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Review article

Health effects of wind turbines on humans in residential settings: Results of a scoping review

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ABSTRACT

Introduction: As the global number of wind turbines has increased steadily in recent years, as has the number of studies about putative health effects in residential settings, it is the review purpose to give an overview of the characteristics and methodologies of the scientific literature around the topic in order to identify research gaps and to derive implications for research and practice. Additionally, study findings from higher-quality observational studies as well as results that seem to be of interest for the scientific and political debate are presented.
Methods: The scoping review was conducted following systematic review methods. Comprehensive literature searches were carried out in several databases, and with extensive hand searches. All review steps were carried out in parallel by two reviewers or by one reviewer and in duplicate checked by another reviewer. The following important methodological criteria were investigated: Reporting, ethical aspects, generalization, selection bias, information bias, confounder bias. Findings from observational studies without a selection bias, information bias, and confounder bias are presented.
Results: 84 articles, that varied significantly in methods and outcomes assessed, met the inclusion criteria. Multiple cross-sectional studies reported that wind turbine noise is associated with noise annoyance, which is moderated by several variables such as noise sensitivity, attitude towards wind turbines, or economic benefit. Wind turbine noise is not associated with stress effects and biophysiological variables of sleep. Results on the impact of wind turbine noise on sleep disburbance, quality of life, and mental health problems differed among cross-sectional studies. There were few studies that addressed the potential impact of turbine noise on clinically apparent health outcomes. There were also few studies on visual risk factors or infrasound exposure. No literature was identified regarding low-frequency noise, electromagnetic radiation, and ice throw.
Conclusions: There is an extensive and diverse body of evidence around health impacts of wind turbines in residential settings, that increased sharply since 2010, showing particularly noise consequences concerning increased noise annoyance with its complex pathways; no relationship between wind turbine noise and stress effects and biophysiological variables of sleep; and heterogeneous findings concerning sleep disturbance, quality of life, as well as mental health problems. Research gaps concern the complex pathways of annoyance, the examination of clinically apparent health outcomes in comparison with non-exposed residents, an objective investigation of visual wind turbine features, the interaction between all wind turbine exposures, and epidemiological observational studies on field low-frequency and infrasound from wind turbines. Future research needs thorough high-quality and prospective study designs.

1. Introduction

The central aim of the Paris Agreement from 2015 is “holding the increase in the global average temperature to well below 2 °C above pre-industrial levels […]”(UNFCCC, 2015). To achieve this aim, amongst others, zero-carbon shares in the energy system need to be doubled every five to seven years, which is consistent with the global 2005–2015 development of renewable energy expansions (Rockström

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et al., 2017). Wind energy systems are a suitable solution to achieve this goal (Rockström et al., 2017). The global cumulative installed capacity of wind energy, as one form of renewable energy, increased continuously from 23.9 GW in 2001 to 539.6 GW in 2017 (GWEC, 2018). The global annual installed wind capacity also rose steadily from 6500 MW in 2001 to 52.6 GW in 2017 (GWEC, 2018). China, USA, and Germany exhibit the highest newly installed as well as cumulative capacity of wind energy worldwide.

Even though the share of renewable energies in general, and wind energy in particular, increased globally, resulting health effects attracted less attention in political as well as in public health discourses, e.g. in the German “Energiewende” -debate (Sutcliffe et al., 2016), thus the integration of public health knowledge is of importance, and the conduct of a comprehensive, systematic analysis on health risks and chances of wind energy production is reasonable (Twardella, 2013).

From 2000 on, more primary research has been executed on health implications of wind turbines on humans in residential settings, leading to numerous narrative and systematic reviews having been published which concentrated on summarizing these results (Arra et al., 2014; Colby et al., 2009; Ellenbogen et al., 2012; Farboud et al., 2013; Fortin et al., 2013; Jeffery and Krogh, 2014; Knopper and Ollson, 2011; Kurpas et al., 2013; McCunney et al., 2014; Merlin et al., 2013; Onakpoya et al., 2015; Ontario Chief Medical Officer of Health, 2010; Roberts and Roberts, 2013; Schmidt and Klokker, 2014). But an overview is missing, that focuses primarily on examining the entire extent, range, and nature of research activities on the topic, comprising also other study designs than observational studies such as experimental studies, intervention studies, qualitative studies, or systematic reviews, as well as all types of wind turbine exposures – apart from solely synthesizing study findings. To provide such an overview, a scoping review seemed to be the best scientific option to embrace the width, heterogeneity, and novelty of the research topic about health effects of wind turbines in residential settings. Scoping reviews are of particular use when a field of research is relatively new or the body of evidence is of a heterogeneous nature (Khalil et al., 2016). The research question in scoping reviews is broad and different study designs may be included, contrary to systematic reviews (Arksey and O'Malley, 2005; Khalil et al., 2016). The methodology applied is based on appropriate concept papers (Arksey and O'Malley, 2005; Daudt et al., 2013; Levac et al., 2010; Peters et al., 2015).

The purpose of this scoping review is to give an overview on the characteristics and methodologies of the scientific literature issuing putative health effects of wind turbines on local residents in order to identify research gaps and to derive implications for research and practice. Important methodologies of each study were regarded to provide the reader the possibility to judge the study findings critically in light of each studies´ methods and to gain an overview of the quality of the study base and thus, eventually to derive the need for appropriate high-quality studies. Additionally, in accordance with the third reason to undertake a scoping review – proposed by Arksey and O'Malley (2005) – findings of observational studies fulfilling specific quality criteria – in respect to selection bias, information bias, adjustment of important confounders, and transferability – are presented. Furthermore, findings of interest for the scientific and political debate on the topic are outlined. In this scoping review, health was defined according to the constitution of the World Health Organization as being “a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity” (WHO, 1946).

2. Methods

The PRISMA -checklist was used as a reporting guideline (Moher et al., 2009), since no specific reporting guideline for scoping reviews is available to date (Colquhoun et al., 2014; Tricco et al., 2016). The protocol of the scoping review was initially published prior to the study conduct in the “International register of systematic reviews” PROSPERO, but was removed from their homepage post hoc with the explanation of being outside the scope of PROSPERO due to the scoping review design (Freiberg et al., 2016). Thus, the study protocol is available on request from the corresponding author. The overall scoping review not only incorporated health effects of wind turbines on humans in residential settings, but also on humans in occupational settings. The results about occupational settings are published elsewhere (Freiberg et al., 2018). The research team consisted of three public health scientists, of whom two have a Masters degree (AF, CS) and one a doctoral degree (MG), and two occupational physicians, of whom one has a doctoral degree (VCM) and one additionally a professor titel (AS). The research members had different experiences in environmental research, with two members writing their Masters respectively Doctoral thesis on the topic of health complaints due to wind turbines (AF, CS), one member with years of scientific experience in environmental medicine (AS), one member experienced in public health research (MG), and one member with practical experiences in occupational and environmental medicine (VCM).

2.1. Identifying the research question

The main research question of this scoping review is: “What are characteristics and methodological aspects of studies investigating putative health effects of wind turbines in residential settings?” Specifically, study characteristics referring to the study design, investigated associations, and temporal and spatial developments as well as methodological aspects are of interest.

A secondary research question is: “What are the findings of observational studies without selection bias, information bias, and confounder bias about health effects of wind turbines on local residents?”

The research questions were concretized according to the PEOS -criteria (Moher et al., 2009) (see Table 1). The rationale for including studies published from the year 2000 and onwards was that this was the year that the government in Germany, a country that serves an international leading role in regard to renewable energy development, passed the first Renewable Energies Act (AEE, 2014; Bundesgesetzblatt, 2000). Subsequently, the portion of renewable energies among the primary energy consumption increased steadily from 1.3% in 1990 to 12.6% in 2016, with electricity having the highest share, that was 3.4% in 1990 and 31.7% in 2016 (BMWi, 2017).

2.2. Identifying relevant studies

In order to identify all available peer reviewed as well as non-peer reviewed articles on the topic, a comprehensive literature search was executed. Initially, the electronic databases MEDLINE and EMBASE via Ovid, and CINAHL via EbscoHost were searched on February 1st, 2016. As search strings were intended to be sensitive, only search terms for the exposure and health outcomes were formulated. Table 2 exemplifies the search string for MEDLINE. The search strategies for the other databases were modified to database-specific requirements and are available from the corresponding author on request.

During the research course it became clear that the aforementioned databases covered only a small proportion of relevant studies, and most included papers were retrieved by hand searches. Consequently, a search of another database, the Web of Science, was executed on November 28th, 2016. The searches within the four databases were updated on September 25th, 2017. Also, several Google Scholar searches were carried out, with search strings, which were created prior to study conduction or during the study course. Furthermore, the following websites of environmental and public health institutions were searched from May to July 2016: World Health Organization, International Labour Organization, European Agency for Safety and Health at Work, The National Institute for Occupational Safety and Health, Health and Safety Executive, Safe Work Australia, German Environment Agency, (German) Federal Ministry of Labour and Social

Table 1
Inclusion and exclusion criteria.

Category	Inclusion criteria	Exclusion criteria
Population	– humans – **age span**: all ages – **geographical zone of interest**: worldwide	– animals
Exposure	– all exposures that emanate from wind turbines or wind farms: noise, low-frequency noise, infrasound, vibrations, electromagnetic radiation, visual risk factors (visibility, shadow flicker, reflections, movement of rotor blades, etc.), ice throw, accidents etc. – **setting**: onshore, offshore	– no restrictions
Outcome	– effects on human health and safety (complaints, diseases, injuries) – **measurement method**: subjective, objective – physiological parameters and surrogate markers	– no restrictions
Study design	– observation study (cohort study (prospective, retrospective), case-control study, cross-sectional study, case studies, case report, ecological study) – intervention study (randomized controlled trial (RCT), non-randomized controlled trial (NRCT), before-after study) – qualitative study (interview, focus group discussion, etc.) – experimental study – review with a systematic review approach (systematic review, scoping review) – content analysis – **language**: English, German – **publication year**: from 2000 on – **publication type**: peer reviewed, non-peer reviewed	– review without a systematic review approach (narrative) – subjective study (editorial, commentary, expert opinion) – only abstract available – animal study – monitoring study – exposure study

Affairs, (German) Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, German Social Accident Insurance, (German) Federal Institute for Occupational Safety and Health, Deutsche Gesellschaft für Arbeits- und Sozialmedizin e. V. (no English translation available), and German Social Accident Insurance. The references of all included studies were fast-forward searched in the Web of Science. Reference lists of all included studies as well as of topic-related key articles were screened for relevant literature. The snowball technique was applied, meaning that references that were not identified by the aforementioned searches, but found via other channels and that seemed eligible, were included.

2.3. Study selection

The screening of the initial database searches in MEDLINE, EMBASE, and CINAHL were performed by two independent reviewers (AF and CS). In case of disagreement between the reviewers, a consensus process took place, consisting of a discussion, and in case of persisting disagreement, the consultation of a third reviewer (AS). The degree of agreement between the two reviewers was calculated for both screening stages, calculating the proportion of observed agreement and Cohen's Kappa (Cohen, 1960). During title and abstract screening, the reviewers were blinded to author names and publication year. During full text screening, all excluded full texts were documented with the reason for exclusion. Title-abstract and full text screening were piloted beforehand. A guideline for both screening stages, comprising the research question and the PEOS -criteria supported the reviewers` decision -making process.

