Review

Scand J Work Environ Health Online-first -article

doi:10.5271/sjweh.3711

Health effects of wind turbines in working environments – a scoping review

by Freiberg A, Schefter C, Girbig M, Murta VC, Seidler A

This first, comprehensive review about health effects occurring in the wind sector indicates there are no wind industry-specific overall health effects. Existing research comprises especially skin disorders, accidents, and noise consequences. There is a need for further research particularly in terms of psychological and musculoskeletal disorders, work-related injury and accident rates, as well as later lifecycle phases.

Affiliation: Boysen TU Dresden Graduate School, Technische Universität Dresden, 01062 Dresden, Germany. alice.freiberg@tu-dresden.de

Refers to the following text of the Journal: 1995;21(5):0

Key terms: complaint; disease; health effect; occupational health; occupational health; review; scoping review; wind; wind industry; wind turbine; worker; working environment

This article in PubMed: www.ncbi.nlm.nih.gov/pubmed/29360123

Scand J Work Environ Health – online first. doi:10.5271/sjweh.3711

Health effects of wind turbines in working environments – a scoping review

by Alice Freiberg, MPH,[1, 2] Christiane Schefter, BSC,[2] Maria Girbig, PhD,[2] Vanise Cleto Murta, MD,[2] Andreas Seidler, MD, MPH [2]

Freiberg A, Schefter C, Girbig M, Murta VC, Seidler A. Health effects of wind turbines in working environments – a scoping review. *Scand J Work Environ Health* – online first. doi:10.5271/sjweh.3711

Objectives The wind industry is a growing economic sector, yet there is no overview summarizing all exposures emanating from wind turbines throughout their life cycle that may pose a risk for workers' health. The aim of this scoping review was to survey and outline the body of evidence around the health effects of wind turbines in working environments in order to identify research gaps and to highlight the need for further research.

Methods A scoping review with a transparent and systematic procedure was conducted using a comprehensive search strategy. Two independent reviewers conducted most of the review steps.

Results Twenty articles of varying methodical quality were included. Our findings of the included studies indicate that substances used in rotor blade manufacture (epoxy resin and styrene) cause skin disorders, and respectively, respiratory ailments and eye complaints; exposure to onshore wind turbine noise leads to annoyance, sleep disorders, and lowered general health; finally working in the wind industry is associated with a considerable accident rate, resulting in injuries or fatalities.

Conclusions Due to the different work activities during the life cycle of a wind turbine and the distinction between on- and offshore work, there are no specific overall health effects of working in the wind sector. Previous research has primarily focused on evaluating the effects of working in the wind industry on skin disorders, accidents, and noise consequences. There is a need for further research, particularly in studying the effect of wind turbine work on psychological and musculoskeletal disorders, work-related injury and accident rates, and health outcomes in later life cycle phases.

Key terms complaint; disease; occupational health; wind industry; worker.

The wind industry is a new and growing industry, with 1.1 million jobs globally in 2016 (1). China, Germany, and USA are the leading employers (1). A survey of the European Wind Energy Association found that wind turbine and component manufacturers employ 59% of wind energy workers (2). With this growth in the number of workers, challenges for occupational health and safety arise (3). Wind turbines can cause different risks for workers such as confined spaces, electrical risks, falls from heights, psychological loads, or exposure to dangerous substances (3–5).

Jobs in the renewable energy sector, eg, the wind industry, are regarded as "green jobs" since they contribute to resource efficiency and low-carbon development (4). The International Labor Organization (ILO) defines green jobs as "decent work which contributes directly to reducing the environmental impact of enterprises, economic sectors or the economy as a whole by reducing energy and resource consumption, *[...]*" (4). Nevertheless, the ILO emphasizes that green jobs do not necessarily translate into decent jobs. Thus, it stipulates the integration of occupational safety and health aspects by evaluating work hazards and risks from a micro- (ie, enterprise) to a macro- (ie, economic sector or economy) level (4). Similarly, the European Agency for Safety and Health at Work points out that working in a green sector like the wind energy industry does not inevitably mean that it is good for workers' health and safety (3).

On- and offshore wind turbines consist of similar components (tower, nacelle, rotor assembly, rotor

1 Boysen TU Dresden Graduate School, Technische Universität Dresden, Dresden, Germany.
2 Institute and Policlinic of Occupational and Social Medicine, Medical Faculty Carl Gustav Carus, Technische Universität Dresden, Germany.

Correspondence to: Alice Freiberg, MPH, Boysen TU Dresden Graduate School, Technische Universität Dresden, 01062 Dresden, Germany. [E-mail: alice.freiberg@tu-dresden.de]

blades), but differences arise in relation to costs, size, transport of components, working environment, novelty, wind conditions, etc. (3). The differing work conditions between the on- and offshore sectors should be kept in mind during any future research.

Health effects arising from wind turbines, primarily from wind turbine noise, among residents living in their surroundings have been investigated in numerous studies and summarized in related systematic reviews and meta-analyses (6–8). On the other hand, statistical data on accidents, injuries and diseases emerging from working in the wind energy sector are lacking (4). Also an overview that outlines all scientific activities regarding the health impact of wind industry work is missing. Thus, the aims of this scoping review were to (i) survey and illustrate the body of evidence about the health effects of wind turbines in the working environment as comprehensively as possible, (ii) identify potential research gaps, and (iii) highlight any resulting need for further research or for the conduction of one or multiple systematic reviews.

Methods

A scoping review was conducted to embrace the width and thematic diversity of health effects of wind turbines in the working environment as a new field of research. Generally, a scoping review is carried out if a research area is broad or new and the research question is not narrowed to a specific problem (as opposed to a systematic review) (9, 10). In contrast to a systematic review, inclusion of different study designs is possible (9). The methodology of this scoping review is based upon established methodological concepts (9, 11, 12) and is extended by the use of a strict review process as is done in systematic reviews, including the commitment of two independent reviewers during the screening of titles, abstracts, and fulltexts, performing duplicate data extraction, and assessing the methodology of the included studies. The PRISMA statement was used as a reporting guideline, since no specific guideline for scoping reviews exists to date (13). The study protocol was published a priori in the "International register of systematic reviews" (PROSPERO) (14). The scoping review comprised the investigation of health effects of wind turbines in the working environment as well as in the living environment. In this article, the results related to the working environment will be presented. Results concerning the living environment will be published elsewhere.

Step 1. Identifying the research question

Both a methodological and a content-related research question were formulated. The methodological research question was as follows: "What does the body of evidence say about the health effects of wind turbines in the working environment, and furthermore, do corresponding research gaps arise?" The content-related research question is: "Does working in the wind industry have an impact on human health?"

Step 2. Identifying relevant studies

A sensitive search strategy was developed to be as comprehensive as possible in identifying relevant research. The search period was set from 2000 to the date of search, since in 2000 the first Renewable Energies Act was adopted in Germany, which subsequently became a role model for energy laws in many other countries (15, 16).

An electronic database search was then undertaken. A sensitive search string was created, using only terms describing the exposure (wind turbines) and the outcome (health effects). MEDLINE (via Ovid), EMBASE (via Ovid), and CINAHL (via EBSCOhost) were searched on 1 February 2016 and, the Web of Science Core Collection was searched on 28 November 2016. The search in the aforementioned four databases was updated on 25 September 2017. Furthermore, the database Scopus was searched on 10 December 2017. The respective search strings can be found in the PROSPERO protocol (14). A fast forward search with all included studies was conducted in the Web of Science Core Collection. Several Google Scholar searches were executed, with some of the applied search strings created a priori and others developed during the search process. Websites of environmental and health-oriented institutions were surveyed from May to July 2016. All searched institutions are listed in the PROSPERO protocol (14). Hand searches were carried out in reference lists of topic-related key articles and of all included studies. References not directly found with the applied search strategies, but that seemed to be relevant, were also checked for eligibility (snowball technique).

