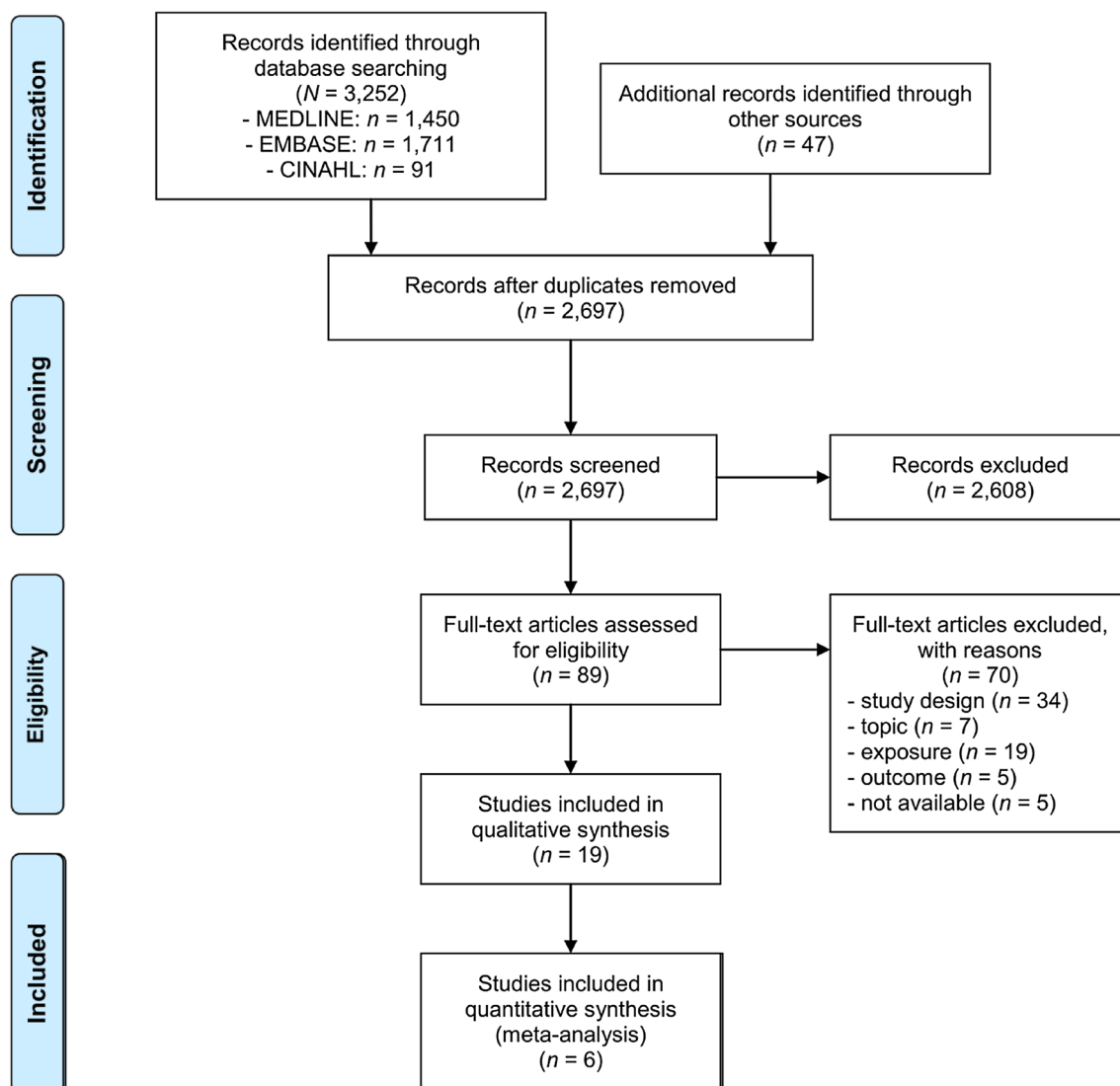


Fig. 1 PRISMA flow diagram

screening was 98.8% and Cohen's Kappa 0.80 (strength of agreement: substantial) and for the full text screening 92.9% and  $\kappa=0.84$ , respectively (strength of agreement: almost perfect).

The study selection process is shown in Fig. 1. Studies that were excluded during full text screening are presented in the Supplementary Material.

### Study characteristics of included studies

Seventeen primary studies published in nineteen articles were included (Feder et al. 2015; Hübner and Pohl 2010; Jalali et al. 2016b, a; Kageyama et al. 2016; Magari et al. 2014; Michaud et al. 2016b, a; Morris 2012; Pawlaczyk-Luszczynska et al. 2014a, b; Pedersen and Persson Waye 2004; Pohl et al. 2012; Schafer 2013; Schneider 2012; Taylor et al. 2013; van den Berg et al. 2008b; Voicescu et al. 2016). The papers of Hübner and Pohl (2010) and Pohl et al. (2012), as well as Van den Berg et al. (2008a, b), were double-publications describing one investigation. All, but one study, were written in English. Of the nineteen articles, six were not published in peer-reviewed journals.

The following study descriptions concern the 17 primary studies. Most studies were cross-sectional studies ( $n=15$ ), and two were prospective cohort studies (Jalali et al. 2016b, a). Most studies were conducted in Canada ( $n=6$ ), Australia ( $n=3$ ), or Poland ( $n=2$ ). Most studies were published in 2010 or later ( $n=15$ ). All studies considered onshore wind turbines and none the offshore setting. The majority of studies took place in mainly rural areas with flat landscapes ( $n=11$ ). The mean age of the study population ranged from 45.5 to 54.3 years in 12 studies. The proportion of females ranged between 43% and 60%. Three studies neither reported the age nor the sex-distributions of the study population (Morris 2012; Schafer 2013; Schneider 2012). Most studies investigated individuals and sample sizes varied greatly (range  $n=31$ –1238, mean  $n=515$ , median  $n=356$ ). Three studies assessed households rather than individuals (Morris 2012; Schafer 2013; Schneider 2012). Most studies reported on response, which ranged between 10.86 and 93% [exceptions: (Pawlaczyk-Luszczynska et al. 2014b; Schafer 2013)]. Ten studies reported the percentage of those residents of the sample who could see at least one wind turbine from their property (mean 88.76%, median 92.45%, range 64.8–100%) (Jalali et al. 2016b, a; Magari et al. 2014; Michaud et al. 2016b; Pawlaczyk-Luszczynska et al. 2014a, b; Pedersen and Persson Waye 2004; Pohl et al. 2012; Taylor et al. 2013; van den Berg et al. 2008a, b), and two studies the percentage of those who perceived shadow flicker (i.e., 39.1% and 11%) (Morris 2012; Schneider 2012). Six studies informed about the average distance between a residence and the nearest wind turbine among all studied residents (mean 0.935 km, range 0.585–1.7 km) (Jalali et al. 2016b; Magari et al. 2014;

Michaud et al. 2016b; Pawlaczyk-Luszczynska et al. 2014a, b; van den Berg et al. 2008a, b).