All other searches, comprising the Web of Science search, the updated database searches, the fast forward search, all Google Scholar searches, and the hand searches were carried out by one reviewer (AF, CS, or VCM) and when a reference seemed to be of relevance, a second reviewer screened the full text for its eligibility (AF, CS, or VCM).

2.4. Extracting and presenting the data

2.4.1. Data extraction

Data of all included studies were extracted in duplicate, meaning that data were extracted by one reviewer (AF or CS) and checked by a second reviewer (AF or CS). Therefore, a standardized data extraction sheet was used. Categories of interest were information on reference (e.g., publication year, journal), study theory (e.g., study design, research question), practical issues (e.g., study course, statistical methods), population (e.g., definition, recruitment, characteristics), exposure/experiment/intervention (e.g., type, operationalization), outcome (e.g., type, operationalization), results (e.g., main results, moderator/mediator effects), others (e.g., author´s conclusions and limitations, conflict of interest, funding). The process was piloted beforehand.

2.4.2. Data analysis

2.4.2.1. Characteristics of the scientific literature. Study characteristics of

Table 2
Search strategy for MEDLINE via Ovid.

Step	Search terms
1	(wind.mp.) or (exp wind/)
2	(technology.mp.) or (technologies.mp.) or (exp energy-generating resources/) or (exp electric power supplies/) or (exp power plants/) or (exp renewable energy/)
3	and/1,2
4	(wind.mp.) adj5 ((converter.mp.) or (converters.mp.) or (facility.mp.) or (facilities.mp.) or (farm.mp.) or (farms.mp.) or (generator.mp.) or (generators.mp.) or (mill.mp.) or (mills.mp.) or (park.mp.) or (parks.mp.) or (plant.mp.) or (plants.mp.) or (station.mp.) or (stations.mp.) or (turbine.mp.) or (turbines.mp.))
5	or/3,4
6	(health.mp.) or (exp occupational health/) or (exp environmental health/) or (diagnosis.mp.) or (complaint.mp.) or (complaints.mp.) or (disease.mp.) or (diseases.mp.) or (disorder.mp.) or (disorders.mp.) or (symptom.mp.) or (symptoms.mp.) or (syndrome.mp
7	(risk.mp.) or (hazar$.mp.) or (safety.mp.) or (accident.mp.) or (accidents.mp.) or (injury.mp.) or (injuries.mp.)
8	(annoy$.mp.) or (exp anxiety/) or (anxiety.mp.) or (exp anxiety disorders/) or (exp depression/) or (depression.mp.) or (exp "quality of life"/) or (quality of life.mp.) or (sleep.mp.) or (exp sleep disorders/) or (exp burnout, professional/) or (burnout.mp.) or (burn out.mp.) or (exp stress, psychological)
9	or/6–8
10	and/5,9

interest were publication data, study design, study region, population of interest, follow-up, and investigated associations. Descriptive statistics (i.e. frequencies and percentages) were used to summarize the data. Further, the results were described as continuous text. Graphical elements such as bubble plots and bar charts should illustrate chronological sequences of different developments and a world map the geographical distribution of study regions.

2.4.2.2. Methodological aspects of the scientific literature. For all study types, it was checked, whether the reporting quality was sufficient for the appropriate study design, with special regard to objectives, research question, setting, population, exposure/intervention/experiment, outcome parameter, study methods, statistical methods, main findings, and the availability of a study protocol. Ethical issues – namely conflict of interest, funding, and ethics committee approval – were investigated. The appraisal was based on statements made by the study authors. For systematic reviews and content analyses, the evaluation of an ethics committee approval was not undertaken, since these study types use already published data. Further, the generalization of the studies was of interest, by assessing, whether the study results could be generalized to the general population in consideration of the study population, setting, and study region. Only for qualitative studies, this aspect was not investigated, since these are not intended to generate generalizable results.

Methodological aspects of interest for epidemiological observational studies and clinical observational studies on the topic were selection bias, information bias, and confounder bias. The estimation of a selection bias was based on the sampling processes and the response rate. If study participants were recruited by randomization or a cencus sampling and/or the study purpose was masked, and the response rate was higher than 50% or it has been assured that a lower response rate had no influence on the outcomes, for example proven by a non-responder analysis, then no selection bias was assigned. For case studies, the response rate was not evaluated, since this study design is not intended to obtain a representative sample. Thus, for case studies, the assessment of a selection bias only based on the sampling process. An information bias was judged for both, the exposure variables and the outcome parameters. No information bias for an exposure and outcome was allocated, if a valid and reliable as well as objective rather than subjective measurement instrument was used. Ideally, outcome parameters should not be causal attributed, to avoid drawing the attention to the exposure. In case of some outcomes such as annoyance, this is not always possible, as it requires the question about the exposure source. Subjective complaints should have been determined with validated questionnaires, and diseases with register data, insurance data, or a dotoral diagnosis. Studies that investigated associations of a specific wind turbine exposure with a health outcome should have included the following three confounders in their analyses: age, sex, and socioeconomic status. Study region and economic benefit from wind turbines were regarded as markers for the socioeconomic status. Confounders must have the following three characteristics: 1.) be an extraneous risk factor for the disease, 2.) be associated with the exposure under study in the source population, and 3.) not be affected by the exposure or the disease (Rothman et al., 2008). It was further examined, whether basic characteristics of the study population were reported.

The findings regarding these methodological aspects were summarized descriptively and tabularly with descriptive statistics using frequencies and percentages.

2.4.2.3. Study findings. Findings on annoyance prevalences are presented descriptively for observational studies which had no selection bias and which reported at least information on the age and sex of the population. The latter claim is of importance for the accuracy of the annoyance results to draw conclusions about their transferability. Results on associations between a wind turbine exposure and a health outcome are outlined, if the study had no selection bias, the exposure and the outcome exhibited no information bias, and the confounders age, sex, and socioeconomic status were considered in the appropriate analysis. The findings are sorted by exposures and health parameters. Further, study findings of scientific or political interest are summarized descriptively. These were results from experimental studies and on the influence of psychological attitudes and expectations on the health impact of wind turbines.

2.5. Collating the data

Collating of the results is done in order to identify implications of the study findings for policy, practice, or research (Khalil et al., 2016). The conclusions drawn in scoping reviews should be consistent with the review objectives and questions based upon the results (Khalil et al., 2016). In accordance with the scoping review methodology, research gaps are identified and recommendations for future research are given (Khalil et al., 2016).

2.6. Consultation exercise

No consultation exercise was undertaken.

3. Results

3.1. Study selection

Fig. 1 presents the study selection process of an overall scoping review investigating health effects of wind turbines in residential settings as well as in occupational settings. However, the number of finally included studies refers only to those concerning this paper about residential settings.

Eighty four papers met the inclusion criteria of the review in regard to residential settings. Of these, 30 articles were found with the initial database searches in MEDLINE, EMBASE, and CINAHL and 44 with the other searches in Google Scholar, in websites, through the fast-forward search, in reference lists, and with the snowball technique. The later executed Web of Science –search yielded 7 new studies and the database update from September 25th, 2017 3 additional studies. For two studies, there was a double publication of the same project. Thus, only the articles with more information were included (Arezes et al., 2015; Lane, 2013), and the other ones disregarded (Arezes et al., 2014; Lane et al., 2016).

For the initial database search in MEDLINE, EMBASE, and CINAHL, which was carried out by two independent reviewers, the agreement for title-abstract screening and full text screening was almost perfect, with a proportion of agreement of 0.97 and 0.90, and a Cohen's Kappa value of 0.82 and 0.81, respectively.

3.2. Study characteristics

3.2.1. General characteristics of the body of evidence

84 publications were included, which originate from 68 conducted studies. For eight of the 68 original studies more than one paper was published. Most papers were published as peer reviewed journal articles (n = 64). Of the 68 original studies, most were cross-sectional studies (n = 30) and experimental studies (n = 23). Only two original studies, with two published articles each, had a follow-up.

In order not to interfere with the reading flow, the references of all included studies are cited in Fig. 2.

Detailed characteristics for each individual study can be found in the appropriate Supplemental file.

More details about general characteristics of the body of evidence are outlined in an Evidence Map (see Table 3).

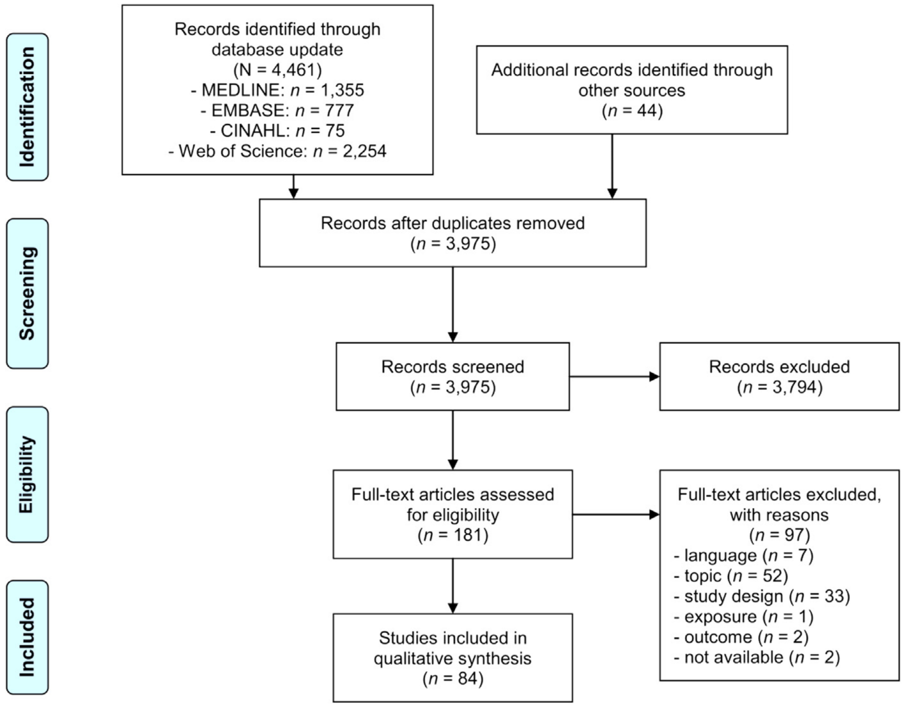

Fig. 1. PRISMA flow chart.

3.2.2. Chronical developments and spatial distribution of the body of evidence

The number of publications that issued health effects of wind turbines in residential settings increased since 2000, but this increase of research is not linear. A strong rise of articles identified in this scoping review occurred since 2012. Of all included studies, 85.7% were published 2010 or later. The chronical development of the scientific landscape is outlined in Table 3 and in Fig. 3.

The original studies were conducted in Europe (n = 32), the Pacific region (n = 18), North America (n = 12), and Asia (n = 45). The countries with at least five publications are Australia, New Zealand, Canada, Sweden, Poland, and the United States. The geographical distribution of the studies is illustrated in an Evidence Map and in a World Map (see Table 3 and Fig. 4).