Step 3. Study selection

Inclusion and exclusion criteria based on the PEOS criteria were defined a priori (13). Humans of all ages worldwide were considered as the population. Animals were excluded. All exposures that emanate from on- and offshore wind turbines were eligible for inclusion (eg, noise, infrasound, low frequency sound, vibration, electromagnetic radiation, shadow flicker, blade glint, ice throw, construction failure, accidents, etc.) irrespective of the life cycle phase (design, manufacture, transport, construction, operation, maintenance, decommissioning, recycling, and waste management). Studies that investigated all kinds of health effects were included, irrespective of whether these were measured subjectively or objectively (complaints, diseases, injuries). Studies that only investigated physiological parameters and surrogate markers were excluded. The following study designs were considered suitable for inclusion: observational studies (cohort studies, case control studies, cross-sectional studies, case series, case reports, ecological studies), intervention studies (randomized and non-randomized controlled trials, before-after studies), experimental studies, qualitative studies (focus group discussions, interviews), and reviews (with a systematic review approach). During the review procedure, content analyses addressing the study topic were also identified. Even if this study design was not initially considered eligible, it was decided to include these studies since they contained relevant information. Not eligible were subjective study types (editorials, comments, expert opinions), abstracts only, animal studies, as well as monitoring and exposure studies. Only studies in German and English were considered. Studies had to be published from 2000 on. Peer reviewed as well as non-peer reviewed publications were eligible.

Two reviewers independently carried out title, abstract and fulltext screening of the initial electronic database searches in MEDLINE, EMBASE, and CINAHL. Disagreements were solved by discussion. In case of a persisting dispute, a third reviewer was consulted. If only a title (not an abstract) was available during title and abstract screening, the study was only excluded if it was clear that the study topic was irrelevant. Otherwise, the fulltext was checked. During the title and abstract screening, reviewers were blinded to author names and publication year. All excluded fulltexts were documented with reason of exclusion. Both screening processes were piloted. A guideline for each screening process was used as a decision aid. Degree of agreement among reviewers was determined calculating the proportion of observed agreement and Cohen's Kappa (17). One reviewer screened titles and abstracts retrieved via the updated database searches and via the Scopus search. Further, one reviewer also carried out all other searches (fast forward search in the Web of Science, Google Scholar searches, website searches of institutions, hand searches). If a fulltext seemed to be relevant, a second reviewer also checked its eligibility.

Step 4. Charting the data

One reviewer carried out data extraction. A second reviewer checked data extraction for each included study (in duplicate check). A standardized data extraction form was used which included information on the references (eg, reference number, author names), methods (eg, study design, study place, setting, objectives), population (eg, sample size, age, gender), exposures (eg, type, assessment instrument), outcomes (eg, type, assessment instrument), findings (eg, main findings, additional findings), and other details (eg, author's conclusions, financing, conflict of interest). Data extraction was piloted beforehand.

Step 5. Collating, summarizing, and reporting the data

One reviewer evaluated methodological strengths and weaknesses of each study during data extraction and implemented into the standardized data extraction sheet. A second reviewer checked this assessment in duplicate. Different assessment criteria guidelines (based on validated critical appraisal tools) were developed beforehand to support the reviewers during this step. The following study designs were considered: observational studies, intervention studies, experimental studies, qualitative studies, and reviews (18–21). This appraisal was piloted by two reviewers.

For the presentation of the appraisal results, it was decided not just to list the strengths and weaknesses of each study, but instead to focus on specific categories that seemed to be of importance for the review topic. For each category, the risk of bias was judged (low, high, unclear) by following formulated criteria. An unclear risk of bias was set if no or insufficient information for judgment was given. There were general categories defined for every study design. Furthermore, every study design received specific categories. One reviewer did an assessment of categories, but it was based on the previously created, double-checked list of methodological strengths and weaknesses of each study. Reasons for judgment were documented for each study.

General categories that were evaluated for every study design were: reporting quality, ethical aspects (comprising conflicts of interest, funding sources, and approval of an ethics committee), and generalization. Reporting quality was of low risk of bias if sufficient information (in relation to each study design) was given for comprehensive understanding of the study. For judgment of the ethical aspects, statements made in the appropriate study were taken as the basis for the decision. Only if there appeared to be a conflict of interest with the author or funding, this was rated as a high risk of bias independent from the study's statement, but only if this could be justified with solid facts. For reviews and content analyses, the evaluation of the category "ethics committee approval" was not applicable, since these study designs work with already published data. For generalization, a low risk of bias existed if the study was transferable to the general population, after taking the study region, setting, and population into account.

Categories for observational studies were: sampling, response rate, eligibility of a comparison group, selection bias, information bias for exposure, information bias for outcome, and consideration of confounders and/or covariates. The sampling procedure had a low risk of bias if it occurred as a census or random selection and a high risk if convenience sampling was used. The response rate was assessed with a low risk of bias if it was higher >50% and/or if the responders and non-responders did not differ in regard to the outcome of interest. For case reports and case series, the response rate was not assessed since these study designs are not intended to recruit a representative sample. If an adequate control group was available, a low risk of bias was assigned. Selection bias was apparent, if the sampling method and/or response rate was rated with a high risk of bias. Information bias for exposure and outcome arose if non-valid, non-reliable, subjective measurement instruments were used. If confounders and/or covariates were considered for data analysis, this was judged as a low risk of bias.

The categories for content analyses were nearly the same as those of observational studies. The judgment criteria of the categories about the eligibility of a comparison group, the information bias for exposure and outcome, and for the consideration of confounders and/or covariates were identical. The categories "sampling" and "response rate" were not evaluated due to the study design. The judgment of a selection bias based on the data collection methods used in the corresponding study.

For systematic reviews, selected categories refer to each review process step. For a low risk of bias, the literature search should have been as comprehensive as possible, searching at least two scientific databases with suitable search terms, conducting hand searches, etc. Ideally, at least two reviewers should independently carry out title, abstract and fulltext screening, data extraction, and critical appraisal, with a high degree of agreement and piloted beforehand. For title, abstract and fulltext screening, an assessment guideline should have been used. For data extractions, a standardized data extraction sheet was necessary, and likewise, for critical appraisals, a valid critical appraisal tool should have been used. For data analysis, appropriate statistical methods should have been used, and study results/conclusions should have been set in relation to the results of the methodological assessment.

Data analysis

The selection process, study characteristics, findings, and methodological results of the included studies were analyzed and summarized tabularly and descriptively.

Step 6. Consultation phase

Consulting experts was not within the scope of this scoping review.

Results

Study selection

The description of the study selection (from searches to full text screening) comprises the search hits for both parts of the scoping review (working environment and living environment). However, only studies on the working environment are included in this paper. Overall, 11 155 references were retrieved via the electronic database searches. Searching other literature sources yielded a further relevant 64 hits. After removing duplicates, for the total scoping review, 9537 titles and abstracts as well as 182 full texts were screened. Finally, 20 publications were relevant for inclusion (22–41). For the title, abstract and fulltext screening of the initial MEDLINE, EMBASE, and CINAHL searches conducted on 1 February 2016, the proportion of observed agreement between the two reviewers was 0.97 and 0.90, and Cohen's kappa of 0.82 and 0.81, respectively, resulting in an almost perfect agreement for both screening phases. Figure 1 visualizes the results of the study selection.

Study characteristics

Of the 20 included articles, 16 were peer reviewed and 4 were non-peer reviewed publications. All studies but 2 were written in English. Of the 20 included articles, 6 were based on two "original" studies (3 publications each). Thus, the following description of study characteristics refers to 16 original studies. There were 6 cross-sectional studies, 6 content analyses, 2 case reports, 1 case series, and 1 systematic review. Of the 16 original studies, 9 were carried out in Europe, 3 in Asia, 2 in the USA, 1 in South America, and 1 in Australia.