Table 2 outlines detailed characteristics of each study.

### Methodological quality of included studies

#### Methodological quality of cross-sectional studies included

For three studies, it is assumed that a selection bias occurred, since the participants were not masked to the study purpose (Morris 2012; Schafer 2013; Schneider 2012). Six studies raised concerns about a non-response bias, having a response smaller than 50% (Kageyama et al. 2016; Morris 2012; Pohl et al. 2012; Schneider 2012; Taylor et al. 2013; van den Berg et al. 2008a, b). Only one study measured the visual exposure (shadow flicker) with an objective instrument by modeling (Voicescu et al. 2016). The description of the sample characteristics and all values was inadequate in three studies (Morris 2012; Schafer 2013; Schneider 2012). Only five studies adjusted the analyses for the confounders "age" and "sex" (Feder et al. 2015; Michaud et al. 2016b, a; Pohl et al. 2012; Voicescu et al. 2016), and four studies, additionally adjusted for "study region" (Feder et al. 2015; Michaud et al. 2016b, a; Voicescu et al. 2016). The internal consistency of the results is questionable in five studies (Feder et al. 2015; Morris 2012; Schafer 2013; Schneider 2012; Taylor et al. 2013).

Seven studies were funded by public sources (Feder et al. 2015; Kageyama et al. 2016; Michaud et al. 2016a; Pawlaczyk-Luszczynska et al. 2014a, b; Pohl et al. 2012; van den Berg et al. 2008a, b). In eight studies, funding was not reported. Only three studies explicitly stated to have no conflict of interest (Kageyama et al. 2016; Michaud et al. 2016b; Voicescu et al. 2016). For one study, the existence of a conflict of interest is assumed, since the study author mentions her interest in wind energy began soon after she learned that a wind turbine was proposed next to her property (Schafer 2013). Only five studies reported that an ethical review approval was acquired (Feder et al. 2015; Magari et al. 2014; Michaud et al. 2016b, a; Voicescu et al. 2016).

Generalizability of the results was judged to be lacking in four studies, since only one wind farm or a restricted geographical area was investigated (Magari et al. 2014; Morris 2012; Schafer 2013; Schneider 2012).

Five studies were evaluated to have a high overall study quality (Michaud et al. 2016b, a; Pawlaczyk-Luszczynska et al. 2014a; Pedersen and Persson Waye 2004; Voicescu et al. 2016), and three studies to have an acceptable overall study quality (Feder et al. 2015; Magari et al. 2014; van den Berg et al. 2008a, b). The remaining studies were judged to have a low overall study quality.

Table 3 details the methodological quality of each cross-sectional study.

**Table 2** Study characteristics of included studies

Study	Study design	Study location	Study period	Sample size, response, lost to follow-up	Study population		Setting	Exposure	Outcome
					♀ (%)	Age (years)			
Feder et al. (2015)	Cross-sectional study	Canada	May–September 2013	<i>n</i> = 1238 RR: 78.9%	50.1	Ø: 51.61* R: 18–79*	(Semi-) rural, flat	(ii): Visual annoyance	(ii): Quality of life
							<i>n</i> WTs: 399 WT capacities: 0.4–3 MW WT height: 80 m* Ø rotor blade: 80 m* distance to WTs: 0.6 km*		
Jalali et al. (2016a)	Prospective cohort study	Canada	t1: March 2014 t2: March 2015	<i>n</i> = 37 RR: ca. 30% LTFU: 47%	56.8	Ø: 54.25 R: 33–78	Rural, flat, agricultural	(i): WT visibility (ii): WT annoyance	(i): Sleep disturbance, daytime sleepiness, insomnia
							<i>n</i> WTs: 5 WT capacity: 1.8 MW WT height: 90 m* Ø rotor blade: 100 m*		
Jalali et al. (2016b)	Prospective cohort study	Canada	t1: March–May 2014 t2: March–May 2015	<i>n</i> = 31 RR: 16% LTFU: 72.09%	58.1	Ø: 53.6 R: 30–72	Rural, flat, agricultural	(i): WT visibility (ii): visual annoyance	(i): Visual annoyance (ii): physical and mental health, quality of life
							<i>n</i> WTs: 5 WT capacity: 1.8 MW WT height: 90 m* Ø rotor blade: 100 m* distance to WTs: 2 km		
Kageyama et al. (2016)	Cross-sectional study	Japan	2010–2012	<i>n</i> = 1079 RR exposed: 49% controls: 45%	56.5	R of 80%: 50–60	Rural	(ii): Visual annoyance	(ii): Insomnia, difficulty falling asleep, difficulty maintaining sleep, light overnight sleep, physical and mental health
							WT capacities: 0.66–3 MW		
Magari et al. (2014)	Cross-sectional study	USA	2011	<i>n</i> = 62 RR households: 93%	43.5	51	Rural, farmland	(i): Shadow flicker, reflections, altered view	(i): Annoyance by shadow flicker, reflections, altered view
							<i>n</i> WTs: 84 WT capacity: 1.5 MW		

Table 2 (continued)