3.2.3. Investigated exposures and associations

Noise as the most investigated wind turbine exposure was issued in 68 articles. Its steady research started in 2007. Most papers on it were published in 2013 and 2016. The main focus in the investigation of noise of wind turbines lies on noise annoyance, sleep disorders, quality of life, general health, and mental health problems. Articles describing the health impact of visual features of wind turbines were irregularly published from the year 2000 onwards. Its research increased in 2012 and most publications were released in 2016. Shadow flicker was the visual feature that was mostly assessed, followed by visibility, reflections, a changed view, blinking lights, and rotor blade movements. Annoyance was investigated for all visual wind turbine-related aspects. Further, for shadow flicker, mental health and physical health as well as health effects in general, and for visibility, sleep disorders, quality of life, emotional reactions, and symptoms which are postulated to be part of the “Wind Turbine Syndrome” were examined in one study each. The combined impact of auditive and visual features of wind turbines was experimentally examined first in a 2012 published study and outlined in further two experimental studies, targeting noise and visual annoyance, cognitive and affective outcomes, and sound stress. The first scientific investigation on the health impact of wind turbine infrasound was published in 2013. No observational studies, but 7 experimental studies were identified, that studied its effects on physical symptoms, affective symptoms, the activation level, and noise annoyance. In addition, 2 systematic reviews reported as well that there was no appropriate evidence from field studies. Health effects of vibrations of wind turbines were surveyed only subjectively in two cross-sectional studies. Two systematic reviews concluded that evidence on the health impact of low-frequency noise is missing. Another systematic review found a lack of evidence concerning the health impact of electromagnetic radiation.

Detailed information about all investigated associations, that are of interest for this scoping review, are presented in an Evidence Map

(Ambrose et al., 2012), (Arezes et al., 2015), (Arra et al., 2014), (Bakker et al., 2012), (Blanes-Vidal and Schwartz, 2016), (Bockstael et al., 2012), (Bolin et al., 2012), (Bolin et al., 2014), (Botelho et al., 2017), (Chapman et al., 2013), (Crichton and Petrie, 2015a), (Crichton and Petrie, 2015b), (Crichton et al., 2013a), (Crichton et al., 2013a), (Crichton et al., 2015), (Feder et al., 2015), (Hafke-Dys et al., 2016), (Harry, 2007), (Hoen et al., 2010), (Hübner and Pohl, 2010), (Inagaki et al., 2015), (Ioannidou et al., 2016), (Iser, 2004), (Jalali et al., 2016a), (Jalali et al., 2016b), (Jalali et al., 2016c), (Kageyama et al., 2016), (Kaldellis et al., 2013), (Kasprzak et al., 2014), (Klaeboe and Sundfor, 2016), (Krogh et al., 2011), (Kuwano et al., 2013), (Lane, 2013), (Lee et al., 2011), (Maehr et al., 2015), (Maffei et al., 2013), (Magari et al., 2014), (Mausfeld et al., 2000), (McBride et al., 2013), (Merlin et al., 2013), (Michaud et al., 2016a), (Michaud et al., 2016b), (Michaud et al., 2016c), (Michaud et al., 2016d), (Morris, 2012), (Mroczek et al., 2012), (Mroczek et al., 2015), (Mulvaney et al., 2013), (Nissenbaum et al., 2012), (Onakpoya et al., 2015), (Paller, 2014), (Pawlaczyk-Luszczynska et al., 2014a), (Pawlaczyk-Luszczynska et al., 2014b), (Pedersen and Persson Waye, 2004), (Pedersen and Persson Waye, 2007), (Pedersen et al., 2007), (Pedersen et al., 2009), (Pedersen et al., 2010), (Persson Waye and Agge, 2000), (Persson Waye and Öhrström, 2002), (Phipps, 2007), (Pierpont, 2009), (Pohl et al., 2012), (Ruotolo et al., 2012), (Schafer, 2013), (Schaffer et al., 2016), (Schmidt and Klokker, 2014), (Schneider, 2012), (Schneider, 2013), (Seong et al., 2013), (Shepherd et al., 2011), (Song et al., 2016), (Taylor et al., 2013a), (Taylor et al., 2013), (Tonin et al., 2016), (Thorne, 2012), (van den Berg et al., 2008), (Van Renterghem et al., 2013), (Voicescu et al., 2016), (Walker et al., 2014), (Walker et al., 2015), (Yano et al., 2013), (Yu et al., 2017), (Zajamsek et al., 2014)

Fig. 2. References of included studies.

Table 3
Evidence Map on study characteristics of the body of evidence.

Publications (*n* = 84)			**n**	**%**
Peer Review	yes		64	76.2
	no		20	23.8
Publication type	Journal article		64	76.2
	Self-publication via the internet		8	9.5
	Conference paper		4	4.8
	Research report		4	4.8
	Master thesis		2	2.4
	Book		2	2.4
Publication years	2000–2004		5	6.0
	2005–2009		7	8.3
	2010–2014		44	52.4
	2015–to date		28	33.3
Language	English		82	97.6
	German		2	2.4
Original studies (*n* = 68)			**n**	**%**
Study design	Cross-sectional study		30	44.1
	Experimental study		23	33.8
	Case studies		5	7.4
	Systematic review		4	6.0
	Prospective cohort study		1	1.5
	Qualitative study		1	1.5
	Mixed-methods study		1	1.5
	Intervention study		1	1.5
	Content analysis		1	1.5
	Repeated cross-sectional study		1	1.5
Follow-up	yes		2	2.9
	no		66	97.1
Study region	Continent	Europe	32	47.1
		Pacific region	18	26.5
		North America	12	17.6
		Asia	5	7.4
	Country	Australia	10	14.7
		New Zealand	8	11.8
		Canada	7	10.3
		Sweden	7	10.3
		Poland	5	7.4
		United States	5	7.4
		United Kingdom	4	5.9
		Denmark	3	4.4
		Germany	3	4.4
		Italy	2	3.0
		The Netherlands	2	3.0
		Portugal	2	3.0
		South Korea	2	3.0
		Japan	2	3.0
		Belgium	1	1.5
		China	1	1.5
		Greece	1	1.5
		Norway	1	1.5
		Switzerland	1	1.5
	Not specified		1	1.5
Population	Residents		44	64.7
	Study subjects		23	33.8
	Acousticians		1	1.5

Abbreviation: *n* number of studies.
Symbol: % percentage.

(Table 4) and information about the historical distribution of publication on each specific wind turbine exposure in a bubble plot (Fig. 5).

3.3. Methodological aspects of the body of evidence

3.3.1. Methodological aspects of all included studies

An Evidence Map on the methodological aspects of the included studies is presented in Table 5.

The reporting quality of only 39 of the 84 included publications was judged to be sufficient (46.4%) and insufficient in the remaining 45 papers (53.6%).

The study findings of 21 of 83 considered publications – except the qualitative study – seemed to be generalizable (25.3%), whereas this was not true for 56 publications (67.5%). For some publications, it was unclear whether the results were generalizable, because no information is given about the electrical power of the wind turbines and, thus, it is unclear whether these were outdated (Bakker et al., 2012; Pedersen and Persson Waye, 2007; Pedersen et al., 2009, 2010; van den Berg et al., 2008).

Thirty articles declared to have no personal conflict of interest (35.7%). For 54 publications (64.3%), no appropriate statement was given. No study reported to exhibit a conflict of interest.

In regard to funding, none of the studies seemed to have a financial conflict of interest. For 45 articles, it was evaluated that there was no conflict of interest due to funding (53.6%) and for 39 publications, it was unclear (46.4%).

Fifty-four studies did not report whether an ethics committee approval existed (68.4%). Twenty-four studies received such an approval (30.4%). One study explained that an ethics approval was "not required due to the low sensitivity of the questions and appropriate provisions for anonymity and confidentiality of the households“ (Phipps, 2007).

3.3.2. Methodological aspects of observational studies

Fifty percent of the observational studies were assessed to have no selection bias, since census or random selection occurred, and the response rate was of no concern. All five case studies presented a selection bias due to convenience sampling (Ambrose et al., 2012; Harry, 2007; Pierpont, 2009; Thorne, 2012; Zajamsek et al., 2014). The 3 prospective cohort studies were judged to have a selection bias due to a low response rate, despite the cencus sampling (Jalali et al., 2016a, 2016b, 2016c). Of the cross-sectional studies, 17 showed a selection bias, 17 showed no selection bias, and for 9 this was unclear.

Twenty-one observational studies (38.9%) were assessed to have an information bias regarding the exposure variables, and 22 studies (40.7%) had none. Eleven articles examined different exposure variables, of which some presented an information bias and some did not (Jalali et al., 2016a, 2016c; Magari et al., 2014; Michaud et al., 2016b; Mroczek et al., 2015; Pawlaczyk-Luszczynska et al., 2014a, 2014b; Pedersen and Persson Waye, 2004; van den Berg et al., 2008; Walker et al., 2014, 2015). Concerning the exposure "noise", most observational studies applied only presence or distance estimates rather than modelling or real-time measurements. Visual aspects were mainly determined with subjective questions, and thus resulted in an information bias. One study modelled the shadow flicker exposure and thus was able to calculate associations and not only prevalence rates (Voicescu et al., 2016), and two others evaluated aircraft obstruction marking exposure objectively (Hübner and Pohl, 2010; Pohl et al., 2012).

In 29 observational studies, the investigated outcome parameters exhibited no information bias (53.7%), whereas an information bias in relation to the investigated outcome parameters occurred in 12 studies (22.2%). Thirteen observational studies (24.1%) examined several outcomes, which were judged differently in regard to an information bias (Blanes-Vidal and Schwartz, 2016; Hübner and Pohl, 2010; Jalali et al., 2016a; Michaud et al., 2016b; Mroczek et al., 2015; Mulvaney et al., 2013; Paller, 2014; Pedersen and Persson Waye, 2004; Pohl et al., 2012; Song et al., 2016; van den Berg et al., 2008; Walker et al., 2014, 2015).

Overall, 15 of the 54 observational studies (27.8%) considered the confounders age, sex, and socioeconomic status in their data analysis. None of the case studies or prospective cohort studies included these factors in their data analyses. Basic information about the study population – at least information about the participants` age and sex – were reported in 39 observational studies – or at least in another paper of the same original study (72.2%).

Detailed information on each study are outlined in the appropriate supplemental file.

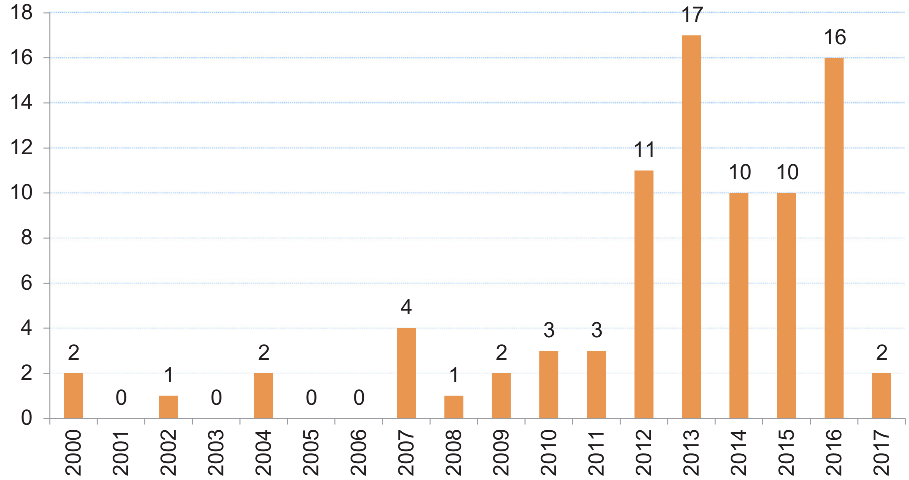

Fig. 3. Number of included articles per year.