The investigated topics were quite manifold, covering different life cycle phases of a wind turbine (manufacture, transport, installation, operation, and maintenance), different exposures, different working fields, tasks, and positions, as well as different health outcomes. Studies focusing on the installation and operation phases mostly focused on onshore wind turbines, with only two studies using the offshore setting and two studies including both, on- and offshore wind turbines. Sample sizes in studies that directly examined study subjects ranged from 10–603. Response rates were high in those cross-sectional studies that reported appropriate values (73–100%) (23, 25, 28–31, 39). Proportions of female workers varied between 0–45.1%. Of the 20 publications, 6 reported on the influence of substances used in rotor blade manufacturer companies on workers' health (27–32), 5 on (on- or offshore) wind turbine accidents (resulting in fatality or injury) (34, 35, 37, 38, 41), 4 on the influence of noise from onshore wind turbines on workers' health (22–24, 40), 2 on medical incidents

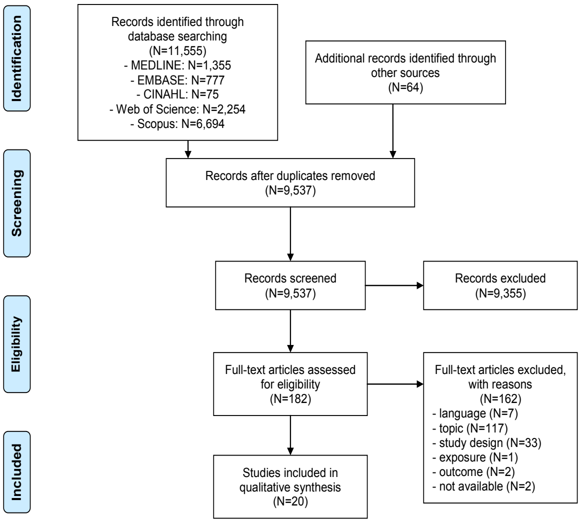

Figure 1. Study selection.

on offshore wind farms (33, 36), 2 on musculoskeletal disorders among onshore wind technicians (26, 39), and 1 on workers' health in coal-fired plants and wind power plants (25).

For further details about study characteristics, please refer to table 1.

Study findings and methodology assessment

The presentation of study findings is sorted by lifecycle and topic. The appraisal results of the methodology of each study follow immediately after the description of the study findings.

Manufacture phase – manufacture of rotor blades

Four studies (with six publications) investigated the impact of substances used in facilities for rotor blade production on workers' health.

One study (with three publications) was carried out in a rotor blade manufacturing facility in Denmark among production workers that were exposed to epoxy resin (29–31). Prevalence rates of work-related allergic contact dermatitis, work-related irritant contact dermatitis, and work-related aggravated dermatoses were 10.9%, 6.1%, and 5.1%, respectively (29). Of all examined workers, 10.9% and 6.1% suffered from occupational contact allergy to epoxy resin and amine hardeners/catalysts, respectively (30). Of all risk factors which were investigated for work allergy, epoxy allergy, and current dermatosis, only current dermatosis had statistically significant risk factors: days off work and work allergy (31). The study could not be generalized since it was conducted in 2001, and thus present working conditions may not be reflected. Only workers exposed to epoxy resin were investigated, so risk ratio calculations were not made.

A content analysis reports a strong increase in epoxy resin eczema in Germany since 2000, primarily among employees of production facilities for wind turbine rotor blades (32). The reporting quality had a high risk of bias since significant pieces of information were missing. Therefore, almost all categories received an "unclear risk of bias". Due to the outdated data used in the study, results do not seem to be generalizable.

Of ten workers from a wind turbine manufacturing facility in Spain suspected to suffer from occupational contact dermatitis, five were diagnosed with occupational allergic contact eczema due to epoxy resin and five were diagnosed with occupational irritant contact eczema due to fiberglass (27). Due to its study design, the case series was evaluated as having a selection bias. Further, confounders were not taken into account. Because different companies participated in the study, a rating with a "low risk of bias" for generalizability was given.

The results of a recent study from the US indicated that workers from a rotor blade manufacturer who were exposed to a higher degree of styrene compared to workers with a lower degree of styrene exposure exhibited a higher risk for developing chest tightness, wheezing, nasal symptoms, asthma-like symptoms, eye symptoms, and visual contrast sensitivity (28). These workers also carried a higher risk of suffering from tritanopia compared to the general population. Almost all study categories had a low risk of bias. The weaknesses of the study were that the (respiratory, nasal, and eye) symptoms had been measured subjectively and that information about conflict of interest was not available.

Transport phase – loading process of a wind tower

One case series published by the National Institute for Occupational Safety and Health (NIOSH) reported on a fatal incident due to a crushing injury of the upper torso of a worker during the loading process of a wind tower section on a railcar with two reach stackers. To help prevent similar occurrences in the future, safety and health implications were formulated (34). A selection bias was present due to convenience sampling. Confounders and covariates were not considered. Ethical aspects were not mentioned within the study. Generalizability of the findings and implications is not given due to the study design.

Construction and operational/maintenance phase – working in the offshore wind industry

In the working environment of four offshore wind farms in Germany from 2008 to 2012, 319 medical incidents

Table 1. Study characteristics [dB=decibel; g=gram; hr=hour; km=kilometer; kW=kilowatt; LAeq=energy-equivalent continuous sound pressure level; mg=milligram; NA=not applicable; NS=not specified; WT=wind turbine(s); yr=years]

Study	Study design	Study period	Country	Setting	Population	Exposure	Outcome parameter
Abbasi et al, 2015a (22), 2015b (24), 2016 (23) (peer review) (English)	Cross-sectional study	2014	Iran	Onshore wind farm with 171 WT, (capacity each: 300–660 kW)	Workers: N=53 - mechanics: N=22 - security staff: N=17 - office staff: N=14 Female: 6% Age (mean): 30.8 yr Response rate: 100%	WT noise (LAeq (8 hr)) - security staff: 66 dB - office staff: 60 dB - mechanics: 83 dB	Noise annoyance: 10-point-Likert-scale Daytime sleepiness: Epworth Sleepiness Scale General health: General Health Questionnaire
Asian et al, 2017 (41) (peer review) (English)	Content analysis	NS	Australia	Wind industry (on/offshore)	Humans	WT (on/offshore): Life cycle phases: transportation, construction, operation, maintenance Main cause factors of accidents: human, system/ equipment, nature	Fatalities, injuries
Cooper et al, 2014 (26) (peer review) (English)	Systematic review	NS	United Kingdom	Onshore wind power industry	Adult wind technicians	Working activities on onshore WT: - ascending and descending wind turbines - taking equipment - ladder climbing - cramped work spaces	Musculoskeletal disorders and other physical disorders: Prevalence, incidence, type and severity of pain, occupational measures (eg, absenteeism)
Dethleff et al, 2016a (36) (peer review) (English)	Content analysis	2011–2013	Germany	Offshore wind farm in installation, operation phase with 80 WT	Workers	Working in the environment of offshore WT	Traumatic injuries, acute diseases: clinical diagnostics
Dethleff et al, 2016b (35) (peer review) (German)	Case report	NS	Germany	Onshore WT	Electrician N=1 Sex: male Age: 37 yr	Working as electrician	Polytrauma after a fall from an intermediate platform on a bottom platform: Clinical diagnostics
ILO, 2010 (25) (Non-peer review) (English)	Cross-sectional study	NS	China	Power industry (under major state supervision and regulatory reform): - 1 wind power plant - 2 coal-fired power plants (large and small)	Workers in the power industry: N=572 - wind power plant: N=52 - large coal-fired power plant: N=361 - small coal-fired power plant: N=159 Female: 45.1% Age (mean) (wind industry): 38 yr Response rate: 97.8%	Working in the power industry: Exposure group: wind power plant Control group: coal-fired power plant	(General) health condition: 1 question Occupational diseases: 1 question
Jia et al, 2016 (39) (peer review) (English)	Cross-sectional study	NS	China	WT manufacture enterprise with 17 onshore wind farms	Operation and maintenance personnel: N=151 Female: 0 % Age (mean): 25.96 yr Response rate: 100 %	Working as operation and maintenance personnel in wind farms: - routine work mainly conducted in nacelle in very narrow space - adopting adverse postures (stoop, squat, prone position)	Low back pain: Nordic Musculoskeletal Questionnaire, palpitation inspection
Lárraga-Pinones et al, 2012 (27) (peer review) (English)	Case series	2009–2011	Spain	WT manufacturer	Workers (suspected to suffer from occupational contact dermatitis): N=10 Female: 20% Age (mean): 33.7 yr Response rate: NA	Working in WT manufactory: Exposure to carbon fiber, synthetic fiber (aramids), epoxy resin, curing agents	Occupational allergic contact eczema, occupational irritant contact eczema: Patch test