Study	Study design	Study location	Study period	Sample size, response, lost to follow-up	Study population		Setting	Exposure		Outcome
					♀ (%)	Age (years)		Wind turbine characteristics		
Michaud et al. (2016a)	Cross-sectional study	Canada	May–September 2013	<i>n</i> = 1238 RR: 78.9%	50.1	Ø: 51.61 R: 18–79	(Semi-) rural, flat	<i>n</i> WTs: 399	(ii): Annoyance by blinking lights, shadow flicker	(ii): Sleep disturbance
								WT capacities: 0.4–3 MW		
								WT height: 80 m		
								Ø rotor blade: 80 m		
								distance to WTs: 0.6 km		
Michaud et al. (2016b)	Cross-sectional study	Canada	May–September 2013	<i>n</i> = 1238 RR: 78.9%	50.1	Ø: 51.61 R: 18–79	(Semi-) rural, flat	<i>n</i> WTs: 399	(i): Blinking lights, shadow flicker, visibility	(i): Annoyance by blinking lights, shadow flicker, visual annoyance
								WT capacities: 0.4–3 MW		
								WT height: 80 m		
								Ø rotor blade: 80 m		
								distance to WTs: 0.6 km		
Morris (2012)	Cross-sectional study	Australia	NR	<i>n</i> = 93** RR: 40%	NR	NR	–	distance to WTs: 5 km and 10 km	(i): Shadow flicker	(i): Annoyance by shadow flicker
Pawlaczyk-Luszczynska et al. (2014a)	Cross-sectional study	Poland	May/June 2011	<i>n</i> = 156 RR survey 1: 71% survey 2: 54%	60.3	Ø: 46.2 R: 15–82	Rural, flat, agricultural	<i>n</i> WTs: 108	(i): Shadow flicker, reflections	(i): Annoyance by shadow flicker, reflections
								WT capacities: 0.15–2 MW		
								WT heights: 30–100 m		
Pawlaczyk-Luszczynska et al. (2014b)	Cross-sectional study	Poland	NR	<i>n</i> = 361 RR: NR	58.4	Ø: 45.5 R: 15–88	Rural, flat, agricultural	–	(i): Shadow flicker, reflections	(i): Annoyance by shadow flicker, reflections
Pedersen and Persson Wayne (2004)	Cross-sectional study	Sweden	May/June 2000	<i>n</i> = 351 RR: 68.4%	58	48	Rural, flat, agricultural, small industries	<i>n</i> WTs: 16 WT capacities: 0.15–0.65 MW WT heights: 47–50 m	(i): Shadow flicker, reflections, altered view	Annoyance by shadow flicker, reflections, altered view

**Table 2** (continued)

Study	Study design	Study location	Study period	Sample size, response, lost to follow-up	Study population		Setting	Wind turbine characteristics	Exposure	Outcome
					♀ (%)	Age (years)				
Hübner and Pohl (2010); Pohl et al. (2012)	Cross-sectional study	Germany	February–September 2009	<i>n</i> = 420 RR: 24.8%	43	51	–	<i>n</i> wind farms: 13 <i>n</i> WTs in each wind farm (median): 8 total capacity each wind farm (median): 14 MW WT height: 138.5 m	(i): Aircraft obstruction markings	(i): Annoyance by obstruction markings, psychological and somatic symptoms, stress, quality of life
Schafer (2013)	Cross-sectional study	Australia	2013	<i>n</i> = 37** RR: NR	NR	NR	–	<i>n</i> WTs: 15 WT capacity: 2 MW WT height: 80 m Ø rotor blade: 46 m distance to WTs: 10 km	(i): Shadow flicker	(i): Annoyance by shadow flicker
Schneider (2012)	Cross-sectional study	Australia	NR	<i>n</i> = 23** RR: 23%	NR	NR	–	<i>n</i> WTs: 140 WT capacity: 3 MW distance to WTs: 10 km	(i): Shadow flicker	(i): Annoyance by shadow flicker
Taylor et al. (2013)	Cross-sectional study	United Kingdom	NR	<i>n</i> = 138 RR: 10.86%	45.6	Ø: 53.8 R: 20–95	Urban	<i>n</i> WTs: 12 WT capacities: 0.6–5 kW	(i): Visibility	(i): General health
van den Berg et al. (2008a, b)	Cross-sectional study	The Netherlands	January 2007–August 2008	<i>n</i> = 725 RR: 37%	49	51	Built-up (villages, cities)	WT capacity: ≥ 0.5 MW distance to WTs: 0.5 km	(i): Shadow flicker, rotor blade movement, altered view	(i): Annoyance by shadow flicker, rotor blade movement, altered view
Voicescu et al. (2016)	Cross-sectional study	Canada	May–September 2013	<i>n</i> = 1238 RR: 78.9%	50.1	Ø: 51.61 R: 18–79	(Semi-) rural, flat	<i>n</i> WTs: 399 WT capacities: 0.4–3 MW WT height: 80 m* Ø rotor blade: 80 m* distance to WTs: 0.6 km*	(i): Shadow flicker	(i): Annoyance by shadow flicker

**Table 2** (continued)

(i): main exposure, (ii) secondary exposure of this systematic review

*Km* kilometer, *kW* kilowatt, *n* sample size, *LTFU* Lost to follow-up, *m* meter, *MW* megawatt, *NR* not reported, *R* range, *RR* response, *t* time of measurement, *WT/WTs* wind turbine/s

Ø: mean, ♀: female

\*Information not reported within the study, but taken from another publication of the same study

\*\*The sample size refers to the number of households, not to the number of individuals

## Methodological quality of prospective cohort studies included

The results of the critical appraisal of the two cohort studies are presented in detail in the supplementary material. The following section gives an overview of the most important methodological aspects. The two cohort studies were derived from the same survey, thus most assessments were consistent, and diverging evaluations are pointed out (Jalali et al. 2016b, a).

The risk for a selection bias is assumed to be high for both studies for several reasons (see Supplementary Material). The risk of an information bias for the exposure is supposed to be rather moderate, since it seems sufficient to answer the questions about the visibility of wind turbines and the visual annoyance with a subjective yes–no option. Regarding the outcomes, the occurrence of an information bias is judged to be unlikely, since suitable, reliable, and valid questionnaires were used. Blinding of the participants to their exposure status was impossible due to the sensitive nature of the topic in the study region. Important confounders such as sex, age, noise sensitivity, or attitude to wind turbines were elevated, but no techniques are described for their correction, control, or adjustment. The exposure time of 9 months from the start of the wind turbine operation to the follow-up was judged to be too short to establish true temporal associations. As the first measurement time was before the operation of the wind turbines started, but when these were already erected, their visual presence could have led to annoyance or health effects among local residents at baseline. Due to small sample sizes at follow-up, the statistical power of both studies is low.