3.4. Study findings

3.4.1. Annoyance prevalence data

Of seventeen observational studies, which had no selection bias and provided information about the population's sex and age, seven contained annoyance prevalence data (Bakker et al., 2012; Magari et al., 2014; Michaud et al., 2016b; Pawlaczyk-Luszczynska et al., 2014a; Pedersen and Persson Waye, 2004, 2007; van den Berg et al., 2008).

Six studies reported a varying prevalence of noise annoyance among residents living in the vicinity of wind turbines between 4.11% and 45% (Bakker et al., 2012; Magari et al., 2014; Michaud et al., 2016b; Pedersen and Persson Waye, 2004, 2007; van den Berg et al., 2008). Prevalences to shadow flicker annoyance varied greatly between 7.8% and 31% in 5 cross-sectional studies (Magari et al., 2014; Michaud et al., 2016b; Pawlaczyk-Luszczynska et al., 2014a; Pedersen and Persson Waye, 2004; van den Berg et al., 2008). Between 7% and 15% of surveyed residents living in the vicinity of wind turbines felt annoyed by reflections of the rotor blades (Magari et al., 2014; Pawlaczyk-Luszczynska et al., 2014a; Pedersen and Persson Waye, 2004). High visual annoyance was 12.9% in one cross-sectional study (Michaud et al., 2016b). Three cross-sectional studies demonstrated a prevalence of annoyance to a changed view by wind turbines between 14% and 28% (Magari et al., 2014; Pedersen and Persson Waye, 2004; van den Berg et al., 2008). The prevalence of high annoyance to blinking lights was around 10% in one cross-sectional study (Michaud et al., 2016b). One cross-sectional study investigated the annoyance to the movement of the wind turbines` rotor blades, which annoyed 27% of the participants (van den Berg et al., 2008). There were 2 cross-sectional studies regarding wind turbine vibrations, of which one found an overall annoyance prevalence of 4% (van den Berg et al., 2008) and one a high annoyance prevalence of 1.5% (Michaud et al., 2016b).

3.4.2. Findings on associations between wind turbine exposures and health outcomes

Eight studies were identified, which reported on at least one association between a wind turbine exposure and a health outcome and which had no selection bias, no information bias in terms of the exposure and outcome, and which considered age, sex, and socioeconomic status as possible confounders in the appropriate analyses (Feder et al., 2015; Michaud et al., 2016a, 2016b, 2016c; Pedersen and Persson Waye, 2007; Pedersen et al., 2010; van den Berg et al., 2008; Voicescu et al., 2016).

Four cross-sectional studies found a statistically significant association between wind turbine noise and noise annoyance ($p < 0.05$) (Michaud et al., 2016b; Pedersen and Persson Waye, 2007; Pedersen et al., 2010; van den Berg et al., 2008). No relationship between wind

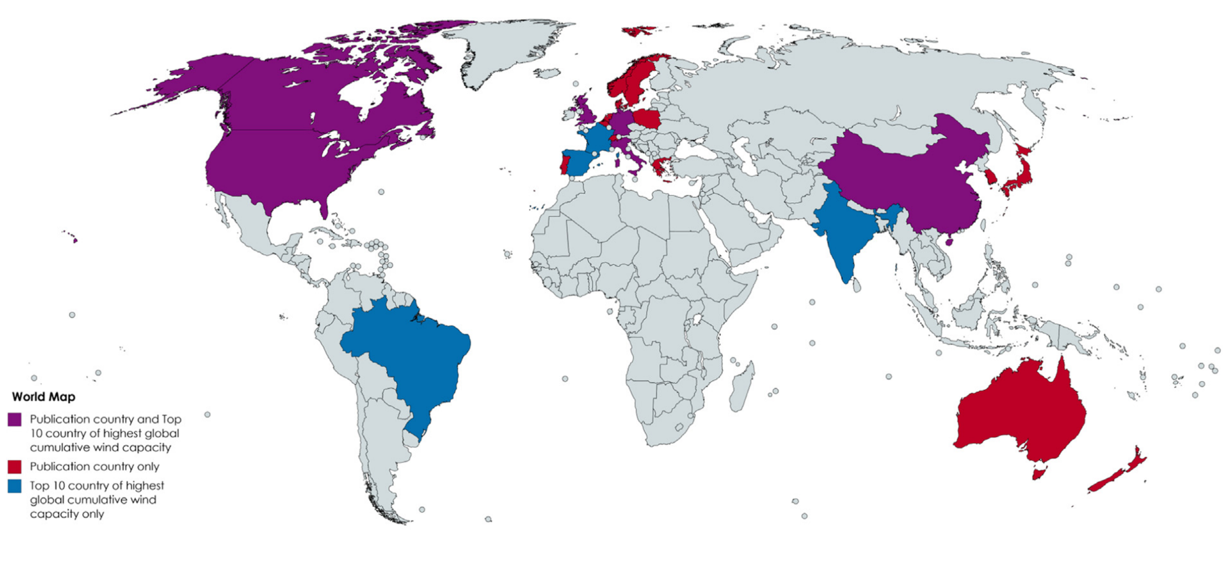

Fig. 4. World map with countries where studies were conducted and the Top 10 countries of global cumulative wind capacities (created with mapchart.net).

Table 4
Evidence Map on all investigated associations of the body of evidence.

Exposure	n	Outcome (in regard to the exposure)	n	%
Noise	68	**Annoyance**	43	63.2
		Sleep disorders	19	27.9
		Quality of life, satisfaction with life	17	25.0
		General health	13	19.1
		Mental health problems	12	17.6
		Headaches/Migraines	8	11.8
		Tinnitus	6	8.8
		Dizziness/ Balance problems	5	7.4
		Excessive tiredness/ fatigue	5	7.4
		Cardiovascular disorders	4	5.9
		Concentration deficits	3	4.4
		Nausea	3	4.4
		Wind Turbine Syndrome	3	4.4
		Diabetes	2	3.0
		Arthritis	1	1.5
		Asthma/bronchitis/COPD	1	1.5
		Blurred vision	1	1.5
		Chest pain	1	1.5
		Chronic disease	1	1.5
		Chronic pain	1	1.5
		External auditory canal sensation	1	1.5
		Restless legs syndrome	1	1.5
		Visceral Vibratory Vestibular Disturbance	1	1.5
		Brain waves	1	1.5
Shadow flicker	13	**Annoyance**	12	92.3
		Cognitive stress	1	8.3
		Mental well-being	1	8.3
		Physical well-being	1	8.3
		Health effects in general	1	8.3
Visibility	7	**Annoyance**	4	57.1
		Sleep disorders (sleep disturbance, daytime sleepiness, insomnia)	1	14.3
		Quality of life, satisfaction with life	1	14.3
		Emotional reactions (valence, arousal)	1	14.3
		10 symptoms which are postulated to be part of the "Wind Turbine Snydrome"	1	14.3
Infrasound	9	**Physical symptoms**	5	55.6
		Health effects in general	2	22.2
		Affective impact (mood)	2	22.2
		Activation level	1	11.1
		Noise annoyance	1	11.1
Reflections	4	**Annoyance**	4	100.0
Changed view	3	**Annoyance**	3	100.0
Blinking lights	3	**Annoyance**	3	100.0
		Psychological and somatic symptoms	1	33.3
		Stress effects	1	33.3
Combination of noise and visual impact	3	**Noise annoyance**	3	100.0
		Visual annoyance	2	66.7
		Cognitive impact	2	66.7
		Affective impact (mood)	1	33.3
		Sound stress	1	33.3
Low-frequency noise	2	**Health effects in general**	2	100.0
Rotor blade movement	2	**Annoyance**	2	100.0
Vibrations	2	**Annoyance**	2	100.0
Stage of development	1	**Psychological disorders**	1	100.0
		Quality of life	1	100.0
Electromagnetic radiation	1	**Health effects in general**	1	100.0

Abbreviations: *COPD* chronic obstructive pulmonary disease, *n* number of studies.
Symbol: *%* percentage.

turbine noise and a worsened quality of life was found in one cross-sectional study ($p > 0.05$) (Feder et al., 2015). One cross-sectional study observed no association between wind turbine noise and sleep disturbance ($p > 0.05$) (Michaud et al., 2016c). One cross-sectional study declared that wind turbine noise was not statistically significantly associated with biophysiological variables of sleep ($p > 0.05$), except with wake after sleep onset (Michaud et al., 2016c). One cross-sectional study showed no association between wind turbine noise and (medication for) depression or anxiety ($p > 0.05$) (Michaud et al., 2016b). One cross-sectional study outlined no association between wind turbine noise and stress ($p > 0.05$) (Michaud et al., 2016a). One cross-sectional study revealed a statistically significant increase of annoyance to shadow flicker with increasing exposure ($p < 0.05$), but this association was not solely predicted by shadow flicker itself, but also by personal variables such as demographics, chronic diseases, or attitude towards wind turbines (Voicescu et al., 2016).

3.4.3. *Findings from experimental studies*

Other reviews on the topic of residential health implications of wind turbines did not systematically include and analyze the results of experimental studies. Experimental studies were eligible in this scoping review, and their most striking findings are described in this section, except the publications on the impact of different expectations on the effect of experimental infrasound, which are outlined under another headline.

3.4.3.1. The impact of experimental wind turbine noise. Ten experimental studies investigated the effect of different wind turbine -related and -unrelated variables on noise annoyance. A masking effect of background noises on noise annoyance was shown if the sound level of a wind turbine was less than 50 dB and less than the background sounds (Bolin et al., 2012). Concerning amplitude modulation, one experimental study found an association of noise annoyance with the fluctuation frequency range ($p < 0.05$), but not with the periodicity of the amplitude modulation ($p > 0.05$) (Schaffer et al., 2016); one experimental study an association of noise annoyance with the modulation depth ($p < 0.05$), but not with the modulation frequency or the modulation intermittence ($p > 0.05$) (Ioannidou et al., 2016); one experimental study confirmed an association between modulation depth and noise annoyance ($p < 0.05$), in addition to the association between the sound pressure level and noise annoyance (Lee et al., 2011); and one experimental study pointed out an association between modulation rate or modulation depth and noise annoyance ($p < 0.05$) (Hafke-Dys et al., 2016). Influencing factors of noise annoyance were the maximal sound pressure level, fluctuation strength, the energy-equivalent continuous sound pressure level, and loudness as well as the position of the listener (Seong et al., 2013), and noise sensitivity (Bolin et al., 2014). The most frequently stated noise descriptors for annoying noise were swishing, lapping, and whistling, and the less annoying ones were low frequency noise and grinding (Persson Waye and Öhrström, 2002). Compared to original wind turbine noise, modified sounds with or without tonal character were felt as being less annoying (Persson Waye and Agge, 2000). Two experimental studies illustrated that wind turbine noise was rated to be more annoying than road traffic noise (Schaffer et al., 2016; Van Renterghem et al., 2013).