Continued

Table 1. continued

Study	Study design	Study period	Country	Setting	Population	Exposure	Outcome parameter
McCague et al, 2015 (28) (peer review) (English)	Cross-sectional study	2013	USA	Rotor blade manufacturer	Production workers: N=355 Female: 24.2% Age (mean): 37.5 yr Response rate: 73%	Exposure to styrene: - current: sum of mandelic acid and phenylglyoxylic acid (in mg)/creatine (in g) - cumulative: average current styrene exposure assigned to each department/job title combination multiplied by number of job months and then summed up Exposure group: ≥ median of Exposure Control group: < median of Exposure Median of Exposure: - current: 53:6 mg/g creatine - cumulative: 2426.4 mg/g creatine	Respiratory, asthma-like, eye and nasal symptoms: Questions adapted from validated survey instruments Color vision abnormalities: Color arrangement test Visual contrast sensitivity: Functional Acuity Contrast Test
Moura Carneiro et al, 2013 (38) (peer review) (English)	Content analysis	NS	Brazil	Onshore wind industry	Humans	Onshore WT in general	Fatalities
NIOSH, 2011 (34) (non-peer review) (English)	Case report	2011	USA	Loading process of a wind tower section on a railcar with two reach stackers	Worker N=1 Sex: male Age: 21 yr	Incident: Crush between the tire of a reach stacker and a railcar	Fatal incident: Report
Pleban et al, 2017 (40) (Non-peer review) (English)	Cross-sectional study	NR	Poland	Onshore wind farms (N=20)	Workers: N=323 - servicing personnel in wind farms: N=50 - other workers (not working in the wind industry, but working in a radius of 3 km around a WT): N=273 Sex, age, response rate: NS	WT noise (A-weighted SPL) - servicing personnel in wind farms: 74.6–83.9 dB - other workers (not working in the wind industry, but working in a radius of 3 km around a WT): 29.9–52.0 dB	Noise annoyance: 11-point-scale
Ponten et al, 2004a (29), 2004b (30), Rasmussen et al, 2005 (31) (peer review) (English)	Cross-sectional study	2001	Denmark	Rotor blade manufacturer	Production workers: N=603 Female: 15.3% Age (mean): 37.6 yr Response rate: 83.3%	Exposure to epoxy resin (in use during whole production process)	Dermatoses, allergy: Very detailed diagnostics (see studies)
Schubert et al, 2004 (32) (peer review) (German)	Content analysis	NS	Germany	Rotor blade manufacturer (specialist companies, affiliated educational facilities)	Plastics processors, laminators	Exposure to epoxy resin and fibreglass	Epoxy resin eczema, work related skin disorders, fibreglass dermatitis
Sovacool et al, 2015 (37) (peer review) (English)	Content analysis	Search period: 1874–2014. Search duration: 6 month	United Kingdom	Wind industry (Onshore, Offshore)	Humans	WT (Onshore, Offshore): Inclusion criteria: energy production and distribution Exclusion criteria: energy consumption or downstream pollution and externalities	Fatalities
Stuhr et al, 2015 (33) (peer review) (German)	Content analysis	2008–2012	Germany	Offshore wind farms (N=4) in installation, operation phase: - WT installation vessel - WT - other vessels - transformer platform	Workers	Working in the environment of offshore WT	Medical incidents (accidents and diseases)

occurred, of which 60% were accidents, 38% diseases, and 2% could not be assigned. Contusions, distortions, cuts, eye injuries, contusion wounds, and fractures were the injuries that emerged the most. Diseases that were documented the most were complaints of the respiratory organs, various pain syndromes, complaints of the digestive tract, general physical and mental well-being, cardiovascular diseases, rashes, and sleep disorders (33). Due to a significant lack of information, the reporting quality of this content analysis was of high risk of bias, and hence, most categories were judged with an "unclear risk of bias".

Of 39 investigated medical evacuations in a German offshore wind farm, 19 were traumatic injuries of traumatological (N=17) and ophthalmological (N=2) nature, 16 acute diseases of internal medical (N=9), general surgical (N=3), orthopedic (N=3), and neurological (N=1) nature, and 4 were not assignable (36). The reporting of this content analysis was judged as low risk of bias. It was unclear if all medical evacuations that happened during the study period were investigated or a convenient selection had taken place. As the study regarded only one German wind farm, study results do not seem to be generalizable.

Operational/maintenance phase – noise exposure of onshore wind turbines

Noise as an exposure of interest and its impact on the health of workers was examined in a cross-sectional study (with three associated publications) by comparing three different working groups that worked at different distances from the wind turbines, and thus were exposed to different noise levels. According to the results, wind turbine noise had a significant influence on developing noise annoyance, daytime sleepiness, and general health complaints among workers (22–24). The three articles (Abbasi et al) may not be generalizable because the power capacity of each wind turbine (330–600 kW) was low compared to those of modern wind turbines and because working conditions in Iran may differ from those in other countries. None of these publications addressed the inclusion of an ethics committee. Two of the Abbasi et al studies (22, 23) declared to have no conflict of interest and one reported that the study was not funded (23).

Another cross-sectional study from Poland reported the prevalence of noise annoyance among workers working as servicing personnel in wind farms or workers working in other professions not related to the wind industry, but in a 3 kilometer periphery around wind farms (40). Around 5% were not annoyed, 68.1% suffered from low annoyance, 17.0% reported average annoyance, and 9.3% stated high annoyance due to noise from wind turbines. The reporting quality of the study was insufficient, consequently most categories of the methodological quality assessment were judged with an "unclear risk of bias". A more extensive publication or research report of this conference paper was not detectable. No comparison group was available. The study population consisted not only of workers of the wind industry but also of other workers working in the surroundings of wind farms (but not working in the wind industry).

Operational/maintenance phase–Accidents

One content analysis reported on 80 fatalities related to onshore wind technology that occurred worldwide between 1970 and 2011 (38). The absolute number of fatalities worldwide increased since 2000, but the relative number decreased. Most fatal accidents claimed one life (N=75), three fatal accidents claimed two lives, one fatal accidents claimed three lives, and another claimed four lives. Another content analysis counted 126 fatalities worldwide between 1874 and 2014 associated with wind turbines and calculated a 0.035 normalized fatality risk per terawatt hour produced by wind energy (37). The reporting quality of both content analyses differed: The report of Moura Carneiro et al (38) had a high risk of bias, while the one by Sovacool et al (37) had a low risk of bias. Sovacool et al (37) compared wind energy with other energy forms, and thus had a low risk of bias in regards to the eligibility of a comparison group. For Moura Carneiro et al (38) there appeared to be a selection bias, and for Sovacool et al (37) a judgment regarding this type of bias could not been made. Both content analyses did not consider associated factors. As to the worldwide scope, both articles could be generalized to other populations.

Another content analysis investigated attributes that predicted fatalities and injuries due to wind turbine accidents in on- and offshore settings (41). Fatalities were predicted by the wind turbine life cycle phase (with most fatalities occurring during construction and maintenance), the country, the setting (onshore or offshore), the power of a wind turbine, the month as well as the day of the accident, and the power of a wind farm. Injuries due to wind turbine accidents were predicted by the power of a wind turbine, the country, the wind turbine life cycle phase, the power of a wind farm, and the year of the accident. The results of the paper seem to be generalizable, since its scope was globally. A selection bias may be present because only the Google search engine was searched and only the first 5000 of 300 000 hits were screened. Furthermore, only newspaper articles were included. It was not stated which languages were considered. It is unclear, whether an information bias for the outcome "injury" is existent, since no appropriate definition was given.

In one case report, the fall of an electrician from an intermediate platform to a bottom platform of an onshore wind turbine was described (35). The man survived but suffered from a polytrauma comprising a concussion, a fracture of the thorax, a burst fracture of the third lumbar vertebral body, a sacrum fracture, and multi-fragment fractures of the lower extremities. The reporting of the article was of low risk of bias. No information bias with regards to the exposure (falls as such) and to the outcome parameter (clinical diagnoses) was evaluated. The generalization of the study results and conclusions are questionable since only one incident was considered.

Operational/maintenance phase – risk of musculoskeletal disorders among onshore wind technicians

A systematic review searched for studies investigating the influence of working activities on onshore wind turbines (eg, ladder climbing or working in confined spaces) on developing musculoskeletal disorders and other physical disorders. No relevant studies were identified despite an extensive literature search. Research from other industries with similar working conditions shows weak evidence for an association between ladder climbing and musculoskeletal diseases, low-back pain, and gonarthrosis. There is, as well, weak evidence for an association between working in confined spaces and low-back pain or gonarthrosis (26). Most categories of the systematic review were of low risk of bias. Only the title, abstract, and full text screening, and data extraction were not described sufficiently.