The authors of both studies declared to have no conflict of interest. Jalali et al. (2016a) reported a public funding source, and that the study attained an ethical approval. Jalali et al. (2016b) made no statements about funding and ethical approval.

The generalizability of the results is questionable due to the small, specific study region where general concerns about wind energy exist. The overall study quality of both cohort studies is judged to be “acceptable”.

## Results shown in included studies

### Health effects of direct and indirect wind turbine visibility

Sixteen studies concerning the health effects of visual aspects of wind turbines were retrieved, thereof ten studies considered direct and eleven indirect visibility.

**Health effects of wind turbine visibility** In two studies of acceptable and high quality, 14.6% and 45.2% of all exposed subjects were “rather or very” and “very or extremely” visually annoyed by wind turbines, respectively (Jalali et al.

**Table 3** Methodological quality of included cross-sectional studies

Study	Intro- duction	Methods	Results										Discus- sion				Other		Overall study qual- ity*			
			2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17		18	19	20
Question	1																					
Feder et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Do not know	(a) Yes (b) Yes	(a) Do not know (b) Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	No	(a) No (b) Do not know	Yes	2	
Kageyama et al. (2016)	Yes	Yes	No	Yes	Yes	Do not know	Do not know	(a) Do not know (b) Yes	(a) No (b) Yes (physical/mental health) (b) No (insomnia)	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	(a) No (b) No	Do not know	3	
Magari et al. (2014)	Yes	Yes	No	No	Yes	Do not know	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	(a) Do not know (b) Do not know	Yes	2	
Michaud et al. (2016a)	Yes	Yes	Yes	Yes	Yes	Yes	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	(a) No (b) Do not know	Yes	1	
Michaud et al. (2016b)	No	Yes	Yes	Yes	Yes	Yes	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	No	Yes	Yes	No	No	Yes	Yes	No	No	(a) Do not know (b) No	Yes	1	
Morris (2012)	Yes	Yes	No	No	Yes	No	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	No	No	No	Yes	No	No	Yes	No	No	(a) Do not know (b) Do not know	Do not know	3	
Pawlaczyk-Luszczyńska et al. (2014a)	Yes	Yes	No	Yes	Yes	Yes	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yrs	Yes	(a) No (b) Do not know	Do not know	1	
Pawlaczyk-Luszczyńska et al. (2014b)	Yes	Yes	No	Yes	Yes	Do not know	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	Yes	No	Yes	Do not know	No	Yes	Yes	Yes	No	(a) No (b) Do not know	Do not know	3	
Pedersen and Persson Waye (2004)	Yes	Yes	No	Yes	Yes	Yes	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	(a) Do not know (b) Do not know	Do not know	1	

Table 3 (continued)

Study	Intro- duction	Methods	Results										Discus- sion		Other		Overall study qual- ity*					
			2	3	4	5	6	7	8	9	10	11	12	13	14	15		16	17	18	19	20
Question	1																					
Pohl et al. (2012)	Yes	Yes	Yes	Yes	Yes	Do not know	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes (annoy- ance) (b) No (symp- toms)	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	(a) No (b) Do not know	Do not know	3	
Schafer (2013)	Yes	Yes	No	No	Do not know	No	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	No	No	No	Do not know	No	No	No	No	No	(a) Do not know (b) Yes	Do not know	3	
Schneider (2012)	Yes	Yes	No	No	Yes	No	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	No	No	No	Yes	No	Yes	No	No	No	(a) Do not know (b) Do not know	Do not know	3	
Taylor et al. (2013)	No	Do not know	No	Yes	Yes	Do not know	Do not know	(a) Do not know (b) Yes	(a) No (b) No	Yes	No	Yes	Yes	Yes	No	Yes	Yes	No	(a) Do not know (b) Do not know	Do not know	3	
van den Berg et al. (2008a, b)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	(a) Yes (b) Yes	(a) Yes (b) Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	(a) No (b) Do not know	Do not know	2	
Voicescu et al. (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Do not know	(a) Yes (b) Yes	(a) Yes (b) Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	(a) Do not know (b) No	Yes	1	

Questions: (1) Were the aims/objectives of the study clear? (2) Was the study design appropriate for the stated aim(s)? (3) Was the sample size justified? (4) Was the target/reference population clearly defined? (Is it clear who the research was about?) (5) Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation? (6) Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation? (7) Were measures undertaken to address and categorise non-responders? (8) Were the (a) risk factors and (b) outcome variables measured appropriate to the aims of the study? 9. Were the (a) risk factors and (b) outcome variables measured correctly using instruments/measurements that had been trialled, piloted or published previously? 10. Is it clear what was used to determine statistical significance and/or precision estimates (e.g., *p* value, confidence intervals)? 11. Were the methods (including statistical methods) sufficiently described to enable them to be repeated? 12. Were the basic data adequately described? 13. Does the response rate raise concerns about non-response bias? 14. If appropriate, was information about non-responders described? 15. Were the results internally consistent? 16. Were the results for the analyses described in the methods, presented? 17. Were the authors' discussions and conclusions justified by the results? 18. Were the limitations of the study discussed? 19. Were there any (a) funding sources or (b) conflicts of interest that may affect the authors' interpretation of the results? 20. Was ethical approval or consent of participants attained?

\*The assessment of the overall study quality based on the evaluations of the questions 5, 6, 8, 9, and 13 and was assessed with 1 = high quality (all answers positive), 2 = acceptable quality (all but one answer positive), or 3 = low quality (more than one negative or unclear answer)

2016b; Michaud et al. 2016b). A cohort study of acceptable quality showed a statistically significant association between the visibility of wind turbines with changes of sleep disturbance over time, but no association with changes of insomnia or daytime sleepiness over time (Jalali et al. 2016a). Furthermore, it was not associated with changes of physical and mental health and satisfaction with life over time (Jalali et al. 2016b). In a cross-sectional study of low quality, seeing a wind turbine from the property was not statistically related to symptoms that are typical for the “wind turbine syndrome” described by Pierpont (2009) (Taylor et al. 2013).