3.4.3.2. The impact of experimental wind turbine infrasound. There was only one study showing the impact of pure experimental wind turbine infrasound – independent whether the study subjects were exposed to different expectations about the effect of infrasound. The article showed a statistically significant change of the high activation level after 20 min of infrasound exposure, but no such change in relation to the general activation, general deactivation, and deactivation – sleep according to categories of the Thayer's test (Kasprzak et al., 2014). Another experimental study initially examined the effect of wind turbine noise on a physiological parameter, and more precisely on brain waves

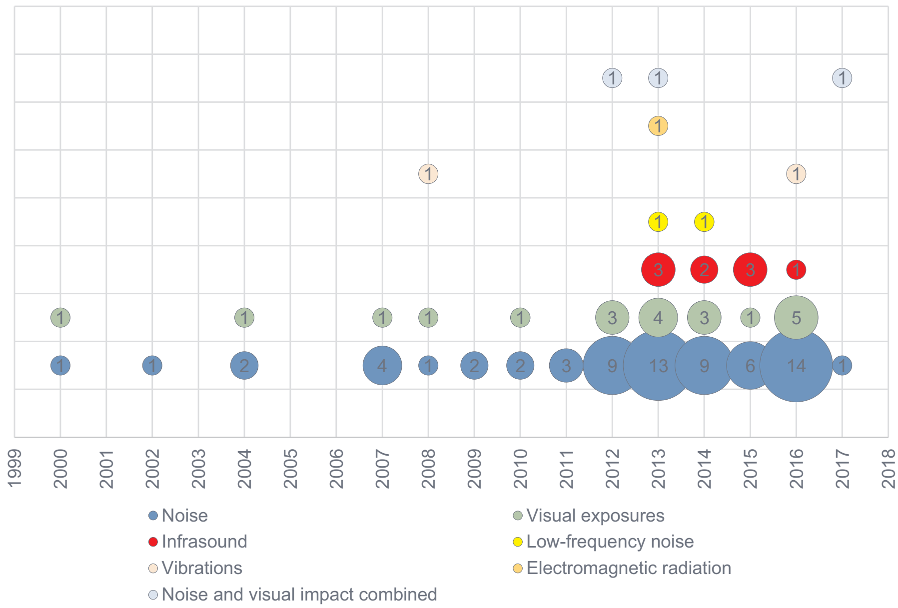

Fig. 5. Number of investigated wind turbine exposures per year.

measured with an electroencephalogram (Inagaki et al., 2015). But the main finding relates to the infrasound exposure and is, that the alpha-wave, which indicates a relaxed and concentrated state, was lowest for the artificially created frequency band of 20 Hz, and the beta-wave, which shows a strain state, highest for this 20 Hz frequency band.

3.4.3.3. The impact of experimental visual wind turbine features. One experimental study showed that periodic shadow flicker did not lead to a substantial elevation of annoyance, but to an increase of demands on psychological and physical resources among study subjects (Mausfeld et al., 2000). The intensity of these effects was influenced by the duration of the shadow flicker and the age of the study subjects, and moderated by the subjective shadow flicker annoyance. Another experimental study demonstrated that pictures of wind turbines were rated just like those of churches in regard to valence and arousal ($p > 0.05$), but better compared to those of pylons and power plants ($p < 0.05$) (Maehr et al., 2015).

3.4.3.4. The impact of combined experimental exposure to auditive and visual emissions of wind turbines. The combination of auditive and visual exposure to wind turbines had an influence on backward counting and distance estimation ($p < 0.05$), but not on short-term verbal memory ($p > 0.05$) according to the results of one experimental study (Ruotolo et al., 2012). In contrast, another experimental study found no impact of a combined visual and auditory wind turbine exposure on backward counting and on mood ($p > 0.05$) (Yu et al., 2017). Auditory emissions influenced visual annoyance, and visual emissions influenced noise annoyance ($p < 0.05$) (Ruotolo et al., 2012). Another experimental study found that this exposure setting impacted visual annoyance and noise annoyance ($p < 0.05$), and that both annoyance reactions were correlated with each other (Yu et al., 2017). Visual annoyance and noise annoyance were both influenced by noise sensitivity ($p < 0.05$) (Ruotolo et al., 2012). Noise annoyance was associated with the number of and distance to wind turbines ($p < 0.05$), but not with the color of wind turbines ($p > 0.05$); and sound stress was associated with the distance to and color of wind turbines ($p < 0.05$), but not with the number of wind turbines ($p > 0.05$) (Maffei et al., 2013).

3.4.4. Findings regarding the influence of psychological attitudes and expectations on the health impact of wind turbines

Results of a qualitative study illustrated that residents who felt that wind turbines disturbed their privacy, experienced wind turbine noise, shadow flicker, and constant rotor blade movement as an intrusion of their recreational areas and houses; had a feeling of uneasiness, fatigue, and helplessness; and experienced a serious loss of well-being and quality of life (Pedersen et al., 2007). In contrast, residents that felt no intrusion into their privacy due to wind turbines believed that they could shut wind turbines mentally out and control their reactions even though they could not physically stop wind turbines from running, and were not concerned by the noise, shadow flicker, and movements of the rotor blades.

The findings of two mixed-methods studies showed that negative health implications and negative consequences on quality of life due to wind turbines were higher in a community of wind turbine opponents than in a supporting community (Walker et al., 2014, 2015).

Six experimental studies on the expectation about the impact of wind turbine infrasound exposure were retrieved. People that received information on the therapeutic effects of infrasound prior to exposure felt less annoyed than people who received information on adverse effects of infrasound ($p < 0.05$) (Crichton et al., 2015). Expectations about infrasound impact had an influence on the occurrence of physical symptoms and negative mood items, meaning that negative expectations increased and positive expectations decreased symptoms and negative mood items ($p < 0.05$) (Crichton et al., 2013a). If negative expectations were further triggered with a biological explanation for symptom development, symptoms and negative mood items got even worse ($p < 0.05$); but if these were triggered with information about the nocebo effect, symptoms and negative mood items could be reversed to baseline values ($p < 0.05$) (Crichton and Petrie, 2015a). Negative expectations about health risks of wind turbine infrasound and resulting deterioration of physical symptoms and negative mood items could be reversed by positively framed health information ($p < 0.05$) (Crichton and Petrie, 2015b). Another study found that in case of the expectation that wind turbine infrasound produces health effects, specific symptoms were caused, both during infrasound and sham infrasound exposure ($p < 0.05$); and in case of no such expectations, no symptomatic changes during (sham) infrasound exposure were observed ($p > 0.05$) (Crichton et al., 2013b). It was shown that the expectation about resulting health effects of infrasound exposure had a statistically significant influence on the number and intensity of symptom occurrence ($p < 0.05$), not the exposure of infrasound itself ($p > 0.05$). A later conducted study confirmed these findings (Tonin

Table 5
Evidence Map on methodological aspects of the body of evidence.

		n	%
All publications (*n* = 84)			
Reporting quality sufficient? (*n* = 84)	yes	39	46.4
	no	45	53.6
	unclear	0	0.0
Generalization* (*n* = 83)	yes	21	25.3
	no	56	67.5
	unclear	6	7.2
Personal conflict of interest (*n* = 84)	yes	0	0
	no	30	35.7
	unclear	54	64.3
Conflict of interest through funding (*n* = 84)	yes	0	0.0
	no	45	53.6
	unclear	39	46.4
Ethics committee approval** (*n* = 79)	yes	24	30.4
	no	1	1.2
	unclear	54	68.4
Observational studies*** (*n* = 54)			
Selection bias	yes	27	50.0
	no	17	31.5
	unclear	10	18.5
Infromation bias – Exposure	yes	21	38.9
	no	22	40.7
	unclear	0	0.0
	mixed****	11	20.4
Infromation bias – Outcome	yes	12	22.2
	no	29	53.7
	unclear	0	0.0
	mixed*****	13	24.1
Consideration of age, sex, and SES as confounders	yes	15	27.8
	no	39	72.2
Reporting of basic information of the population (sex, age)****	yes	35	64.8
	no	15	27.8
	in another paper of the same original study	4	7.4

Abbreviation: *n* number of studies, *SES* socioeconomic status.
Symbol: *%* percentage.
* The generalization of the one included qualitative study was not judged, since this study type is not intended to generate generalizable results.
** For the four included systematic reviews and the one included content analysis, the category "ethics committee approval" was not assessed, since these study types use already published data.
*** Observational studies comprised prospective cohort studies, repeated cross-sectional studies, cross-sectional studies, case studies, and mixed-methods studies.
**** The study investigated different exposure variables, which were judged differently within this scoping review – in regard to an information bias of these exposures.
***** The study investigated different outcome parameters, which were judged differently within this scoping review – in regard to an information bias of these outcomes.
****** If basic information – at least of age and sex – of the study population were reported in another paper of the same original study, this counts as well.

et al., 2016).

A content analysis pointed out that the rate of noise and health complaints from residents living near wind farms in Australia increased since 2009, because anti wind farm groups focused more strongly on corresponding health issues (Chapman et al., 2013).

3.5. Other findings

This scoping review retrieved no field studies on the health implications of wind turbine infrasound. This finding was confirmed by 2 systematic reviews (Merlin et al., 2013; Schmidt and Klokker, 2014). No primary studies on the health effects of low-frequency noise of wind turbines were found within this scoping review. Two systematic reviews also failed to identify any appropriate primary studies (Merlin et al., 2013; Schmidt and Klokker, 2014). One systematic review found no studies on electromagnetic radiation and health (Merlin et al., 2013). Likewise, this scoping review identified no relevant primary studies.

Findings of studies that did not fulfil the established quality criteria in regard to prevalence and associations as well as findings from systematic reviews and intervention studies are outlined in a supplemental file.

4. Discussion

4.1. Body of evidence

4.1.1. Summary of the body of evidence

Eighty-four articles that varied significantly in methods and assessed associations met the inclusion criteria of this scoping review. The body of evidence around health effects resulting from wind turbine exposures is diverse, increased sharply since 2010, and is still growing. The vast majority of research was conducted in OECD Member countries such as Australia, New Zealand, Canada, or Sweden. Wind turbine noise was the most frequently investigated exposure. Annoyance reactions were assessed in many studies, mostly regarding wind turbine noise, but also regarding shadow flicker, blinking lights, or vibrations. In connection with visual aspects of wind turbines such as shadow flicker or blinking lights, most appropriate epidemiological studies investigated annoyance, but few other symptoms or diseases. No infrasound field studies were identified, as was literature on low-frequency noise, electromagnetic radiation, and ice throw. In general, studies on the impact of wind turbines on clinically apparent health effects, meaning clinical diseases, are sparse.

4.1.2. Chronical developments

The increasing number of publications issuing the residential health impact of wind turbines could be due to the linear increase of the global cumulative capacity of wind energy since 2001 (Fig. 6), but also due to the increasing number of medical publications in general (Bastian et al., 2010). That the growth of publication is non-linear could be explained by the relatively small number of identified papers. As the database search update took place in September 2017, the number of investigations from 2017 is rather low. The reason for the strong increase of scientific literature since 2012 may lie in an intensified public attention – by residents, opponents, politics, or the scientific community. A content analysis that was included in this scoping review pointed out that 90% of wind turbine noise and health complaints in Australia were made after 2009, even though wind farms existed since 1993 and 69% of the wind farms started their operation prior to 2009 (Chapman et al., 2013). The authors explained this elevated rate with the increased awareness and proclamation of corresponding health issues by anti wind farm groups. Another content analysis observed that the number of fright factors about wind turbine health effects used in local newspapers increased since the implementation of the so called Green Energy Act in Ontario, Canada (Deignan et al., 2013), which could result in fear, concerns, and anxiety in the community.