In 2016 a Chinese cross-sectional study reported an elevated 12-month prevalence of low-back pain among operational and maintenance personnel of onshore wind farms (88.74 %) (39). Statistically significant risk factors were squatting >4 hours a day, lifting objects weighing >10 pounds if done >2 minutes for >2 hours a day, and the presence of somatization. The prevalence rate should be treated with caution since no comparison group was existent. The sampling of participants was not described, leading to uncertainty regarding selection bias. It was also unclear which confounders were used for logistic regression analyses.

Operational/maintenance phase – comparison of workers' health in coal-fired and wind power plants

In one study, the health of workers in China employed in coal-fired plants or wind power plants was compared. Workers of the wind industry reported better general health and less occupational diseases than workers of the coal-fire industry (25). The reporting quality of the study was rated as "high risk of bias" because relevant information about exposure, outcome parameters, and statistical methods was not available. Participants seemed to be recruited using convenience sampling, and thus selection bias was assigned. Outcomes of interest were measured with one subjective question in each case, so that information bias was probable. Working conditions in China are probably different from those in other industrial nations, and therefore there was a high risk that the study findings were not generalizable. Ethical issues were not mentioned.

Overall, the methodical quality varied a lot across studies and within studies. The reporting quality of most articles was good. Ethical issues were not addressed in most studies. Generalization was often unclear due to either missing data or uncertainty of judgement, or of high risk of bias.

For detailed study findings, please refer to table 2.

The methodological assessment of the 13 publications with an observational study design and six content analyses are illustrated in table 3 and of the systematic review in table 4.

Discussion

A total of 20 studies met the inclusion criteria. The body of evidence is manifold and comprised different lifecycle stages as well as different work environments. The methodical quality of the included studies varied a lot, thus some results are more trustworthy than others. According to the study findings, wind turbines have an impact on human health in the working environment during different life cycle stages. These are discussed in more detail hereafter.

Summary of the body of evidence

Different lifecycle phases of wind turbines were surveyed. In rotor blade manufacturing facilities, exposure to epoxy resin is associated with allergic skin disorders (27, 29–32), while styrene exposure is connected to nasal, respiratory, and eye complaints among production workers (28). Noise from onshore wind turbines poses an increased risk for noise annoyance, sleep disorders, and lowered general health for employees (22–24, 40). Diverse accident and injury cases occurred during the installation and operation of German offshore wind farms (33, 36). Around one hundred fatal accidents in the surroundings of operating wind turbines occurring globally were reported, most of these probably affecting humans in working environments (37, 38). Fatalities and injuries due to wind turbine accidents may be predicted by various attributes (eg, lifecycle phase, power of the wind turbine, or country) (41). Workers of wind power plants state to have better health and fewer occupational

Table 2. Study findings [ANOVA=analysis of variance; B=B coefficient; CI=confidence interval; cpd=cycles per degree; dB=decibel; Df=degree of freedom; F=F-value; hr=hour; MANOVA=multivariate analysis of variance; OR=odds ratio; r=correlation coefficient; SMR=standardized morbidity ratio; WT=wind turbine; β=beta coefficient; η^2=partial Eta square]

Study	Outcome parameter	Study findings	Influencing factors
Abbasi et al, 2015a (22) (cross-sectional study, N=53)	Noise annoyance, daytime sleepiness, general health	Relationship "WT noise and …" (MANOVA, included variable: age) - noise annoyance: P<0.001, η^2=0.83, R^2=0.877 - daytime sleepiness: P<0.001, η^2=0.79, R^2=0.835 - general health: P=0.014, η^2=0.17, R^2=0.441 Pairwise comparisons of noise exposure groups for … (Scheffe's post hoc test) - noise annoyance: 66 dB vs. 60 dB: P<0.05, 83 dB vs. 66 dB: P<0.05, 83 dB vs. 60 dB: P<0.05 - daytime sleepiness: 66 dB vs. 60 dB: P<0.05, 83 dB vs. 66 dB: P<0.05, 83 dB vs. 60 dB: P<0.05 - general health: 66 dB vs. 60 dB: P>0.05, 83 dB vs. 66 dB: P<0.05, 83 dB vs. 60 dB: P<0.05 Relationship "… and general health" (Multivariable regression (Forward method), significant variables: WT noise, daytime sleepiness, non-significant variables: distance to WT, noise annoyance, age) - WT noise: B=-0.39, β=-0.61, P=0.002 - daytime sleepiness: B=2.62, β=1.27, P=0.001, R^2=0.62 Relationship "Distance to WT and …" (MANOVA, included variables: age, noise annoyance) - daytime sleepiness: Type III sum of squares=35.373, Df=2, F(2,39)=23.9, P<0.001, η^2=0.55 - general health: Type III sum of squares=48.213, Df=2, F(2,39)=1.27, P=0.291, η^2=0.06	Covariates: noise annoyance: age daytime sleepiness: - age - noise annoyance - distance to WT general health: - age - daytime sleepiness - noise annoyance
Abbasi et al, 2015b (24) (Cross-sectional study, N=53)	Daytime sleepiness	Correlation "WT noise and daytime sleepiness" (Pearson correlation coefficient) - r=0.87 (P<0.05) Relationship "WT noise and daytime sleepiness" (Linear regression, reference category: office staff (83 dB)) - security staff: B=1.92, β=0.28, P=0.00 - mechanics: B=6.51, β=1.02, P=0.00, R^2=0.78 Relationship "WT noise and daytime sleepiness" (Multiple regression, adjusted for age, work experience) - B=0.26, β=0.82, P=0.001, R^2=0.83	Covariates: - age - work experience
Abbasi et al, 2016 (23) (Cross-sectional study, N=53)	General health	Correlation "WT noise and …" (Pearson correlation coefficient) - general health: P<0.05 - subscale "somatic symptoms": P<0.05 - subscale "anxiety and insomnia": P<0.05 - subscale "social dysfunction": P<0.05 - subscale "depression": P<0.05 Relationship "WT noise and …" (ANOVA) - general health: P<0.05 - subscale "somatic symptoms": P<0.05 - subscale "anxiety and insomnia": P<0.05 - subscale "social dysfunction": P<0.05 - subscale "depression": P<0.05 Relationship "WT noise and …" (multiple regression, reference category: mechanics (83 dB), adjusted for age, work experience, only significant results reported) - general health: office staff (60 dB): B=-6.07, β=-0.41, P=0.003, security staff (66 dB): B=-3.9, β=-0.28, P=0.03 - subscale "anxiety and insomnia": office staff (60 dB): B=-1.62, β=-0.3, P=0.023 - subscale "social dysfunction": security staff (66 dB): B=-2.3, β=-0.41, P=0.003	No covariates: - age - work experience
Asian et al, 2017 (41) (Content analysis)	Fatalities, injuries	Ranking of attributes for predicting fatalities due to wind turbine accidents (Kullback-Leibler divergence) - wind turbine life cycle phase: information gain=0.234 - country: information gaiN=0.156 - onshore/offshore: information gain=0.109 - power of a wind turbine: information gain=0.098 - month of the accident: information gain=0.089 - day of the accident: information gain=0.062 - power of a wind farm: information gain=0.060 Ranking of attributes for predicting injuries due to wind turbine accidents (Kullback-Leibler divergence) - power of a wind turbine: information gain=0.114 - country: information gain=0.093 - wind turbine life cycle phase: information gain=0.068 - power of a wind farm: information gain=0.048 - year of the accident: information gain=0.030	See column "study findings".