**Health effects of an altered view due to wind turbines** A cross-sectional study of high quality found a prevalence of general annoyance by an altered view due to wind turbines of 14.7% (Pedersen and Persson Waye 2004) and two studies of acceptable quality detected a prevalence of general (outdoor) annoyance of 27% and 28%, respectively (Magari et al. 2014; van den Berg et al. 2008a, b). Information about the pooled prevalence of general annoyance by an altered view due to wind turbines is outlined in the Supplementary Material.

A cross-sectional study of low quality evaluated a medium effect size of annoyance by landscape changes, that was perceived higher than other wind turbine features (e.g., noise or obstruction markings) (Pohl et al. 2012).

The meta-analysis of two eligible studies reporting the prevalence of high annoyance caused by an altered view due to wind turbines resulted in a pooled prevalence of 6% (95% CI 4–8%) with a heterogeneity that might be not important ( $I^2=0\%$ ) (Fig. 2) (Magari et al. 2014; van den Berg et al. 2008a, b).

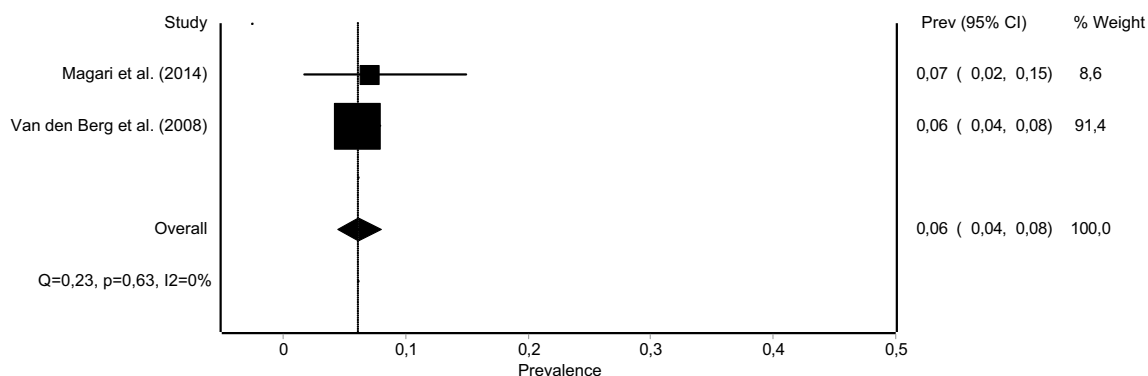
**Health effects of wind turbine obstruction markings** One cross-sectional study of high quality reported that 11.2% of the exposed participants were highly annoyed by blinking lights (Michaud et al. 2016b). Another cross-sectional

study of low quality identified a similar prevalence of being “rather or very” annoyed by obstruction markings (15.7%) (Pohl et al. 2012). In this study, the prevalence of general annoyance by day and night markings was nearly identical, being 29.7% and 28.6%, respectively. The prevalence of psychological and somatic symptoms as well as stress effects due to obstruction markings was negligible (0–1.9%). Residents declared a slight deterioration of quality of life due to day markings.

**Health effects of wind turbine rotor blade movement** In a cross-sectional study of acceptable quality, 19% of exposed residents felt annoyed by the movement of the rotor blades (van den Berg et al. 2008a, b). According to another study of low quality, the annoyance by rotor blade movements was judged to be rather low (Pohl et al. 2012).

**Health effects of wind turbine reflections** Two studies of high quality stated a prevalence of general annoyance by wind turbine reflections of 6.7% and 13.2%, respectively (Pawlaczyk-Luszczynska et al. 2014a; Pedersen and Persson Waye 2004). In a study of acceptable quality, the general (outdoor) annoyance was 14% (Magari et al. 2014) and in a study of low quality it was 15.8% (Pawlaczyk-Luszczynska et al. 2014b). Residents in a study of low quality rated the annoyance by reflections as rather low (Pohl et al. 2012). Details on the pooled prevalence of general annoyance by wind turbine reflections are illustrated in the Supplementary Material.

**Health effects of wind turbine shadow flicker** A study of high quality showed a statistically significant association between shadow flicker and high shadow flicker annoyance in two logistic regression models (OR = 1.70 (95% CI 1.37–2.11) and OR = 2.04 (95% CI 1.56–2.66), but shadow flicker exposure explained only 11% of the variance in these models (Voicescu et al. 2016). Other variables that were no reactions to the operation of wind turbines (e.g., con-



**Fig. 2** Pooled prevalence for high annoyance by an altered view due to wind turbines

cern about physical safety, audibility of wind turbines, or noise sensitivity) or that were strongly associated with high shadow flicker annoyance (e.g., annoyance by other wind turbine features) were more capable in predicting the extent of shadow flicker annoyance.

Prevalence of general annoyance by shadow flicker of wind turbines was 8.9% and 24.5%, in two high-quality studies (Pawlaczyk-Luszczynska et al. 2014a; Pedersen and Persson Waye 2004); 16% and 29%, respectively, in two studies of acceptable quality (Magari et al. 2014; van den Berg et al. 2008a, b); and 28.5% in an low-quality study (Pawlaczyk-Luszczynska et al. 2014b). The Supplementary Material details data on the pooled prevalence of general annoyance by wind turbine shadow flicker.

Three studies reporting on the prevalence of high annoyance caused by wind turbine shadow flicker were pooled (Magari et al. 2014; Michaud et al. 2016b; van den Berg et al. 2008a, b). A pooled prevalence of 6% (95% CI 3–11%) with substantial to considerable heterogeneity ( $I^2 = 88\%$ ) was calculated (Fig. 3). Sensitivity analyses in terms of sample size and setting were carried out. If the study with the lowest sample size was excluded from calculations, the pooled prevalence did not change (Magari et al. 2014). The pooled prevalence increased slightly to 9%, if only the studies from rural areas and with the highest number of wind turbines were considered (Magari et al. 2014; Michaud et al. 2016b).

Three studies of low quality reported prevalence rates of shadow flicker annoyance by households, which ranged between 13 and 90% (Morris 2012; Schafer 2013; Schneider 2012).