4.1.3. Spatial distribution

The ranking order of continents, where most research on the topic was conducted, namely Europe, the Pacific region, North America, and Asia, does not correspond with the hierarchy of continents in regard to the highest installed cumulative wind capacity, with Asia (228.5 GW) heading, followed by Europe (178.1 GW), North America (105,3 GW), Latin America/Caribean (17.9 GW), the Pacific Region (5.2 GW), and Africa (4.5 GW) (GWEC, 2018). Of all the 19 countries that were identified as study regions, 6 of these are amongst the Top 10 countries with the highest cumulative capacity of wind energy globally: China, the United States, Germany, United Kingdom. Canada, and Italy. In the United States and Canada with one of the highest cumulative wind capacity of 89.1 GW and 12.2 GW (GWEC, 2018), respectively, at least five studies on health effects of wind turbines in residential settings were conducted. Only one study was conducted in China, that is by far the leading country in regard to cumulative wind capacity (188.2 GW)

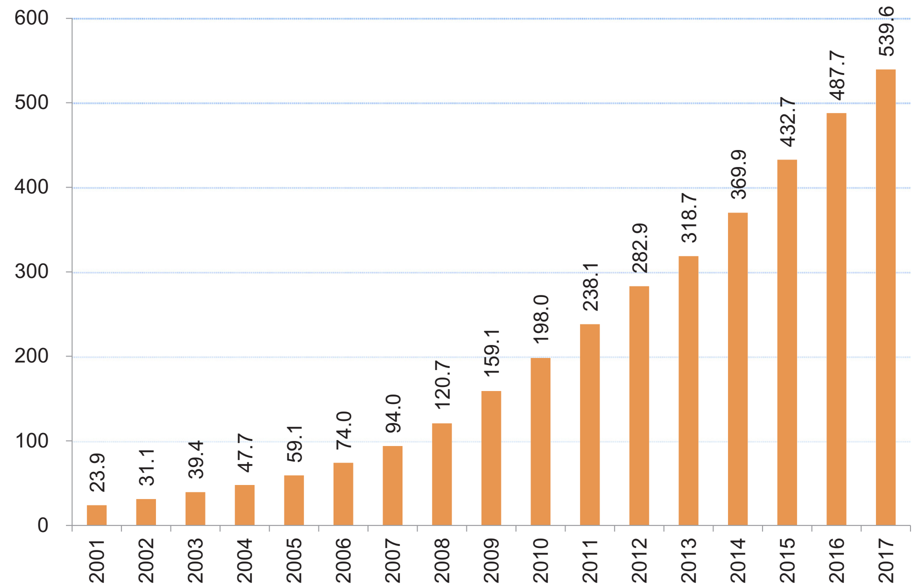

Fig. 6. Global cumulative installed wind capacity (in gigawatt) (GWEC, 2018).

(GWEC, 2018). Also in Germany, with the third highest capacity of wind energy worldwide (56.1 GW), and in Italy, ranking 10th place (9.5 GW), only two and one appropriate studies, respectively, were executed (GWEC, 2018). Four articles are from the United Kingdom, that holds the 6th place among the Top 10 countries. Even though Australia and New Zealand have a relatively low capacity of installed wind power of 4.6 GW and 623.0 GW (GWEC, 2018), respectively, compared to the global Top 10 countries and most European countries, most included studies were conducted there. One reason for this high number of research papers could be a high public resistance towards wind turbine projects in these countries that is – in reply to this – taken up by scientists. As already pointed out, the number of health complaints due to wind farms raised in Australia after 2009 (Chapman et al., 2013). In New Zealand, the negative perception of wind energy projects is increasing (Graham et al., 2009). The same circumstance of an elevated research activity about the health impact of wind turbines compared to other countries could count for Canada, since it is a highly debated political issue there (Deignan et al., 2013; Watson et al., 2012). There is no obvious reason, why so many studies were executed in Sweden and Poland, although both countries rank only 7th and 8th place in Europe regarding installed wind capacity with 6.7 GW and 6.4 GW, respectively, as no evident community opposition is documented. The high amount of Swedish publications on residential health effects of wind turbines could be justified by the work of two Swedish researchers, Eja Pedersen and Kerstin Persson Waye, whom were one of the first scientists studying intensively on the topic since the 2000s (Pedersen and Persson Waye, 2004, 2007; Persson Waye and Agge, 2000; Persson Waye and Öhrström, 2002).

4.2. Study findings

4.2.1. Comparison of annoyance prevalences and association data between higher-quality and lower-quality studies

In the following section, studies which fulfilled the established criteria for the reporting of annoyance prevalence and associations are referred to as studies of higher methodological quality. Studies not fulfilling these criteria are designated as studies of lower methodological quality. Please note, that these designations only comprise the appropriate results, not the overall methodology of a study. For most findings, only studies which did not meet the quality criteria, were included (see Supplemental File – Study findings). For most outcomes, for which at least one higher quality study was identified, more lower-quality studies were available (i.e. prevalence of noise annoyance, visual annoyance, and shadow flicker annoyance, and association of wind turbine noise with noise annoyance, quality of life, sleep disturbance, biophysiological variables of sleep, depression/anxiety, and stress). For only few results, only higher-quality studies were identified (i.e. annoyance to a changed view due to wind turbines, annoyance to rotor blade movement, annoyance to vibrations, and association between shadow flicker and annoyance).

Comparing the findings from studies of higher quality with those of lower-quality studies produced mixed results. In most cases, there is an almost predominant consensus about the findings between studies of higher and lower quality – more precisely for annoyance to shadow flicker, reflections, and blinking lights as well as for the association of wind turbine noise with annoyance, biophysiological variables of sleep, and stress. In case of noise annoyance, the prevalences reported in studies of lower methodological quality were higher than those reported in higher-quality studies. Further, some findings differed among the studies, regardless of the methodological quality – namely for visual annoyance and for the associations of wind turbine noise with quality of life, sleep disturbance, and depression/anxiety.

Concerning annoyance to reflections of rotor blades, one cross-sectional study of lower methodological quality identified a similar prevalence as higher-quality studies of 15% (Pawlaczyk-Luszczynska et al., 2014b). The prevalence of annoyance to blinking lights of around 10% found in higher-quality studies was nearly the same in a cross-sectional study of lower quality (15.7%) (Hübner and Pohl, 2010). In regard to shadow flicker annoyance, the varying range shown in cross-sectional studies of higher quality (7.8–31%) was nearly identical in 3 lower-quality observational studies (8.6–27.1%) (Pawlaczyk-Luszczynska et al., 2014b; Schafer, 2013; Schneider, 2012). Only one study of lower quality reported much higher prevalences of shadow flicker annoyance of 77% and 90% (Morris, 2012). The finding of a statistically significant association between noise of wind turbines and annoyance that was found in 4 cross-sectional studies of higher methodological quality was confirmed by 9 lower-quality studies (Bakker et al., 2012; Blanes-Vidal and Schwartz, 2016; Klaeboe and Sundfor, 2016; Pawlaczyk-Luszczynska et al., 2014a, 2014b; Pedersen and Persson Waye, 2004; Pedersen et al., 2009; Song et al., 2016; Yano et al., 2013). Only one prospective cohort study of lower quality found no association between distance to wind turbines and noise annoyance ($p > 0.05$) (Jalali et al., 2016a). There is consistency regarding the observation that there is no association between noise from wind turbines and biophysiological variables of sleep between the higher-quality study and the lower-quality study (Lane, 2013). Further, a lower-quality prospective cohort study demonstrated no temporal association between wind turbine noise and objective sleep parameters measured with polysomnography ($p > 0.05$) (Jalali et al., 2016b). Only some subjective parameters were associated with noise from wind turbines. The result of a cross-sectional study of higher methodological quality, which observed no relationship between wind turbine noise and stress, was also outlined in two lower-quality cross-sectional studies (Krogh et al., 2011; van den Berg et al., 2008).

The range of prevalence of noise annoyance was greater in 11 studies of lower quality compared to the higher-quality observational studies (6–100% versus 4.11–45%) (Botelho et al., 2017; Jalali et al., 2016a; Kaldellis et al., 2013; Morris, 2012; Mulvaney et al., 2013; Schafer, 2013; Schneider, 2012, 2013; Song et al., 2016; Thorne, 2012; Zajamsek et al., 2014). In 7 out of these 11 publications, the prevalence of noise annoyance was higher than the highest value mentioned in one of the 6 higher-quality observational studies of 45%.

The prevalence of high visual annoyance was much higher in a lower quality observational study (45.2%) (Jalali et al., 2016a) compared to the value shown in the higher-quality study of 12.9%. The overall visual annoyance prevalence, which was not reported in the cross-sectional study of higher methodology, was around 10% in 2 other cross-sectional studies of lower quality (Kageyama et al., 2016; Kaldellis et al., 2013). The finding of a statistically non-significant association between noise of wind turbines and a worsened quality of life was also observed in 3 cross-sectional studies of lower quality (Krogh et al., 2011; Michaud et al., 2016b; Paller, 2014). On the contrary, 5 other lower-quality cross-sectional studies showed an existent association between wind turbine noise and quality of life ($p < 0.05$), whereas 3 studies demonstrated a deterioration (Nissenbaum et al., 2012; Phipps, 2007; Shepherd et al., 2011) and 2 papers an improvement of quality of life (Mroczek et al., 2015, 2012). Two follow-up studies of lower methodological quality demonstrated no temporal association between wind turbine noise and quality of life ($p > 0.05$) (Jalali et al., 2016a; McBride et al., 2013). The non-existent relationship between noise of wind turbines and sleep disturbance that was shown by one higher-quality study was only demonstrated by one cross-sectional study of lower quality (van den Berg et al., 2008). On the contrary, the majority of lower-quality cross-sectional studies outlined a statistically significant association (Bakker et al., 2012; Krogh et al., 2011; Nissenbaum et al., 2012; Paller, 2014; Song et al., 2016). A prospective cohort study of lower quality observed no temporal association between wind turbine noise and sleep disturbance ($p > 0.05$) (Jalali et al., 2016c). The outcome of a lacking statistically significant relationship between noise from wind turbines and depression or anxiety was also illustrated in 2 lower-quality cross-sectional studies (Krogh et al., 2011; Mroczek et al., 2015), in contrast to the finding of another cross-sectional study of lower methodological quality, which found a relationship (Nissenbaum et al., 2012). In a lower-quality prospective cohort study, the risk of developing depression differed statistically significantly before and after the exposure to wind turbine noise ($p < 0.05$) (Jalali et al., 2016a).

The differences of results shown among cross-sectional studies of varying methodological quality underscore the importance to consider methodological aspects when interpreting the findings from studies on controversial topics like the health impact of wind turbines, as bias like selection bias, information bias, or confounder bias may distort these results. The prevalence of noise annoyance was reported to be much higher in cross-sectional studies of lower methodological quality and in case studies as in higher-quality cross-sectional studies, which could be due to differential selection bias within these studies, indicating that more wind turbine opponents took part. Nevertheless, the comparison of annoyance prevalence should be interpreted with caution, as different definitions of annoyance were used within the studies, with different wording of the questions and some studies using only yes/no response options and others numerical scales like 4-point, 5-point, 7-point or 11-point scales.