Continues

Table 2. continued

Study	Outcome parameter	Study findings	Influencing factors
Cooper et al, 2014 (26) (systematic review)	Musculoskeletal disorders and other physical disorders	Descriptive summary of results: - relationship between working as onshore wind technician and musculoskeletal and related physical disorders → number of studies: N=0 Evidence from similar industries: - common occurrence of ladder-related injuries (falls most likely, associated with fractures), particularly among older workers and/or among those with longer work experience in the industry → number of studies: N=3 - typical work activities of construction workers and offshore petroleum workers (e.g., walking/climbing stairs, kneeling) are similar to work activities of onshore wind workers (e.g., ladder climbing, confined space working) → number of studies: N=2 - ladder climbing increases risk of developing musculoskeletal diseases, low back pain and knee osteoarthritis and confined space working increases risk of developing low back pain and knee osteoarthritis → number of studies: N=5	/
Dethleff et al, 2016a (36) (content analysis)	Traumatic injuries, acute diseases	Medical evacuations (overall: N=39): - traumatic injuries: N=19 (49 %), acute diseases: N=16 (41 %), assignment not possible: N=4 (10 %) Traumatic accidents: - traumatological: N=17, ophthalmological: N=2 - contusion, distortion: N=9, laceration: N=7 Acute diseases: - internal medical: N=9, general surgical: N=3, orthopedic: N=3, neurologic: N=1 - of the internal medical diseases: cardiovascular disorders: N=4, gastrointestinal disorders: N=4	/
Dethleff et al, 2016b (35) (case report, N=1)	Polytrauma after a fall from an intermediate platform on a bottom plate	Descriptive summary: - concussion - fracture of the thorax with multiple rib fractures and a pulmonary contusion - burst fracture of the third lumbar vertebral body without neurological deficits - sacrum fracture - multi-fragment fractures of the lower extremities (unilateral tibial multi-fragment plateau fracture, unilateral fibula fracture, unilateral compartment syndrome of the shank, bilateral calcaneal multi-fragment fracture)	/
ILO, 2010 (25) (cross-sectional study, N=572)	General health condition, occupational diseases	Prevalence (in %, wind power plant–large-scale coal-fired plant–small-scale coal-fired plant) General health condition: - healthy: 98–79,9–76.8 - average: 0–18,8–18.3 - frail: 0–1–4.9 - gravely ill: 2–0–0 Occupational diseases: - yes: 0 – 47–55 - no: 89 – 26–16 - not sure: 11 – 27–29	/
Jia et al, 2016 (39) (cross-sectional study, N=151)	Low back pain	12-month-prevalence (in %, study population): 88.74	Risk factors: - squatting > 4 hr/day - lifting objects weighing >10 lb if done > 2x/min, > 2 hr/day - presence of somatization Protective factor: - backrest
Lárraga-Pinones et al, 2012 (27) (Case series, N=10)	Occupational allergic contact eczema, occupational irritant contact eczema	Prevalence (of all 10 suspected cases) - occupational allergic contact eczema (due to epoxy resin): N=5 - occupational irritant contact eczema (due to fibreglass): N=5	/

Continues

Table 2. continued

Study	Outcome parameter	Study findings	Influencing factors
McCague et al, 2015 (28) (cross-sectional study, N=355)	Respiratory, asthma-like, eye and nasal symptoms, color vision abnormalities, visual contrast sensitivity	Relationship "Styrene exposure and …" (Logistic regression, adjusted for smoking, gender, race, age; only significant results reported) Current styrene exposure: - chest tightness: OR=2.9 (95% CI: 1.2–6.7) Cumulative styrene exposure: - wheeze: OR=1.3 (95% CI: 1.1–1.5) - nasal symptoms: OR=1.2 (95% CI: 1.1–1.4) - eye symptoms: OR=1.2 (95% CI: 1.1–1.4) - asthma-like symptoms: OR=1.2 (95% CI: 1.1–1.5) Color vision abnormalities–prevalence comparison study population vs. population (population values from literature) - Protanopia: Male: SMR=1.5 (95% CI: 0.6–2.9), Female: unable to calculate because number observed was zero - Deuteranopia: Male: SMR=0.6 (95% CI: 0.3–1.1), Female: unable to calculate because number observed was zero - Tritanopia: Male: SMR=270 (95% CI: 105–536), Female: SMR=360 (95% CI: 73–1031) Relationship "Current styrene exposure–visual contrast sensitivity" (linear regression, effect change per 1% change in current styrene exposure, adjusted for age, smoking, glaucoma, cataracts, macular degeneration, alcoholic consumption during last 24 hr, visual acuity) - 1.5 cpd: effect estimate=-0.02 (P=0.04) - 3 cpd: effect estimate=-0.034 (P=0.03) - 6 cpd: effect estimate=-0.049 (P<0.01) - 12 cpd: effect estimate=-0.03 (P=0.04) - 18 cpd: effect estimate=-0.015 (P=0.06)	/
Moura Carneiro et al, 2013 (38) (content analysis)	Fatalities	Fatalities worldwide (1970–2011): N=80 Fatalities worldwide (ordered by period): - 1970–1979: N=1 - 1980–1989: N=8 - 1990–1999: N=15 - 2000–2009: N=40 - 2010: N=6 - 2011: N=10 Increase of the absolute number, but decrease of the relative number of fatalities worldwide since 2000	-
NIOSH, 2011 (34) (case report, N=1)	Fatality	Descriptive summary: occurrence of a fatal incident of a worker due to a crushing injury to the upper torso during the loading process of a wind turbine tower section on a railcar with two reach stackers	/
Pleban et al, 2017 (40) (cross-sectional study, N=323)	Noise annoyance	Prevalence of noise annoyance (in %, study population) - no: 5.6 - low: 68.1 - average: 17.0 - high: 9.3	/
Ponten et al, 2004a (29) (cross-sectional study, N=603)	Allergic contact dermatitis, irritant contact dermatitis	Prevalence (in %, all workers–only patch tested workers) - work related caused allergic contact dermatitis: 10.9–20.3 - work related caused irritant contact dermatitis: 6.1–11.4 - work related aggravated dermatoses: 5.1–9.5 - no relation: 5.3–9.8	/
Ponten et al, 2004b (30) (cross-sectional study, N=603)	Occupational contact allergy	Prevalence of occupational contact allergy to … (in %, study population) - … epoxy resin: 5.6 - … amine hardeners/ catalysts: 4.1	/
Rasmussen et al, 2005 (31) (cross-sectional study, N=603)	Work allergy, epoxy allergy, current dermatitis	Risk factors (Logistic regression, here only significant ORs reported, non-significant ORs see study) Work allergy (only patch tested workers) - significant: none - non-significant: gender, age, seniority, atopy, previous hand eczema, dry hands, skin-relevant hobby, daily use of skin lotion Epoxy allergy (only patch tested workers) - significant: none - non-significant: gender, age, seniority, atopy, previous hand eczema, dry hands, skin-relevant hobby, daily use of skin lotion Current dermatitis (all workers) - significant: days off work (>3 vs. 0–3): OR=2.0 (95% CI: 1.2–3.5), work allergy: OR=5.4 (95% CI: 3.0–9.9) - non-significant: gender, age, seniority, atopy, previous hand eczema, dry hands, skin-relevant hobby, daily use of skin lotion	See column "study findings".

Continues

Table 2. continued

Study	Outcome parameter	Study findings	Influencing factors
Schubert et al, 2004 (32) (Content analysis)	Work related skin disease, glassfibre dermatitis	Descriptive summary: Results of the "Gewerbeärztlicher Dienst Thüringen" (2000–2002): - procedure for recognition of an occupational diseases for skin diseases due to work related epoxy resin exposure: N=92 Results of a rotor blade manufacturing facility (2000–2002): - reports of suspected cases of skin diseases due to work related epoxy resin exposure: N=74 Results of a 3-month occupational training to become a composite technician: - occurrence of work related skin diseases (among all participants): N=67/188 (35.6%) Results of a company with permanent laminators: - occurrence of work related skin diseases: N=61 - from 2000 to 2002 about half of epoxy resin exposed workers suffered from work related skin diseases and left the company - occurrence of glassfibre dermatitis: 20%	/
Sovacool et al, 2015 (37) (Content analysis)	Fatalities	Fatalities worldwide (1874–2014): N=126 Normalized risk/TWh (1990–2013)=0.035	-
Stuhr et al, 2015 (33) (Content analysis)	Medical incidents (accidents and diseases)	Medical incidents (overall: N=319): accidents: N=190 (60%), diseases: N=123 (38%), fatal incident: N=4 (1,3%), assignment not possible: N=2 (0,7%) Diseases: complaints of the respiratory organs: N=20, various pain syndromes: N=20, complaints of the digestive tract: N=13, general physical and mental well-being: N=13, cardiovascular disease: N=7, rashes: N=6, sleep disorder: N=5, individual cases (e.g., infection, irritation): N=36, not specified: N=3 Accidents: contusion: N=52, distortion: N=21, cut: N=20, eye injury: N=19, contusion wound: N=18, fracture: N=11, burning, laceration, abrasion: each N=2–4, amputation: 0,5% (only percentage values available), others: 15% (only percentage values available), assignment not possible: N=11	/

diseases compared to coal-fired plant workers (25). According to a systematic review from 2014, no evidence was identified on the association between working on onshore wind turbines and the risk of musculoskeletal disorders (26). A later-published cross-sectional study observed a very high prevalence of low-back pain among operation and maintenance personnel working on onshore wind farms (39). A fatal incident that occurred during the loading process of a wind tower was reported (34) as was a polytrauma of an electrician after a fall from an onshore wind turbine (35).