### Health effects due to annoyance by visual wind turbine features

Four studies examined the association between annoyance by visual wind turbine features and residential health.

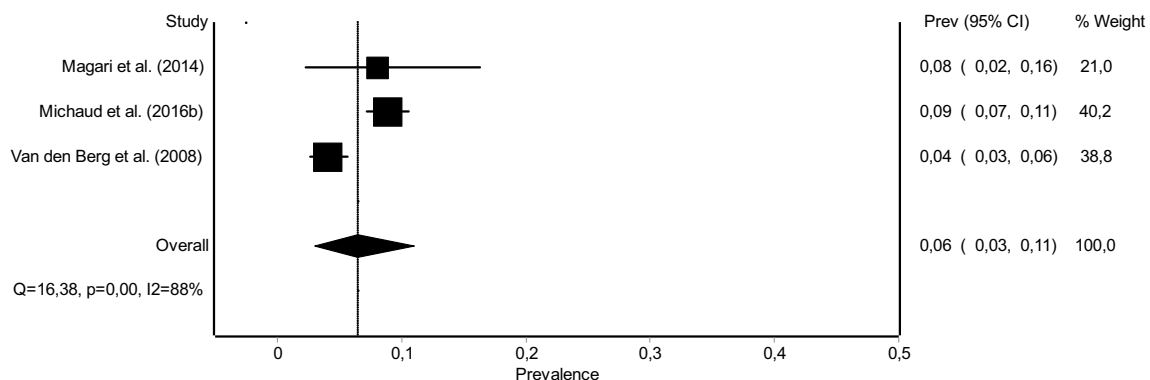
**Health effects due to visual annoyance by wind turbines** One cohort study of acceptable quality illustrated a significant relationship between visual annoyance and changes over time for satisfaction with life and mental health, but not for physical health (Jalali et al. 2016b). On the contrary, a cross-sectional study of acceptable quality found a significant association between the quality of life -domains “physical health” and “environment”, but not for the “psychological” and “social relationships” domains or overall quality of life and satisfaction with health (Feder et al. 2015). In a study of low quality, feeling visually annoyed by wind turbines was associated with insomnia and some sleep problems (difficulty initiating and maintaining sleep, and light overnight sleep) as well as with the high risk groups “eyes and skin” and “digestion” of the Total Health Index (Kageyama et al. 2016).

**Health effects due to annoyance by blinking lights of wind turbines** One cross-sectional study of high quality pointed out that being annoyed by blinking lights of wind turbines was statistically significantly associated with sleep disturbance ( $p < 0.001$ ), awaking bouts during sleep ( $p = 0.0309$ ), and the total sleep time ( $p = 0.0006$ ) (Michaud et al. 2016a).

**Health effects due to annoyance by shadow flicker of wind turbines** One high-quality cross-sectional study outlined a statistically significant association between annoyance by shadow flicker and sleep disturbance ( $p < 0.001$ ), and the total sleep time ( $p = 0.0019$ ) (Michaud et al. 2016a).

### Wind turbine visibility in combination with wind turbine noise

Only one study of high quality provided information about the combined effect of shadow flicker and wind turbine noise, and its impact on high shadow flicker annoyance (Voicescu et al. 2016). Residents who could hear the noise of wind turbines were about 11 times more highly annoyed



**Fig. 3** Pooled prevalence for high annoyance by wind turbine shadow flicker

by shadow flicker than those who could not hear wind turbines (OR = 10.68 (95% CI 5.07–22.51)). According to an univariate analysis, the statistical interaction term between shadow flicker and noise of wind turbines of a logistic regression model was statistically significant ( $p = 0.026$ ). The direction of the interaction term was not reported, so it is unclear how the risks of the two exposures deviate from multiplicity. Separate logistic regressions for each shadow flicker exposure group showed a statistically significant association between wind turbine noise and high shadow flicker annoyance only for the group with the lowest shadow flicker exposure (OR = 2.62 (95% CI 1.64–4.20)). The variance of high shadow flicker annoyance explained by shadow flicker exposure (maximum minutes per day) was statistically weak and nearly the same as that of wind turbine noise exposure (i.e.,  $R^2 = 10\%$ , and  $R^2 = 9\%$ , respectively). The explained variance somewhat improved from  $R^2 = 10\%$  to  $R^2 = 15\%$ , when the interaction between shadow flicker and noise levels was taken into account. But this interaction was no longer significant in the final multiple regression models, when other factors that were related to high shadow flicker annoyance were included.

Detailed information on the results and on all meta-analyses about high and general annoyance prevalences are outlined in the Supplementary Material.

## Discussion

### Health effects of direct and indirect wind turbine visibility

The hypothesis that wind turbine visibility influences the health of residents was confirmed with regard to annoyance and sleep disturbance over time.

#### Annoyance

The large difference of the prevalences of high annoyance by wind turbine visibility of 45.2% and 14.6%, respectively, might be explained by the fact that Michaud et al. (2016b) and Jalali et al. (2016b) used different annoyance rating scales. Further, the controversy about wind energy among residents in the study region of Jalali et al. (2016b) may have led to the high value of 45.2%. One possible influencing factor for the large range of the prevalences of general annoyance by wind turbine reflections, shadow flicker, and an altered view may be different study periods. This finding is confirmed by Chapman et al. who observed that reporting of wind turbine-induced symptoms in Australia increased with the publication of the book “*Wind turbine Syndrome*” (Pierpont 2009), which may have raised health concerns among residents (Chapman

et al. 2013). Wind turbine reflections were rated to be less annoying than an altered view by turbines or shadow flicker, possibly because modern wind turbines have matt, non-reflective rotor blades, which aim to reduce the visual impact of reflections (UBA 2014).

It should be kept in mind that visual annoyance contains a causal attribution, so that only visually exposed residents are eligible for its evaluation. Due to a missing control group, the calculation of an association is not possible. Thus, in relation to this health outcome, surveying its prevalence among exposed residents was the focus of this systematic review, to describe the seriousness of this problem. Nevertheless, we decided to include the cross-sectional study of Voicescu et al. (2016), which presented odds ratios for the association between shadow flicker exposure and shadow flicker annoyance. Typically, the calculation of an odds ratio requires the absence of the exposure in the control group (Szumilas 2010). In this study, the exposure groups referred to the maximum minutes of shadow flicker per day among visually exposed residents. In case of a missing non-exposed control group, the association always will be positive. Nevertheless, the study is considered to be important, since a dose–response relationship was shown. Even though it should be noted that causal attribution might increase the awareness of the respondents about a risk and thus might increase the occurrence of a health outcome (Basner and McGuire 2018).