4.2.2. Discussion of the study findings in context of the scientific literature

The existing or contrary associations identified with this scoping review between wind turbine noise and annoyance and sleep disorders, respectively, were also reported in other systematic reviews (Merlin et al., 2013; Onakpoya et al., 2015; Schmidt and Klokker, 2014). The findings on the relationships between noise from wind turbines and reduced quality of life and on the non-existing association between shadow flicker and health effects that were outlined by other systematic reviews are not consistent with the results of this scoping review (Arra et al., 2014; Merlin et al., 2013; Onakpoya et al., 2015). This contradiction could be explained by the fact that those reviews were published prior to the publication of important primary studies on the topic, which were included in this scoping review.

Most experimental studies investigated the influence of several wind-turbine related variables on noise annoyance. Annoyance was shown to be associated with the sound pressure level. This finding is in line with results from cross-sectional studies. The influence of different factors of the amplitude modulation like fluctuation frequency, or modulation depth varied in various experiments. There was only one field study that investigated the impact of different factors on noise annoyance, showing that the angular blade velocity, fluctuation of the blades, and the sound pressure level increased noise annoyance (Bockstael et al., 2012). Two studies, one experimental and one cross-sectional, illustrated a masking effect of wind turbine noise through background sounds (Bockstael et al., 2012; Bolin et al., 2012). These findings firstly underpin the fact that wind turbine noise annoyance is a complex matter, which is influenced by production-related variables, amongst others. Secondly, the results could be used to steer the localization and/or the operation of wind turbines in order to reduce noise annoyance. So far, there is only one intervention trial, which outlined that a specific noise-reduced operation of wind turbines, whereby the rotational speed of the rotor blades was throttled, had no statistically significant effect on noise annoyance ($p > 0.05$) (Hoen et al., 2010). Thus, currently, no statements can be made on the impact of such operational interventions. This finding is in line with recent WHO -recommendations regarding the effectiveness of interventions for wind turbine noise exposure (WHO, 2018). To protect the general population from unacceptable noise and its consequences, statutory emission guide values are necessary (Bunz et al., 2016). In addition, setback distances are recommended (Ellenbogen et al., 2012; Merlin et al., 2013), but standard definitions are not suitable, since these do not take different subjects of protection and local interests into account (UBA, 2015) and since the sound propagation depends on many constructional aspects of wind turbines (WHO, 2018). There is also no clear evidence on Moreover, such setback distances are not associated with the acceptance of wind turbines or stress effects (Hübner and Pohl, 2015). The current “Environmental Noise Guidelines for the European Region” recommends that wind turbine noise levels should be reduced below 45 dB (L_{den}), based on an 10% -increase of the prevalence of being highly annoyed (WHO, 2018). The World Health Organization further notes, that the noise exposure from an environmental source like a wind turbine may be reduced through simple measures like insulating windows or building barriers (WHO, 2018).

With respect to visual wind turbine features, mostly annoyance reactions, but only a few other health outcomes were researched in primary studies. According to the results of a simulation study, which did not meet the inclusion criteria of this scoping review, the risk of developing epileptic seizures due to shadow flicker of large wind turbines is low (Smedley et al., 2010), because the flash frequency is below the recommended maximum level of three rotations per second (Harding et al., 2008). To minimize the risk of epilepsy, rotor blades should not be reflective, and the shadow cast by one turbine should not be seen on another one (Harding et al., 2008).

Some studies were retrieved that showed that the impact of wind turbines on the resident's health was influenced by psychological factors. Negative beliefs, attitudes, and expectations on the health impact of a wind turbine led to negative health consequences such as annoyance, worsened quality of life, physical symptoms, and negative mood (Chapman et al., 2013; Crichton et al., 2013a, 2013b, 2015; Crichton and Petrie, 2015a, 2015b; Pedersen et al., 2007; Tonin et al., 2016; Walker et al., 2014, 2015). One paper offered psychological explanations for the occurrence of wind turbine related symptoms among residents: Pure negative expectations of resulting health effect can cause such complaints as a kind of "nocebo effect"; existing or new symptoms are misclassified; and social factors such as media reporting or activities of lobby groups may increase the reporting of complaints (Rubin et al., 2014). Furthermore, psychological and social factors such as general attitude towards wind energy, economic benefits, perceived inequalities, community involvement, or social influence processes seem to influence the community response to wind turbines, meaning acceptance or opposition (Christidis et al., 2017; Devine-Wright, 2005; Graham et al., 2009; Johansson and Laike, 2007; Jones and Eiser, 2009; Mulvaney et al., 2013). Thus, in planning and construction phases of new wind turbine projects these findings should be taken into account – beside operational and institutional considerations such as emission guide values or noise-reduced operation – to avoid corresponding health effects in individuals and to increase the support from the community (WHO, 2018).

There was no literature on ice throw and electromagnetic radiation of wind turbines. The risk for ice throw is avoidable due to prevention measures such as warnings, setbacks, gated access, heated rotor blades, or de-icing systems (Bunz et al., 2016; Ellenbogen et al., 2012; Fortin et al., 2013). Further, since wind turbines are no significant sources of electromagnetic radiation – comparable to common household appliances – (Fortin et al., 2013; Merlin et al., 2013), negative health effects are not expected.

4.3. Research gaps and need for further research

Several research gaps were identified within this scoping review (see Fig. 7).

4.3.1. The complex pathways of annoyance

Annoyance and its accompanied interdependencies is a complex issue. According to Guski et al., noise annoyance is "a multifaceted concept, covering mainly immediate behavioral noise effects aspects, like disturbance and interfering with intended activities, and evaluative aspects like nuisance, unpleasantness, and getting on one's nerves" (Guski et al., 1999). Annoyance is defined as an health outcome. The association between wind turbine noise and annoyance is influenced by several moderator variables like noise sensitivity, wind turbine visibility, or economic benefit (Arezes et al., 2015; Berglund et al., 1999; Michaud et al., 2016d), which are challenging to assess and which have not been addressed in detail in past health studies (WHO, 2018). Annoyance can further act as a mediator variable between wind turbine features and other health outcomes – some of serious nature like cardiovascular diseases, bronchitis, migraines, or arthritis (Botelho et al., 2017; Niemann et al., 2006; WHO, 2009). According to the World Health Organization, "although high annoyance is not classified as a disease in the International Classification of Disease, it does affect the well-being of many people and therefore may be considered to be a health effect falling within the WHO definition of health (WHO, 2011). A few studies graded their annoyance ratings as "high annoyance" (e.g., in regard to noise, blinking lights, shadow flicker, or vibration) (Bockstael et al., 2012; Hübner and Pohl, 2010; Michaud et al., 2016b; Schaffer et al., 2016; Song et al., 2016), but most studies used multilevel classifications. To date, high annoyance targets only community noise, but no other non-noise exposures (Michaud et al., 2018b). Further, there is no equivalent accepted measure for lower magnitudes of annoyance (Michaud et al., 2018b). Two recent publications argue, that there should be an overall "aggregated" annoyance measure which takes the multiple features of wind turbines into account – apart from simply focusing on noise annoyance (Michaud et al., 2018b, 2018c). Thus, a single construct that comprised annoyance reactions to wind turbine noise, shadow flicker, blinking lights, visual impacts, and vibrations was developed. It was shown that the overall annoyance increased with decreasing distance from a residence to a wind turbine (Michaud et al., 2018c). Furthermore, the aggregated annoyance reaction was statistically associated with several health effects, namely chronic pain, sleep disturbance, tinnitus, headaches/migraines, dizziness, high noise sensitivity, high blood pressure, and stress (Michaud et al., 2018b). The authors concluded that such an aggregated annoyance score could be taken into account during the development of wind energy projects by juridictions as well as the estimation of the benefit of mitigation measures. They further emphasized that the shown association between the aggregated wind turbine annoyance and health implications should not be interpreted as causality; that there are other factors, which may influence the annoyance of residents towards wind turbines such as perceived impacts on property value or wildlife; and that more research on this premature research field is warranted. It should be noted that health effects of wind turbines caused by other factors such as real estate prices could be causal.

Future studies should account for the complex pathways of annoyance as an outcome parameter – that is influenced by different moderator variables – or as a mediator variable for other health outcomes. Based on the recent findings reported by Michaud et al. (2018a, 2018b), an overall measurement of the multiple exposures of wind turbines with an aggregated instrument – that takes note of all magnitudes of annoyance – should be considered in future studies.

4.3.2. Measurement of visual wind turbine features

Regarding visual exposure wind turbine studies, the exposure variables were not the primary focus of the study but rather a by-product. Furthermore, apart from one study (Voicescu et al., 2016), none graded the visual risk factors allowing for association calculations. Thus, observational studies that measure visual aspects of wind turbines gradually are needed like it is the done with wind turbine noise.

4.3.3. Combination of several wind turbine exposure variables

Most studies regarded exposures such as noise, visual aspects, or vibrations isolated and not in combination. Derived from the aforementioned discussion on the interaction between the different exposures with respect to annoyance, it is questionable, whether it is appropriate to distinguish between different wind turbine features regarding other health effects, as a wind turbine is a complex technology.

There is a need to research …
… the complex pathways of annoyance. … the potential of an aggregated annoyance measure. … visual wind turbine features using graduated measuring scales. … the interaction between several wind turbine exposures (e.g., noise, shadow flicker, blinking lights, vibrations). … concreate health effects. … the influence of wind turbine infrasound and low-frequency noise exposure in the field.
There is a need to conduct …
… longitudinal studies. … studies in countries with a high number of newly installed wind turbines which have conducted less or no research on the topic of residential health effects of wind turbines yet (e.g., China, India, or Brazil). … epidemiological observational studies of high methodological quality.

Fig. 7. Need for future research.

Furthermore, experimental studies demonstrated the combined impact of auditive and visual emissions of wind turbines on health parameters (Maffei et al., 2013; Ruotolo et al., 2012; Yu et al., 2017). Thus, the interaction between wind turbine noise, visual features, vibration, etc. and its combined impact on resident´s health should be examined to a larger extent and eventually one measurement instrument capturing all relevant exposures needs to be developed.

4.3.4. Clinically apparent health effects

Studies on clinically apparent health effects such as cardiovascular diseases or migraines are rare and the few available ones missed to use objective measurement instruments in the form of a doctoral diagnosis or registry data, and rather relied on subjective yes-no questions about the clinical occurrence. Only one study assessed the occurrence of a disease – namely anxiety or depression – with a doctoral diagnosis (Nissenbaum et al., 2012). Biophysiological variables of sleep were evaluated with the objectively polysomnography or actigraphy in 3 papers (Jalali et al., 2016b; Lane, 2013; Michaud et al., 2016c). One publication measured stress with objective measures such as hair cortisol or blood pressure and additionally with the Perceived Stress Scale (Michaud et al., 2016a). In some other studies, at least validated questionnaires were used. Literature that examined, whether there are particularly vulnerable population groups for specific health effects of wind turbine exposures – e.g., different age groups – is sparse.

Thus, it would be valuable to compare clinically apparent health outcomes among residents living near wind turbines with those residing in areas without wind turbines, using objective clinical diagnosis or data from clinical registries.