Chemical exposures

Studies on chemical exposures were only retrieved for the production phase of rotor blades. The finding that epoxy resin systems can cause allergic reactions and result in contact eczema in the occupational setting is not restricted to production workers in rotor blade manufactories (42). Due to its excellent mechanical and chemical features, epoxy resin is used in several industrial sectors (eg, building industry, metal industry, chemical industry) (43) and hence, many professions (eg, painters, plastics processors, pavers, floorers, chemical plant operators, metal workers) are affected (43, 44). Preventive measures (eg, proper risk education and wearing adequate gloves at work) are essential due to the high prevalence of dermatological complaints, and since the substitution of epoxy resin in these industries is hardly possible (31, 43). The finding of an increased risk for respiratory symptoms due to occupational styrene exposure in the study of McCague et al is in line with a recent review which concluded that styrene exposure is a potential risk factor for non-malignant respiratory disease (45). The increased occurrence of visual contrast sensitivity in the study population was also found among professionals working with styrene in reinforced plastic plants (46, 47), but not among workers from a boat building plant (48). Even though styrene exposure concentrations in the investigated facility were mainly below thresholds recommended by the NIOSH or the American Conference of Governmental Industrial Hygienists, health effects occurred (28). The occurrence of such serious respiratory and visual complaints due to styrene exposure in wind blade facilities stresses the crucial need for advanced worker protection (eg, respiratory protection, eye protection) (28). An exposure study measuring styrene concentrations in the same facility prior to the McCague et al (49) study showed that the magnitude of exposure to styrene could be reduced through the implementation of preventive measures for the glue wipe task.

Noise exposure

Noise exposure was only examined during the operational phase of onshore wind turbines. An increased risk of noise annoyance, sleep disorders, and general health problems due to exposure to noise from onshore wind turbines does not solely emerge among workers, but also

Table 3. Methodological assessment of observational studies and content analyses [LR=low risk; HR=high risk; NA=not applicable; UR=unclear risk]

Study	Reporting quality	Selection process				Information bias		Inclusion of confounders	Generalization	Ethical issues		
		Sampling	Response rate	Eligibility comparison group	Bias	Exposure	Outcome			Conflict of interest	Funding	Ethics committee
Abbasi et al, 2015a (22)	LR	LR (complete survey)	LR	LR	LR	LR	LR	LR	HR	LR	UR	UR
Abbasi et al, 2015b (24)	LR	LR (complete survey)	LR	LR	LR	LR	LR	LR	HR	UR	UR	UR
Abbasi et al, 2016 (23)	LR	LR (complete survey)	LR	LR	LR	LR	LR	LR	HR	LR	LR	UR
Asian et al, 2017 (41)	LR	NA	NA	HR	HR	LR	LR (fatalities) UR (injuries)	HR	LR	UR	UR	NA
Dethleff et al, 2016a (36)	LR	NA	NA	HR	UR	UR	LR	HR	HR	LR	LR	NA
Dethleff et al, 2016b (35)	LR	HR	NA	HR	HR	LR	LR	HR	HR	LR	UR	UR
ILO, 2010 (25)	HR	HR (convenience)	LR	LR	HR	UR	HR	HR	HR	UR	UR	UR
Jia et al, 2016 (39)	LR	UR	LR	HR	UR	LR	LR	UR	HR	LR	LR	LR
Lárraga-Pinones et al, 2012 (27)	LR	HR (convenience)	NA	HR	HR	LR	LR	HR	LR	LR	UR	UR
McCague et al, 2015 (28)	LR	LR (complete survey)	LR	LR	LR	LR	LR [a] HR [b]	LR	HR	UR	LR	LR
Moura Carneiro et al, 2013 (38)	HR	NA	NA	HR	HR	LR	LR	HR	LR	UR	LR	NA
NIOSH, 2011 (34)	LR	HR (convenience)	NA	HR	HR	LR	LR	HR	HR	UR	UR	UR
Pleban et al, 2017 (40)	HR	UR	UR	HR	UR	HR	LR	HR	UR	UR	LR	UR
Pontén et al, 2004a (29)	LR	LR (complete survey)	LR	HR	LR	LR	LR	HR	HR	UR	LR	LR
Pontén et al, 2004b (30)	LR	LR (complete survey)	LR	HR	LR	LR	LR	HR	HR	UR	LR	LR
Rasmussen et al, 2005 (31)	LR	LR (complete survey)	LR	HR	LR	LR	LR	LR	HR	UR	LR	LR
Schubert et al, 2004 (32)	HR	NA	NA	HR	UR	UR	UR	HR	HR	UR	UR	NA
Sovacool et al, 2015 (37)	LR	NA	NA	LR	UR	LR	LR	HR	LR	UR	UR	NA
Stuhr et al, 2015 (33)	HR	NA	NA	HR	UR	UR	UR	HR	HR	LR	UR	NA

[a] Color vision abnormalities, visual contrast sensitivity.

[b] Subjective symptoms.

among residents living in the vicinity of onshore wind turbines (6–8). In contrast to residents, who are exposed to wind turbine noise during the day and night, workers are only exposed during their working time. It is not clear from the study if workers also lived near the wind turbines of concern and thus were also exposed to wind turbine noise while sleeping, or if sleep disturbances due to wind turbine noise occurred independently from their living situation (and if so, why).

Accident risks

Two studies reported accident data from the German offshore wind industry (33, 36). Both studies aimed to gain knowledge about actual prevalence rates of medical incidents occurring on offshore wind farms in order to improve emergency care measures, not to solely show the amount of injuries and accidents that were attributable to the work. Thus, it should be kept in mind that not all injuries and accidents presented were work-related. In addition to prevalence rates, information on accident causes and working activities associated with accidents were given. Of all accidents of which information on accident causes were available, 59% were mechanically caused, 23% were so called "stumble, slip, and fall" accidents, 6% of the accidents were of electrical background, 3% were diving accidents, 2.5% were related to hazardous substances, and 2.5% were heat-related accidents. The working activities related to accidents were craftwork (36%), loading work (17%), general locomotion (15%), lifting and carrying tasks (5%), crew transfer, diving tasks, and cleaning work (3% for each case). The study

Table 4. Methodological assessment of the systematic review [LR=low risk; HR=high risk; UR=unclear risk]

Study	Reporting quality	Review process						Generalization	Ethical issues	
		Literature search	Title-abstract screening	Full text screening	Data extraction	Critical appraisal	Data analysis,-synthesis		Conflict of interest	Funding
Cooper et al, 2014 (26)	LR	LR	UR	UR	UR	LR	LR	LR	LR	LR

authors compared their results with data from other industries. The distribution of accident types is similar for on- and offshore industries. Furthermore, the bodily locations of injuries in the offshore wind industry resemble those occurring in the German construction industry. Moreover, the number of extremity and head injuries, as well as the causes for injuries are in line with occupational accident data in Germany (33). The four fatal incidents occurring within four years in the vicinity of four offshore wind farms seems to be high, but it is unclear if these were caused by offshore work. Since the number of workers employed in the study period is not available, direct comparison with other data on fatal accidents at work is not possible. Dethleff et al (36) observed no fatal incident among their study population. According to statistics of the Employers' Liability Insurance Associations responsible for, amongst others, offshore wind workers, 33 and 54 fatal accidents occurred during installation and operation, respectively, in 2012 in Germany (50).