Even though it is recommended that environmental health burdens are measured with “a high level of annoyance” (WHO 2011), only one of the included studies used the definition of high annoyance proposed by the International Commission on the Biological Effects of Noise (Fields et al. 2001; Michaud et al. 2016b).

#### Other health effects

It has been proposed that shadow flicker from wind turbines may cause photosensitive seizures, but no appropriate epidemiological studies were identified within this review. The corresponding risk for large wind turbines, is considered to be low, since the flashing frequency does not exceed 0.3–1.0 Hz (BIS 2018; Harding et al. 2008; Smedley et al. 2010). The risk for smaller wind turbines with potential frequencies of 3 Hz is also negligible, when the distance between the observer and the wind turbine is higher than the ninefold of the wind turbines’ height (Smedley et al. 2010).

No study on the health effects of offshore wind farms was retrieved. According to experimental results, the visual impact from offshore wind farms may lead to visual disabilities among coastal users (Ladenburg and Dubgaard 2009).

## Health effects due to annoyance by visual wind turbine features

Regarding the first subgoal of this systematic review, the results retrieved are not homogeneous. The hypothesis that annoyance by wind turbine visibility has an effect on the health of people living in their proximity was only partly confirmed—namely regarding the residents' sleep.

In the course of this systematic review, visual annoyance was treated as a health outcome for the main goal and as an exposure variable for the first subgoal. It was shown that direct wind turbine visibility influenced the occurrence of sleep disturbances among residents, and that visual annoyance also led to sleep disorders. Thus, it seems possible that visual annoyance acts as a mediator between wind turbine visibility and certain health effects. To date, annoyance of residents was mainly investigated in relation to environmental noise and is defined “as a feeling of discomfort which is related to adverse influence upon an individual or a group by any substance or circumstance” (Maschke and Niemann 2007). If noise annoyance is regarded as an exposure, mediator, or health outcome, depends on the research question of a study. According to observational studies, it can be seen as a health outcome, and further, it may increase the risk for other diseases (Bakker et al. 2012; Maschke and Niemann 2007; Shepherd et al. 2011). The WHO points out that “although annoyance cannot be classified as a “health effect”, it does affect the well-being of many people and therefore may be considered to fall within the WHO-definition of health as being “a state of complete physical, mental and social well-being”. No such debate was conducted in the context of visual wind turbine exposures, even though it may be transferable as well (WHO 2011).

## Wind turbine visibility in combination with wind turbine noise

Three visual and noise wind turbine exposures are possible: (1) wind turbines are visible and audible; (2) wind turbines are audible, but not visible; and (3) wind turbines are visible, but not audible.

Regarding the second subgoal of this review—and regarding the first scenario with a combined visual and audible wind turbine exposure—only one included study considered the relationship between a visual exposure and its corresponding annoyance at varying levels of noise exposure (Voicescu et al. 2016). Wind turbine noise exposure increased the reported annoyance by shadow flicker only among the group exposed to the least shadow flicker per day. This may indicate that the dominant source model or strongest component model (Pierrette et al. 2012) may be applicable for exposures to multiple wind turbine features. Noise became the dominant source and reactions to noise

explained more of the annoyance when shadow flicker was less frequent. In categories of increased shadow flicker exposure, where noise did not help to predict the reported visual annoyance, the shadow flicker may have been the dominant factor and outweighed any impact of noise on annoyance. When wind turbines were both, visible and audible, noise was perceived as more annoying than visual features in seven out of nine included studies (Magari et al. 2014; Michaud et al. 2016b; Pawlaczyk-Luszczynska et al. 2014a, b; Pedersen and Persson Waye 2004; Schneider 2012; van den Berg et al. 2008a, b), even though fewer residents were exposed to noise than to visual aspects according to four studies, which gave information on both exposure prevalences (noticing/hearing versus seeing wind turbines 47.4–63.5% versus 87.9–96.8%) (Michaud et al. 2016b; Pawlaczyk-Luszczynska et al. 2014a, b; Pedersen and Persson Waye 2004).

The scenario, where wind turbines are audible, but not visible is conceivable (e.g., due to architectural or landscape conditions). Research has shown that noise annoyance is significantly reduced, when wind turbines are not visible (Klaeboe and Sundfor 2016; Pedersen et al. 2009).

The scenario of seeing, but not hearing wind turbines seems to be rather unlikely, but not impossible. Blinking lights of offshore wind farms, for example, are visible from the coast but not audible. A special case of this scenario—not issued in any research paper yet—would be, where wind turbines are visible and sometime audible or not, depending on the wind direction.

Generally, it is assumed that humans perceive their environment in a holistic way (Szychowska et al. 2018) and that the processing of visual and auditive exposures is closely interlinked (Ruotolo et al. 2012). In addition, besides visual and noise exposures of wind turbines, other variables such as economic benefit, attitude towards wind energy, or noise sensitivity further seem to influence the health of residents. According to Szychowska et al. (2018), it seems to be difficult, if not impossible, to figure out, which of these variables has the strongest influence on health, which is a moderator or a mediator for other variables. The differential relationship between annoyance to visual exposures with varying levels of visual and acoustic exposures observed by Voicescu et al. (2016) demonstrates how difficult it is to consider annoyance to individual wind turbine characteristics, when the persons are simultaneously exposed to multiple features. Consequently, Michaud et al. (2018b) developed a construct to consider the collective annoyance attributed to multiple visual and acoustic wind turbine features, which was associated with different health complaints (Michaud et al. 2018a).