4.3.5. Wind turbine infrasound exposure

Field studies about wind turbine infrasound noise health effects are lacking. The current scientific knowledge about wind turbine infrasound does not preclude the utilization of wind energy in regard to health (Bunz et al., 2016) and the scientific evidence does not indicate that infrasound can directly impact human health (Berger et al., 2015). Wind turbine infrasound emission is estimated to be comparable or even lower than other natural and anthropogenic sources (Berger et al., 2015; Bunz et al., 2016). The infrasound component of wind turbine noise measured in one study was below the human perception levels (Berger et al., 2015). Even though, Salt and colleagues claim that it cannot be ruled out that wind turbine infrasound has an influence on the physiology of the human ear (Salt and Hullar, 2010; Salt and Lichtenhan, 2014). They further suggest that long-term exposure may influence human health. The results of the included experimental studies indicate that health symptoms and negative mood caused by infrasound are rather influenced by negative expectations than by the exposure itself, and may be reversed by positively framed health information. These findings are supported by results of a content analysis which labels the occurrence of such symptoms as a psychogenic “communicated disease” (Chapman et al., 2013). To understand and address local concerns about wind energy, it is important to effectively engage a community in the planning phases building trust between the residents and the wind turbine developers (Stewart and Aitken, 2015).

No peer-reviewed studies pertaining to low-frequency wind turbine noise were found. However, according to two investigations, A- and C-weighted sound pressure levels highly correlated with each other (Berger et al., 2015; Keith et al., 2016). As a result, Berger et al. reasoned, in conjunction with low levels of infrasound measured, that outdoor noise guidelines based on A-weighted sound pressure levels are effective measures to evaluate, monitor, and protect residents (Berger et al., 2015). Other authors, on the other hand, suggested that noise mitigation measures should not solely rely on A-weighted sound pressure levels, but consider full-spectrum monitoring (Keith et al., 2016; Salt and Lichtenhan, 2014).

To make definitive statements about the impact of infrasound and low-frequency noise of wind turbines on local residents, appropriate epidemiological observational studies are warranted.

4.3.6. Longitudinal studies

Only two original studies had a follow-up, and thus considered health outcome changes before and after the erection of wind turbines (Jalali et al., 2016a, 2016b, 2016c; McBride et al., 2013). Overall, the study results pointed out no time effects concerning quality of life and sleep parameters, but this evidence is too sparse to draw definite conclusions. A cross-sectional study that compared quality of life among residents living near wind turbines in different development stages found some differences for specific quality of life domains, but reported the direction of causality only in parts (Mroczek et al., 2015). More prospective studies should be undertaken which consider time effects of exposure to wind turbines such as the occurrence of more symptoms in planning or construction phases or habituation effects during operation (WHO, 2018). For social sciences, it would be interesting to investigate the sentiments and attitudes towards wind energy and wind turbines among residents before the start of a wind project in their community and whether these changed during the different life cycle phases. Some studies reported that residents initially welcomed wind turbines, but changed their attitude after the installation and experience of adverse health effects (Krogh, 2011; Nissenbaum et al., 2012).

4.3.7. Studies from countries with a high number of newly installed wind turbines

The vast majority of research was conducted in OECD Member countries such as Australia, New Zealand, Canada, or Sweden. Since the wind industry is growing globally, and three Non-OECD –countries, namely China, India, and Brazil, were among the Top 5 -countries of newly installed wind capacities globally in 2017 (GWEC, 2018), more research from these geographical regions is needed.

4.3.8. Need for observational studies of high methodological quality

The majority of included studies were published in peer-reviewed journals. However, some self-published surveys were also available. Results of the latter should be interpreted with caution as the ones that were retrieved were of very poor scientific quality, primarily exhibiting selection bias, information bias, and confounder bias; and as the formulated hazard potential for a resident's health is much higher as compared to that of cross-sectional studies of higher methodological quality. Thus, a critical consideration of study methods is advisable. In terms of outcome measures, there were large differences among the studies in regard to their quality criteria. Some studies used valid and reliable instruments, while others asked only a single question about the occurrence of a specific disease. For instance for sleep disturbance, many studies used the well-established Pittsburgh Sleep Quality Index (Jalali et al., 2016c; Michaud et al., 2016c; Nissenbaum et al., 2012; Paller, 2014; Thorne, 2012), but others asked a question about its onset (Iser, 2004; Taylor et al., 2013a, 2013b; Harry, 2007; Krogh et al., 2011; Phipps, 2007; Pierpont, 2009; Song et al., 2016). The latter procedure carries the risk to overestimate the real prevalence of a complaint or a disease. All observational studies with comparison groups used residents who were less exposed to wind turbines as controls. None had a control group that consisted of residents not living near wind turbines in a similar setting. The results of only one quarter of the studies was judged to be generalizable.

As quality assessment showed that some studies lacked a thorough scientific standard, future studies should account for essential principles. Participants should be selected by census or random sampling. Response rates should be sufficiently large or at least non-responders should be accounted for. An eligible comparison group should be available. For the exposure and outcome measurement reliable and valid instruments should be used. Analyses of associations should be adjusted for “actual” confounding factors, but should avoid over-adjustment. A generalizable setting and population should be selected. In addition, vulnerable populations like children or elderly people should be taken into account (WHO, 2018).

4.4. Strengths and limitations

The design of a scoping review best served the study purpose in summarizing the body of evidence around health effects of wind turbines in residential settings, in order to identify potential research gaps and to point out the need for further research. In addition to the high-quality systematic review of Merlin et al. (2013), this scoping review considered case studies, experimental and intervention studies, as well as qualitative studies apart from observational studies and systematic reviews. Additionally to basic process steps described in methods papers (Arksey and O'Malley, 2005; Daudt et al., 2013; Levac et al., 2010), the review procedure was as stringent and systematic as that of systematic reviews: two reviewers executed most review stages, and methodological aspects of included studies were critically appraised. The latter is not intended for scoping reviews, but as it seems that the topic of health implications of wind turbines in residential settings is a controversial one (Graham et al., 2009), the study authors decided to show content-related findings as well as methodological aspects of included studies to provide the reader the possibility to judge study findings critically in light of each study´s method. Furthermore, the quality assessment helped to gain an overview of the quality of the study base.

For observational studies, the occurrence of a selection bias and information bias as well as the adjustment of confounders were evaluated. A selection bias may lead to a difference of the association between an exposure and an outcome between study participants and non-participants or non-responders (Tripepi et al., 2010). Since the health impact of wind turbines in residential settings presents a controversial issue in some communities (Chapman et al., 2013), there is a risk for a higher response among wind turbine opponents. An information bias occurs during data collection and may lead to a misclassification of an exposure or an outcome (Tripepi et al., 2010). As wind turbine risk factors such as noise or shadow flicker have a wide range of exposure levels, it is necessary to measure and classify these exposures with valid and reliable instruments. Since some complaints attributed to wind turbines might be caused by psychological mechanisms (Rubin et al., 2014), it is also of importance to diagnose symptoms and diseases accurately. Confounders should have been included in the assessment of associations, as these may distort the true relationship between an exposure and an outcome (Skelly et al., 2012). We regard the restriction to the three “core” confounders “age”, “sex”, and “socioeconomic status” as scientifically sound. We did not consider common causes of sleep disorders, cardiovascular diseases etc. like “food intake” and other lifestyle factors as appropriate confounders, since these constitute rather risk factors on the outcome level, but not on the exposure level. Further, these lifestyle factors may constitute intermediate factors. For example, wind turbine noise could lead to an increased stress level, which in turn could increase food intake and thus facilitate the development of such diseases. The rationale for determining economic benefit as marker for socioeconomic status was based on the assumption that residents who benefit economically from wind turbines also own a property with at least one wind turbine on it. Further, a benefit could be due to a financial participation or even an equity investment in wind turbines, which both are entailed with a higher socioeconomic status. But as these assumptions might be more of a speculative nature, future studies should determine the socioeconomic status with valid instruments. Furthermore, we did not consider “noise sensitivity” as confounder – as it was done in several studies – since it primarily acts as an effect modificator that should be regarded as such (e.g., stratification). Nevertheless, it is essential not only to assess these types of bias, in order to judge the accuracy of the findings, but further to look at the consistency among the results of several studies.

In terms of the judgment of the generalization of the results of a study, it should be pointed out that different researchers may use different criteria. This is the case in relation to the papers of the Health Canada´s Community Noise and Health study (CNHS). The results of these articles were judged to be generalizable in this scoping review based on the fact that several large study regions, with wind turbines of different electricity power outputs were investigated and participants were selected randomly (Feder et al., 2015; Michaud et al., 2016a, 2016b, 2016c, 2016d; Voicescu et al., 2016). Other studies also fulfilled our criteria and were judged to be generalizable as well (Blanes-Vidal and Schwartz, 2016; Hübner and Pohl, 2010; Kageyama et al., 2016; Kuwano et al., 2013; Mroczek et al., 2015, 2012; Pawlaczyk-Luszczynska et al., 2014a, 2014b; Pohl et al., 2012; Yano et al., 2013). On the contrary, the authors of the CNHS themselves declared that their findings are not generalizable as the selection of the study regions was not random (Michaud et al., 2018a). We see that highlighting the generalization of all the aforementioned studies is important, since many other studies in contrast only used one small study region, investigated only wind turbines with low electrical power output, took place in very specific landscapes, and/or selected participants not randomly, and thus were determined not to be generalizable.

As to this very comprehensive overview, an in-depth analysis and discussion of all considered topics is not possible. Relevant research published in other languages than English and German could have been missed. During the review process, some modifications to the study protocol were carried out. The decision to search the Web of Science was made a posteriori after it became clear that the databases selected previously, namely MEDLINE, EMBASE, and CINAHL, did not list as many appropriate references as assumed. By searching the Web of Science further, eligible publications were identified. Initially, content analyses were not taken into account, but were included a posteriori as it appeared that these contained relevant data. Physiological parameters or surrogate markers, a priori not considered as relevant outcome parameters, were included a posteriori. According to methods papers, such an iterative approach is welcomed in a scoping review (Arksey and O'Malley, 2005; Daudt et al., 2013; Levac et al., 2010).

5. Conclusions

There is an extensive and diverse body of evidence around health impacts of wind turbines in residential setting of varying methodological quality that increased sharply since 2010 onwards, and that is still growing. The vast majority of studies were conducted in OECD Member Countries. Studies from Non-OECD countries with a high number of newly installed wind turbines are missing. Wind turbine noise was the most frequently investigated exposure. Annoyance reactions to all wind turbine exposures, but especially to noise, were assessed in many studies. In connection with visual aspects of wind turbines, most studies investigated annoyance, and only a few other health complaints. Other wind turbine operations such as infrasound, low frequency noise, ice throw, vibration, or electromagnetic radiation were investigated in only a few papers, or not at all. In general, studies on the impact of wind turbines on clinically apparent health effects are sparse. Findings from cross-sectional studies of higher methodological quality – that were supported by findings from lower-quality observational studies – illustrated an existing association between wind turbine noise and annoyance and no association between noise from wind turbines and stress effects and biophysiological variables of sleep. In higher quality studies, wind turbine noise was not associated with restricted quality of life, sleep disturbance, and anxiety and/or depression, which contrasts – at least partly – with findings from lower-quality studies. Research gaps concern the complex pathways of annoyance, the objective investigation of visual wind turbine features, the interaction between all wind turbine exposures, the impact of wind turbines on clinically apparent health outcomes, and epidemiological observational studies on low-frequency and infrasound from wind turbines. Future research on the topic needs thorough high-quality and prospective study designs.

Declarations of interest

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Appendix A. Supporting information

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