Despite an extensive literature search, only two case reports about accident consequences were found (34, 35). Another NIOSH report describes a fatal incident of a construction worker falling from a wind tower, but was not included since it was published prior to 2000 (51). According to the findings of a risk estimation method for onshore wind farms, maintenance workers carry a higher occupational risk than construction workers, and most important hazards are falling from heights and being hit by falling objects (52). To avoid such risks, preventive measures (eg, safety training, positioning of signs and warnings for dangerous areas, or monitoring of safe work practices) are recommended (52).

Globally, around 100 fatal accidents in the environments of operating wind turbines were identified (37, 38). The absolute number of wind turbine fatalities is smaller compared to fatalities of fossil fuel and hydroelectricity facilities, and is equal to fatalities in facilities of other forms of renewable energy, but wind energy has the highest normalized fatality risk (per terawatt hour) among all energy forms investigated (followed by hydroelectricity, solar energy, and biomass energy) (37). Another content analysis presented attributes for predicting such fatal accidents in wind turbine settings (eg, the lifecycle phase or the power of a wind turbine) (41). All three included content analyses did not specify the population of interest. Since it is assumed that most subjects were workers, it was decided to assign the content analyses to the working environment scoping review. Nevertheless, it cannot be guaranteed that some accidents also concerned the general population.

Physical exposures

The included systematic review found no studies on musculoskeletal disorders among technicians of the onshore wind industry and concludes that research related to the unique nature of ladder climbing and confined space working on onshore wind turbines is needed (26). A later published study observed a very high prevalence of low-back pain among operation and maintenance personnel, whose working tasks mainly took place in very narrow spaces and necessitated adverse postures like stooping, squatting or prone positioning (39). It should be noted that the study had no comparison group, and thus the actual risk could not be calculated. In regard to physical exposures, working on onshore wind turbines is comparable to working activities of other professions like telecommunication workers, offshore oil and gas workers, construction and maintenance workers, firefighters, military personnel, and electricians (26, 53, 54).

General health risks

The comparison of workers' health between coal-fired and wind power plants in China needs to be interpreted carefully (25). The two health outcomes of interest (general health and occupational diseases) were only determined by one question each. The study setting and resulting work conditions are probably not comparable to those of other industrial nations. Other studies comparing these two energy sectors concerning workers' health were not identified.

Wind-industry-specific risks and risk patterns

Health effects associated with exposure to substances used in the rotor blade production like epoxy resin or styrene are not a wind-industry-specific problem, but rather appear in other industries as outlined above. Similarly, physical risk factors occurring during the operation of onshore wind turbines are not specific to the wind industry.

Working in the offshore wind industry is characterized by its remoteness, difficult accessibility, and long working hours (53). During the construction and the operational phases of offshore wind farms, physical, chemical and biological exposures, accident hazards, and musculoskeletal and psychological strains may occur (53–55). These risks are typical for working activities in complex, big construction sites, large-scale electrical plants, or offshore oil and gas rigs. However, further industry-specific hazards exist, such as the transfer of people from a vessel or helicopter to the offshore turbine or the exposure to adverse weather conditions (53).

As described, most of the job hazards of the wind energy industry are not unique, but the combination of these hazards as well as the sometimes special and extreme working conditions are (3).

Research gaps and need for research

With respect to the onshore wind industry, no observational studies on health impacts among employees working in the construction phase or during the operational and maintenance phase concerning psychosocial, or chemical exposures were identified, and only one concerning physical exposures exists. Since working conditions differ among on- and offshore wind turbines, appropriate research in the area of onshore wind turbines should be conducted to provide first hints about specific work-related risks as well as disorders (26).

The number of injuries and accidents that are attributable to work on off- and onshore wind turbines in comparison to other industries is unknown.

Results of the scoping review also reveal a lack of research concerning health effects in the offshore wind industry. Currently, physical and psychological strains of offshore wind industry employees are being examined in the German "BestOff" study in order to develop a concept for reducing these strains (www.bestoff-offshore.de). Due to the specific working conditions of offshore wind farms, workers in Germany have to undergo an occupational health eligibility check (56). A need for psychological and physical health promotion of offshore workplaces is suggested (57).

No studies were carried out in the later phases of the wind turbine life cycle (decommissioning, recycling and waste management), probably because the wind energy sector is a relatively young industry. According to the European Agency for Safety and Health at Work, the challenge in the repowering and decommissioning phase is mainly about personnel issues (eg, subcontracts, shortage of trained workers). Dismantled blades can be disposed via landfill, incineration, or recycling, which present individual risks of soil and air pollution with different substances (3).

Although there is an increase in the annual installed capacity of wind energy in Latin America and Asia (58), and although 41 000, 48 000, and 507 000 direct and indirect wind power jobs have been reported in Brazil, India, and China (1), respectively, studies from these continents and countries are rare or missing.

Strengths and weaknesses of the review

A scoping review was executed to summarize the width and novelty of the scientific topic of health effects of wind turbines in the working environment based on appropriate methodological concepts, but with the rigorous and transparent procedure of a systematic review. A comprehensive search strategy was applied. The systematic selection process was based on well-defined inclusion and exclusion criteria. Two independent reviewers carried out most of the review steps (in parallel or at least in duplicate). Methodology assessment, even if it is not obligatory in scoping reviews (10), was undertaken to provide an overview of methodological aspects that seemed to be of importance.

During the review process, some modifications were adopted. Initially, it was planned to only search MEDLINE, EMBASE, and CINAHL. A later examination of all included studies revealed, that most of these studies were retrieved by hand searches, and not via the aforementioned databases. Furthermore, many of the studies identified by hand searches were not listed in MEDLINE, EMBASE, and CINAHL (and thus could not be found with these database searches), but instead were found in the Web of Science and Scopus. As a result, it was decided to search these two databases a posteriori. Thereby, further relevant studies were identified. Only one reviewer screened the identified titles and abstracts of the updated database searches and the Scopus search. Nevertheless, a second reviewer double-checked full-texts of relevance. Furthermore, content analyses were included, although not considered a priori. The categories of methodology assessment were defined in a later review phase. Such an iterative procedure is explicitly encouraged in methodological papers concerning scoping reviews (9, 11, 12).

Due to the diversity of the considered study designs, it was not possible to use one unique appraisal tool for methodology assessment. The procedure applied carries the risk of subjectivity, and thus assessment results should be regarded with caution. Categories and judgment criteria were based upon validated appraisal tools, but still selected subjectively; thus, validity cannot be guaranteed. Furthermore, only one reviewer performed the risk of bias judgment. However, the judgment was based on the evaluation of methodological strengths and weaknesses of each study, which a second reviewer double-checked.

Pure exposure studies were not considered within this scoping review. Thus, studies comparing wind industry-specific exposure rates with respective rates occurring in other industries could have been missed. In case of similar exposure rates, health impacts from these sectors could have been transferred to the wind energy setting.

Concluding remarks

During the lifecycle of a wind turbine, different work activities take place, eg, manufacture of rotor blades, transportation of a wind tower, installation of the whole wind turbine assembly, maintenance tasks on operating wind turbines, dismantling, and waste management. Hazards associated with these activities resemble those of other industries, but the combinations of these hazards as well as some specific working conditions characterize the unique position of the wind industry. A principal distinction should be made between working conditions on off- and onshore wind turbines, especially in regard to weather conditions and accessibility of the workplace. To date, no specific overall health effects of working in the wind sector have been shown. Based on previous research, health risks in the occupational setting of wind turbines comprise in particular skin disorders due to epoxy resin in the rotor blade production, wind turbine accidents and resulting injuries and fatalities, and consequences of noise from onshore wind turbines on workers' health concerning annoyance, sleep, and general health. There is a need for further research particularly in terms of psychological disorders associated with working on offshore wind turbines – due to, amongst others, increased mobility requirements and social isolation – and in terms of musculoskeletal complaints and diseases among on- and offshore workers due to working in confined spaces or ladder climbing. Furthermore, research is needed in relation to work-related injuries, accident rates, and health risks associated with the decommissioning, recycling, and waste management phase of wind turbines.

Conflict of interest

The authors declare no conflict of interest.

Funding

None. PROSPERO registry number: CRD42016035836

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Received for publication: 13 September 2017