## Influence of setting characteristics on the results

The influence of the distance between residences and wind turbines on the visual health impact of the turbines was

examined in four included studies, which presented contradictory results. Two studies illustrated a declining annoyance prevalence by visual wind turbine features with increasing distance (Pawlaczyk-Luszczynska et al. 2014a, b), and two studies found no statistical relevant influence of the distance on visual annoyance (Jalali et al. 2016b; Pohl et al. 2012). Nevertheless, it seems plausible that wind turbine visibility—and its impact on residents' health—increases with a declining distance to wind turbines. The studies included in this systematic review were mainly conducted in flat, rural areas, with wind turbines smaller than 100 m, so that no clear statements about the visual impact of wind turbines of larger height and in hilly, built-up, or coastal areas can be made.

### Quality of the evidence

When interpreting the results of studies on the health effects of wind turbines, it is important to consider the respective methodological quality. Overall, the critical appraisal of the studies illustrated a methodological heterogeneity. The results did not differ substantially between studies of high or acceptable quality compared to studies of low quality. Only one study of low quality reported a much higher annoyance prevalence by shadow flicker of 90% (Morris 2012), compared to all other studies that reported this value.

Generally, there is no methodical standard for the determination of visual exposures of wind turbines, in contrary to recommendations for noise measurements (Fields et al. 2001, ISO/TS 15,666 2003). Only one study determined the exposure of shadow flicker objectively (Voicescu et al. 2016). The evaluation of visual annoyance varied greatly across the studies, with only four studies referring to those residents who could see wind turbines from their residence (Jalali et al. 2016b; Magari et al. 2014; Pohl et al. 2012; van den Berg et al. 2008a, b) and with ten studies referring to the overall study population, which also comprised residents for whom wind turbines were not visible from their residence. The latter approach may underestimate the visual impact of wind turbines, since people who are not visually exposed, can per se not be visually annoyed.

### Strength and limitations of the systematic review

This systematic review is the first research paper that surveyed the body of evidence about the health effects of direct and indirect visibility of wind turbines in residential areas as its primary focus. In addition, for the first time, findings on the topic were summarized quantitatively in meta-analyses. The search strategy was created sensitively. In terms of the inclusion of studies, no restrictions in regard to language and time of publication was set. To ensure transparency and stringency, the review protocol was published a priori

on PROSPERO. For using the AXIS tool, an overall study assessment was self-established by defining categories, which seemed to be of importance.

The searching terms for the database search strings were formulated in English, which made it less likely to find non-English articles. As only seven of the twenty included articles were identified within MEDLINE, EMBASE, and CINAHL, it appears that also other topic-related databases should have been searched (e.g., the Web of Science or Scopus). Nevertheless, due to the other comprehensive searches, it appears that no other relevant studies have been missed. Since only few studies were included in the meta-analyses, conducting sensitivity analyses with the a priori established categories was not always possible. In addition, the significance and the generalizability of the pooled results is restricted due to the heterogeneity and low number of included studies. The occurrence of a publication bias was not investigated due to the low number of studies (Lauterbach 2010). A publication bias, due to self-published surveys conducted by private persons with interest in wind energy, seems to be possible. Subgroup analyses were planned in regard to different aspects (e.g., commissioning date of wind turbines, attitude towards wind energy), but not conducted due to inconsistent information reported in the studies.

### Conclusions

Seventeen primary studies on health effects due to visual wind turbine features were included in this systematic review. There were no indications for serious health impairments reported for any of the visual exposures. Most studies primarily investigated prevalence of annoyance among residents living up to 1200 m away from the nearest wind turbine, which ranged between 7 and 31%, depending on the visual exposure type (e.g., shadow flicker, reflection). The pooled prevalence of high annoyance was equal for shadow flicker and an altered view due to wind turbines (6%). The significance of the pooled prevalences is restricted due to the low number and heterogeneity of the included studies. The results on other health effects are too inconsistent to make a concluding statement. There are some indications that the visual exposure of wind turbines increases sleep disturbance among residents. For all other investigated health outcomes, no significant associations were observed. Annoyance by direct visibility, shadow flicker, and blinking lights—as exposure—was significantly associated with an increased risk for sleep disorders (e.g., insomnia or sleep quality). Only one paper described the combined impact of visual and noise exposures of wind turbines on residents' health, indicating a complex relationship. Overall, the results did not differ substantially between studies of high or acceptable quality compared to studies of low quality. The actual extent

and the significance of the results are difficult to assess due to differences in settings, and populations, as well as the methodological quality of the included papers.

## Implications for practice

To reduce health effects due to direct or indirect visibility of wind turbines, several constructional solutions of the technology can be addressed, such as a need-based site selection or a reduced gloss level and reflectivity of the rotor blades (LANUV 2002). Ideally, for aircraft obstruction markings, LED lights with intensity adjustment as well as a synchronized lighting of various turbines, seem to be the best technical measures (Pohl et al. 2012). To promote the public acceptance of such projects, the planning phase of new wind farms should be transparent for the public and involve the concerns of the municipalities and citizens (Hübner and Pohl 2014), and the visual impact of this renewable technology taken into account (Kokologos et al. 2014; Molnarova et al. 2012; Tsoutsos et al. 2009), since opposition against wind turbines was shown to result in more health effects and concerns (Pedersen et al. 2007; Walker et al. 2014, 2015).

## Implications for research

Due to the low number of studies researching the topic of health effects due to visual wind turbine features and due to the heterogeneity of the available studies—regarding study characteristics, results, and methods—further high quality research is needed. If possible, observational studies from a generalizable setting with a representative population using objective exposure and outcome measurement instruments should be conducted. In particular, the evaluation of visual exposures should be standardized—oriented towards noise research—making the respective annoyance prevalences comparable. Investigations should differentiate between the various types of aircraft obstruction markings. Furthermore, the combined impact of visual and audible aspects of wind turbines on residents' health, and the complex interdependency with other variables (e.g., attitude towards wind energy, economical benefit) should be taken into consideration. The role of visual annoyance as a possible mediator for other health effects should be investigated. In addition, studies should examine the influence of the distance between turbines and residences, with regard to a possible dose–response relationship with visual effects. Moreover, the impact of other setting criteria (e.g., landscape type, turbine height, direction of the buildings) should be considered. Prospective cohort studies, starting in the planning or construction phases of wind farms, should be undertaken, illustrating possible health effects of wind turbine visibility over time. Health impact assessments on the risks and chances

of (visual exposures of) wind turbines should be done, in comparison with other renewable, fossil, and nuclear energy generation systems.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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